APPENDIX A

INVESTIGATIONS OF THE EFFECTS OF POROUS PAVEMENT ON TRAFFIC NOISE AND TRAFFIC NOISE PREDICTION

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INTRODUCTION

One missing element in implementing pavement type in TNM is the effect of sound absorbing pavements on the predicted noise levels. Currently in TNM, pavements are modeled as acoustically hard so that all of the incident sound from the vehicles is completely reflected. For porous pavements (pavements with more 15% interconnected air voids), two effects contribute to reducing the wayside noise levels[1]. First is the reduction of the source mechanisms related to air displacement in the tread pattern as it rolls in and out of contact with the pavement, often referred to as tread air-pumping. This effect is captured by OBSI measurements made close to the tire-pavement noise source. The second effect occurs as the sound propagates away from the vehicle. Any sound incident on the pavement is partially absorbed reducing the noise level for receivers along the roadway relative to that for a non-porous surface.

EXPERIMENTAL INVESTIGATIONS

These two porous pavement effects were clearly indicated in measurement results obtained under Caltrans-sponsored work done at the National Center for Asphalt Technology Test Track in Alabama. In this research, sound propagation measurements were made over both porous and non-porous asphalt concrete (AC) pavements[2]. The sound propagation effect was isolated using a compact loudspeaker ground level noise source to simulate tire/pavement noise. Simultaneously, the source levels were measured with sound intensity and the sound pressure levels were measured at locations 25 ft (7.5 m) and 50 ft (15 m) away with microphones positioned 5 ft (1.5 m) above the ground (Figure A1). The sound pressure levels were subtracted

Figure A1: Photograph of sound propagation tests over a porous pavement at NCAT from a ground level speaker source and microphones 25 ft and 50 ft distant from the sound intensity levels to obtain the attenuation between the source and receiver. The attenuation values were then subtracted from an arbitrary source level of 100 dB in each one-third octave band to produce the lower plots of Figure A2. These plots then provide a

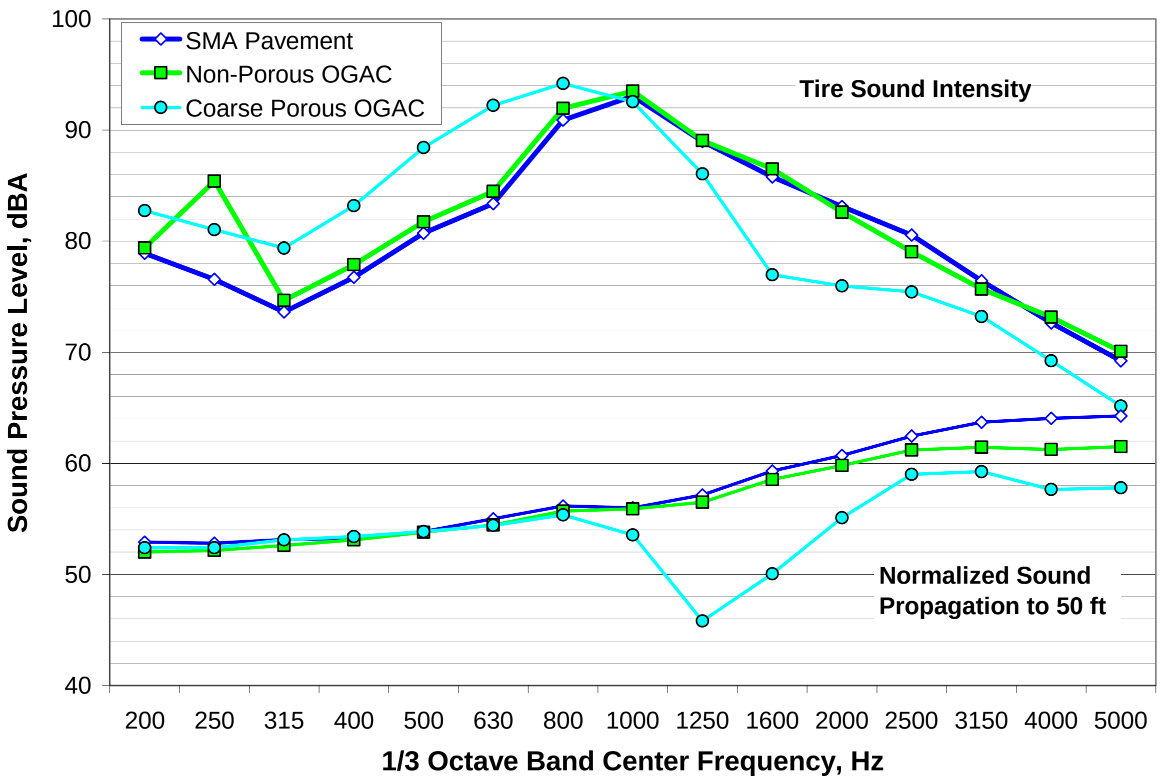

Figure A2: Tire noise sound intensity and sound propagation for a ground level speaker noise source over porous and non-porous pavements

visualization of how the difference in sound absorption between the porous and non-porous pavements will affect the sound levels received for a defined source level. In the upper portion of this figure, the reduction in tire noise source strength as measured with OBSI is shown and displays a characteristic dip centered at 1600 Hz. To further isolate the propagation effect, the difference in attenuation between the porous and non-porous pavements was calculated. Figure A3 shows the resulting increase in attenuation (i.e. lower noise levels) for the porous relative to the non-porous pavement. For this particular porous pavement, a large, almost 11 dB excess attenuation is seen at 1600 Hz for propagation over 50 ft of the porous pavement with positive but lower values between 1000 and 5000 Hz. For propagation over 25 ft of porous pavement, this effect is somewhat reduced.

The results of Figure A3 can be applied to a typical highway noise L_{eq} (equivalent continuous noise level) spectra measured at 50 ft to examine the potential effect of the porous pavement. Data from the Arizona QPPP were used as measured for the asphalt rubber friction course[3]. The attenuations for 25 ft and 50 ft of propagation over the porous pavement were subtracted from the QPPP results producing the plots shown in Figure A4. The corresponding overall A-weighted sound pressure levels were calculated and are also shown in Figure A4. These indicate

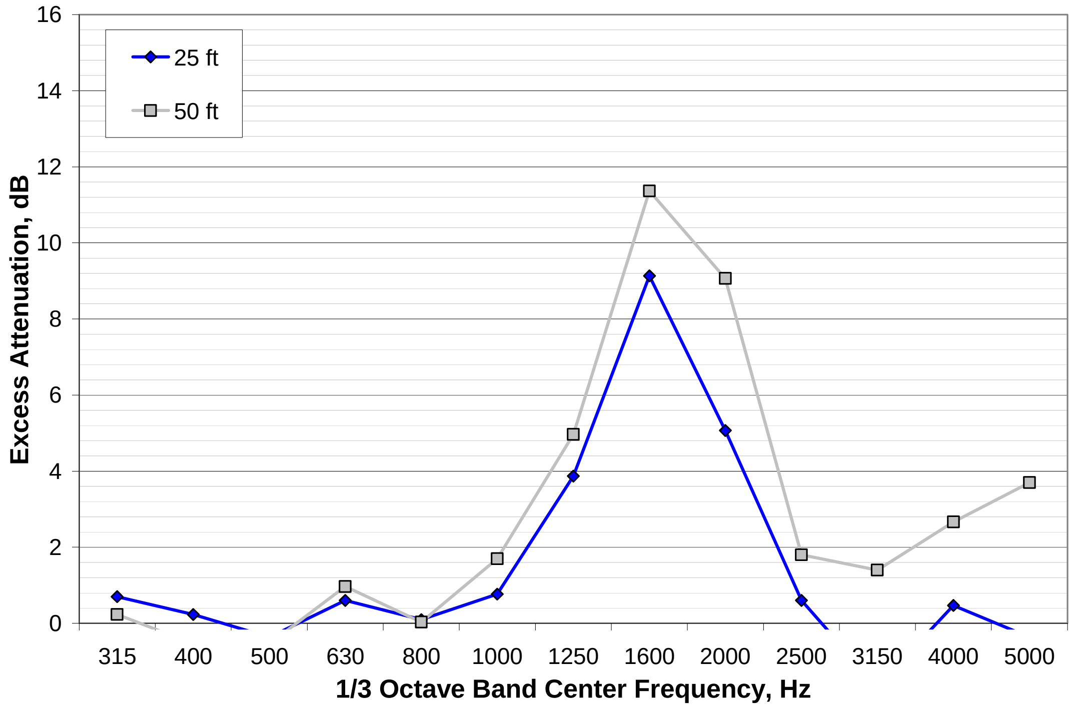

Figure A3: Increase in attenuation for sound propagation over a porous pavement compared to a non-porous pavement

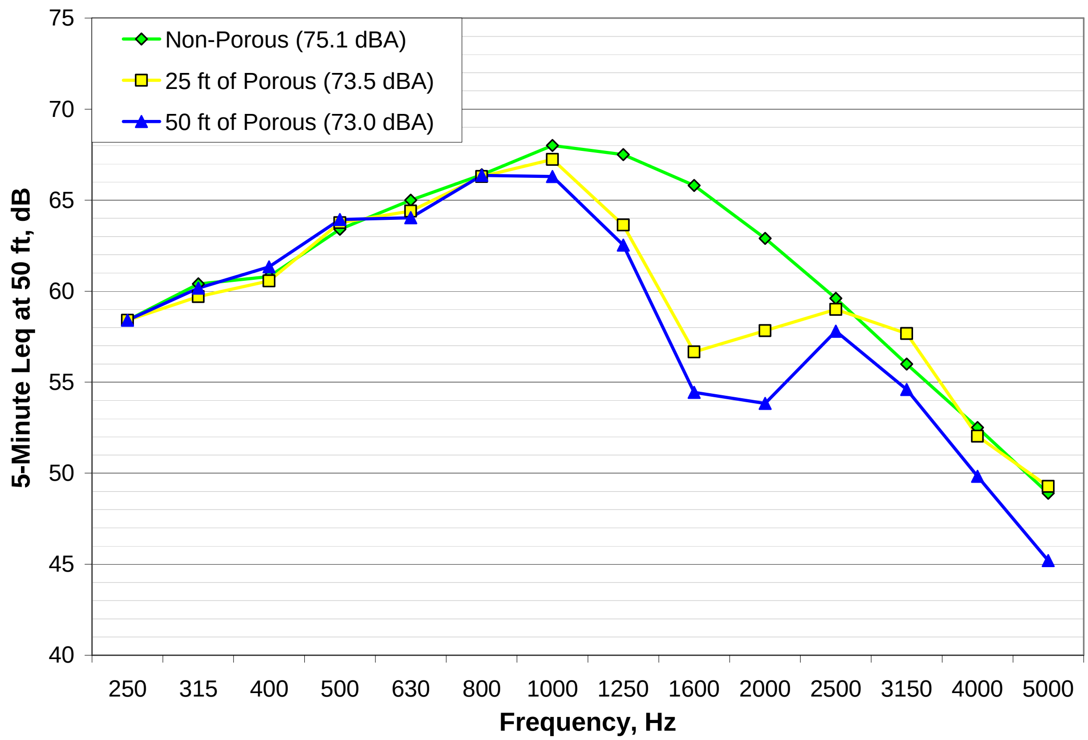

Figure A4: Calculated effect of sound propagation over different lengths of porous pavement compared to non-porous for wayside CTIM measuremetns a 1.6 dB reduction for propagation over 25 ft of porous asphalt and a 2.1 dB reduction for propagation over 50 ft of porous asphalt. The resultant spectra shapes are very similar to those measured for Caltrans I-80 Davis quieter pavement project in which a porous open graded asphalt concrete overlay was placed on an existed aged dense graded asphalt concrete[4] (Figure 6).

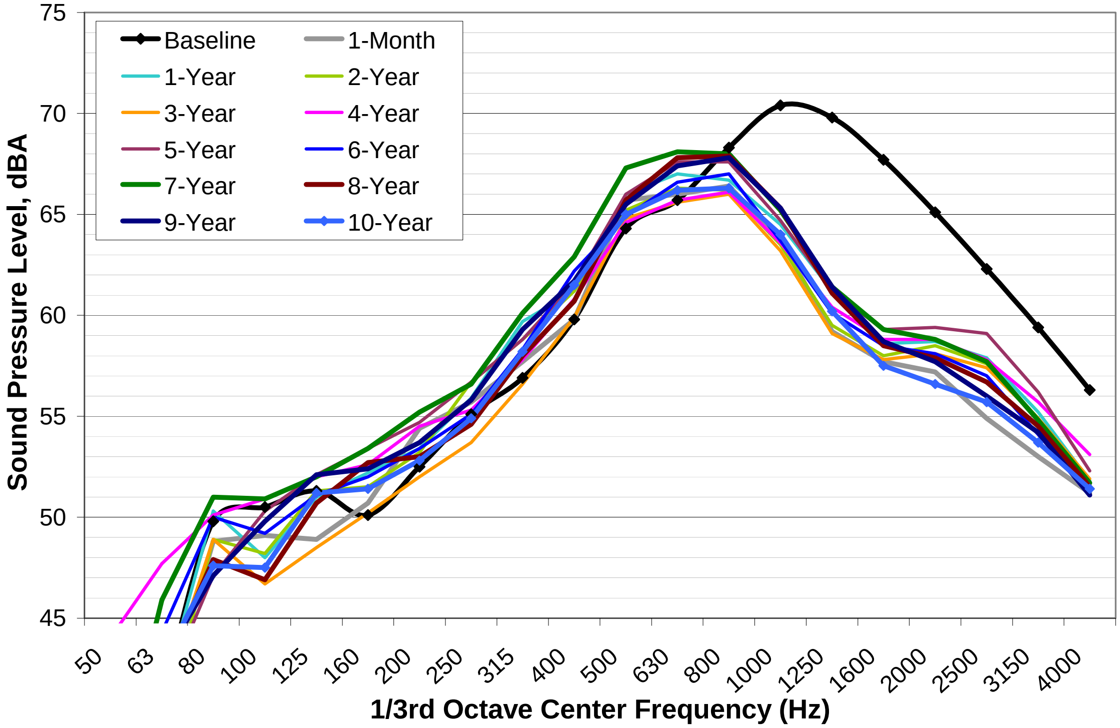

Figure A5: 5-minute Leq wayside sound pressure levels at Caltrans I-80 Davis pavement research for original DGAC and OGAC porous overaly up to 10 years old

THEORETICAL INVESTIGATIONS

The effects of porous pavement can also be evaluated using TNM. In the current model, all roadway pavements are taken to be acoustically hard with an EFR of 20,000 cgs rayls, where 1 rayl = 1000 Pascal·second/meter. Using a modified version of the model, the EFR value for the pavement can be changed to a point that it approaches values that would be expected for a porous pavement. Initially, this was evaluated for FHWA under the TNM Pavement Effects Implementation Study[5] for a few cases. The complete results of this analysis have been made available to the Research Team for consideration in the development of the Working Plan for Phase II. For this analysis, a two-lane highway and an eight-lane case were considered using traffic mixes and site geometries from actual cases taken from the TNM validation study and the Arizona QPPP. TNM v2.5 was run for both hard and soft ground next to the highway and in the median. For the pavement, EFR values ranged from 2,000 to 20,000 cgs rayls. A range values from 4,200 to 20,000 cgs rayls had been measured previously on a number of generally non-porous pavements. The lower value of 2,000 cgs rayls was added to be represent a range reported in the literature of about 1,400 to 2,000 cgs rayls for more porous pavements[6,7,8]. Predicted traffic noise levels were then calculated over a range in distance of 50 to 1000 ft from the center of the near lane of travel. In Figure A6, predicted TNM results at a distance of 50 ft

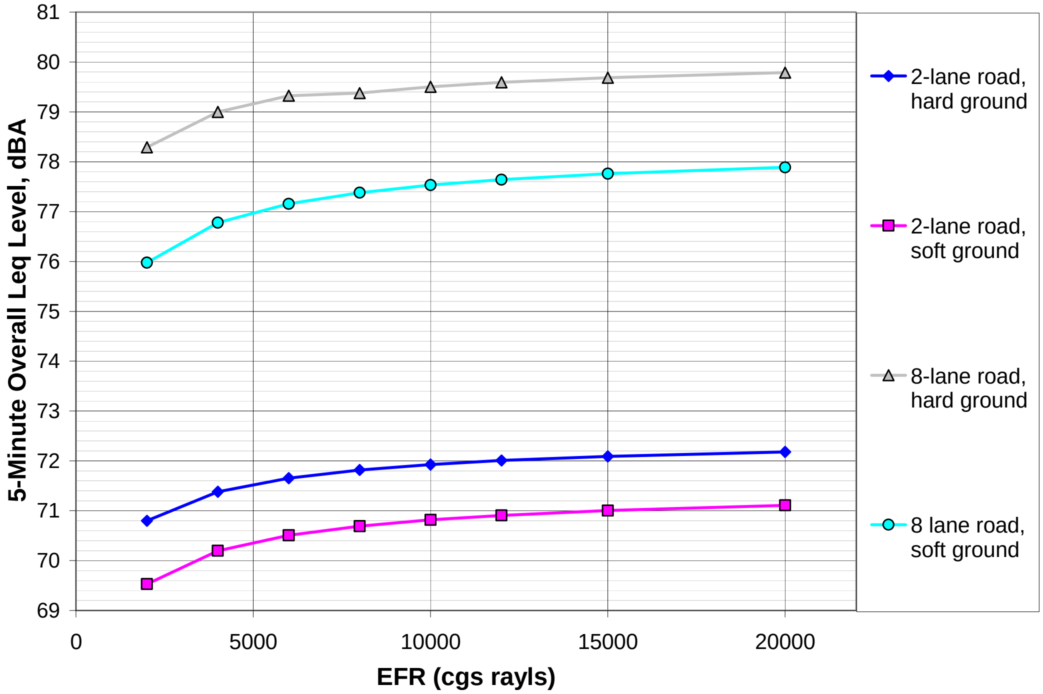

Figure A6: Overall TNM results for different highway and site configurations for a microphone location 50 ft from the center of the near lane

for 2 and 8 lane roadways and soft and hard ground types are plotted against the EFR values of the pavement. These results indicate that for the 8 lane roadway, going from an acoustically hard pavement (20,000 cgs rayls) to pavement with some sound absorption (2,000 cgs rayls) produced almost a 2 dB reduction in the predicted level. As would be expected, for the 2 lane case where less propagation is over the absorptive pavement, the effect is about 1 dB.

One-third octave band spectra with EFR values as a parameter are shown in Figure A7 as calculated with the modified TNM at 50 ft for the 8-lane freeway case and soft ground. These results indicate that the reductions with decreasing EFR are frequency dependent. In the extreme, around 2000 and 2500 Hz, the levels with the more absorptive 2,000 cgs rayls pavement are about 4 dB lower than the impervious pavements (12,000 to 20,000 cgs rayls). The frequency region where the reductions take place are also very similar to those observed from Figures A4 and A5. The effect of absorptive pavement is not just localized near the edge of the freeway at 50 ft, but extends out in distance to 800 ft as shown in Figure A8.

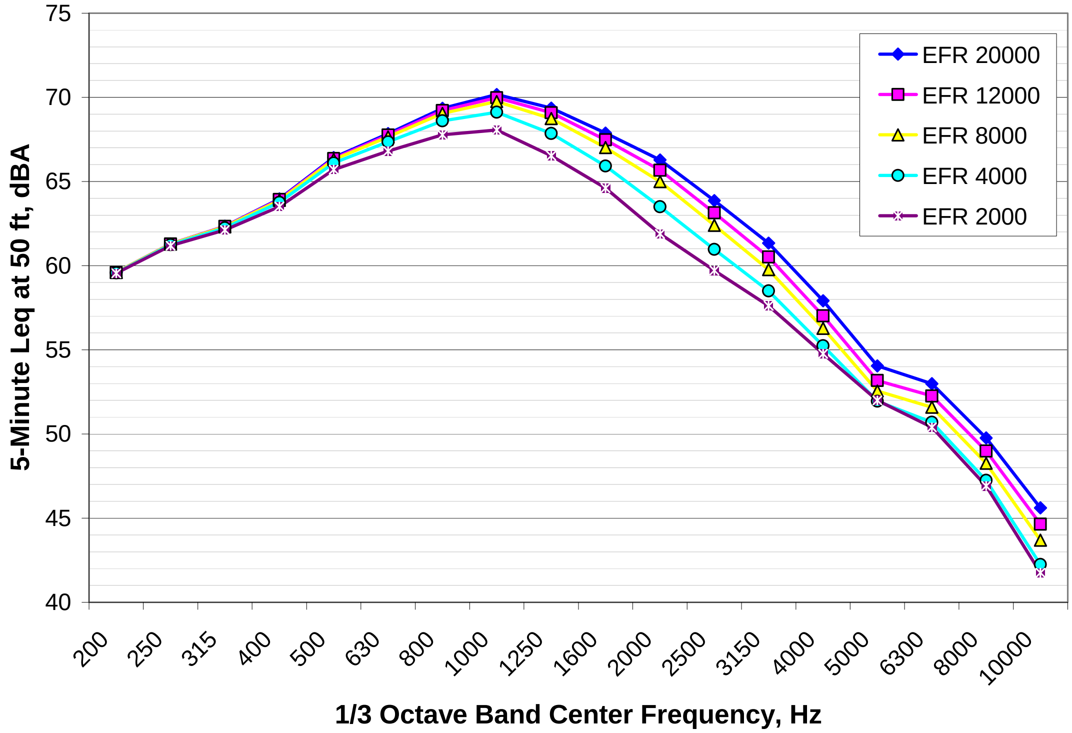

Figure A7: TNM results for 8 lane highway with pavement of varying sound absorption (EFR values) with soft ground beyond the edge of pavment

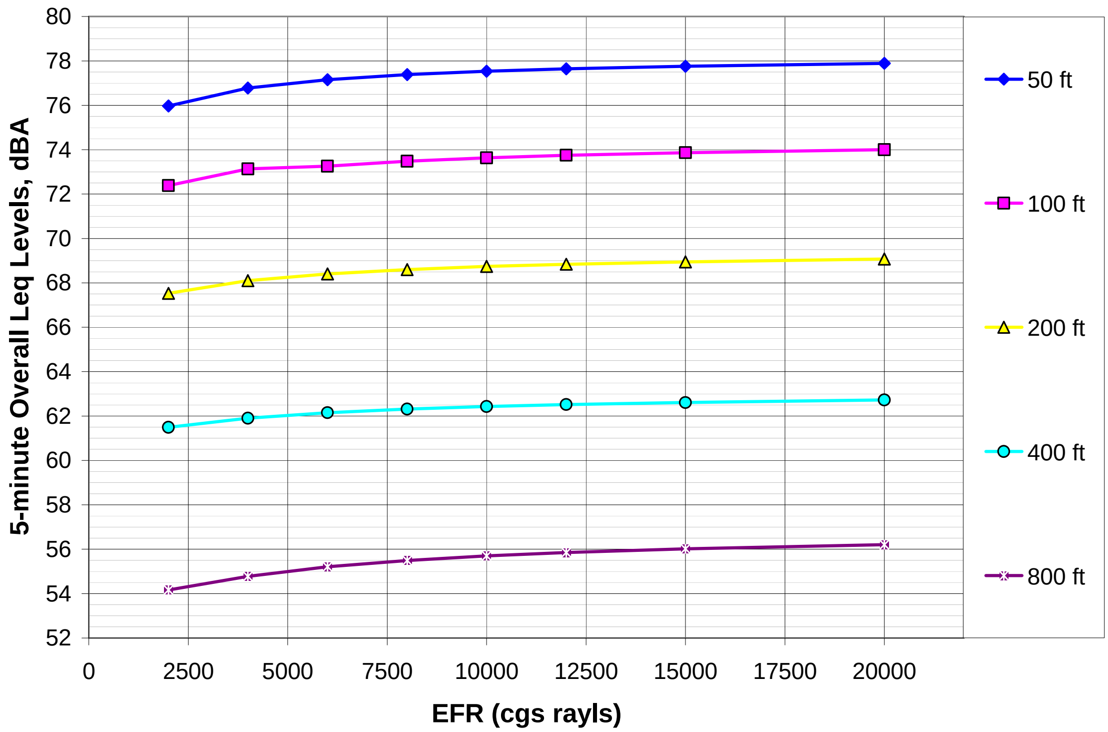

Figure A8: Overall TNM results for 8 lane highway with pavement of varying sound absorption (EFR values) with soft ground beyond the pavement at varying distance

The results of the TNM study and field data of Figure A2 indicate that the sound absorption produced by porous pavements will have an effect on both measured and predicted traffic noise levels. For assessing the performance of quieter, porous pavements over time, monitoring and accounting for this parameter is of some importance. Although the effect of porous pavements on tire/pavement source levels can be monitored with on-board measurements, the effect of the sound absorption on the propagation of sound to the receiver location needs to be considered as an added noise reducing feature of the pavement. If absorption is included in TNM as part of the analysis of noise mitigation for a project, then some means of monitoring its performance over time should be added to monitoring tire/pavement source levels.

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APPENDIX B

LIFE CYCLE COST ANALYSIS

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INTRODUCTION

Life cycle cost analysis (LCCA) is an economic evaluation of feasible alternative investment strategies. LCCA enables an equitable comparison of the total cost for various competing pavement design alternatives (new or rehabilitation). Costs to be considered in the LCCA include all agency costs that are incurred over the life of each alternative, such as initial construction costs, future maintenance and rehabilitation costs, and future salvage value. Costs borne by the users of the facility, such as user delay and vehicle operating costs, may also be considered, especially in heavily trafficked urban areas. User costs typically represent expenses that are not directly incurred by the agency, but instead reflect the costs to the users of the facilities due to construction delays or additional vehicle wear and tear.

Since maintenance and rehabilitation costs can be expected to occur at various times throughout the life of the pavement, the costs are converted to an equivalent basis for comparison. This conversion allows an agency to compare one strategy that might have high initial costs and low annual maintenance costs with another that might have a lower initial construction cost but higher maintenance and rehabilitation costs. In order to compare strategies with costs incurred at different times throughout the analysis period, the costs are normally brought back to a baseline period, such as the year in which the project will be constructed. Various techniques are available to convert future costs to a present value.

The results of the LCCA analysis will identify a lowest cost alternative; however, it should be recognized that LCCA is only a tool to be used in conjunction with other engineering based decisions in the selection of the most appropriate pavement design or rehabilitation alternative. Many highway agencies consider competing alternatives to be equivalent if the difference in their LCC is less than 10 percent. When this is the case, factors other than LCC (e.g. constructability, pavement type of adjacent segments, future capacity improvements) would be considered for selecting the viable alternative.

Common pavement applications of LCCA include the following (FHWA, 2003; Caltrans, 2007):

- Evaluation of new pavement structures (flexible, rigid or composite);
- Evaluation of pavement rehabilitation strategies;
- Evaluation of alternatives or strategies with different pavement lives.

CONDUCTING A LIFE CYCLE COST ANALYSIS

There are four primary steps for conducting a LCCA (FHWA, 2002).

1. **Establish design alternatives.** A minimum of at least two distinct pavement design or rehabilitation strategies must be considered in the LCCA. For new construction, this could include a hot mix asphalt (HMA), portland cement concrete (PCC) and/or composite (typically considered to be HMA over PCC) pavement alternative. In the case of rehabilitation, this could include such options as a HMA overlay, a PCC overlay, or diamond grinding.

2. **Determine activity timing.** This step establishes the timing of future rehabilitation and/or maintenance treatments for each alternative. Each agency establishes the timing of the various rehabilitation treatments, typically based on desired levels of pavement condition (cracking, rutting and/or roughness thresholds). The concept of initial construction and subsequent rehabilitation treatments in relation to pavement condition is shown in Figure B1.

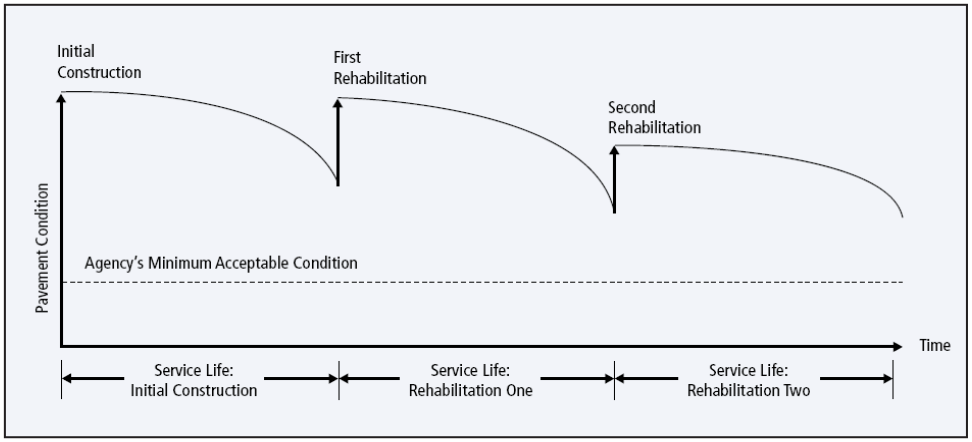

Figure B1: Pavement service life (FHWA, 2002).

Treatment service life (or performance period) is defined as the timing between rehabilitation and/or maintenance treatments. Timing for rehabilitation and/or maintenance treatments is usually based on existing construction and pavement performance history contained within an agency's pavement management system. When the service life is unknown or not well established (e.g. due to new technology or materials) engineering judgment will be required to determine an appropriate service life. Though pavement service life can vary widely from region to region due to various climatic and loading effects, Table 1 provides a summary of typical treatment service lives.

3. **Estimate agency and user costs.** As previously mentioned, agency costs should include all costs associated with the initial construction, rehabilitation and maintenance of the pavement facility (Figure B2) over the specified analysis period (described below). Costs that are similar (e.g. guardrail, right-of-way, lighting, signage) for each alternative can be excluded from the cost estimate. Estimates for future rehabilitation and/or maintenance costs should be determined based on constant dollars and discounted to the present using a discount rate (discussed below). Using constant dollars and discount rates eliminates the need to use inflation factors for future costs (WSDOT, 2005). Details of agency and user costs are further described below:

Table B1: Typical pavement performance lives (Hall et al., 2001, FHWA[1]).

Treatment Type	Performance Life (years)
Fog or slurry seals	3 – 5
Chip seals	3 – 7
Patching	4 – 8
Crack sealing	1 – 3
Joint resealing	5 – 10
Thin HMA overlay of HMA pavement	4 – 8
HMA surface recycling without overlay	4 – 8
Open-graded friction course	8 – 12
HMA overlay	8 – 15
Diamond grinding	10 – 15
Load transfer restoration	10 – 15
PCC overlay	15 – 30
PCC pavement	20 – 50

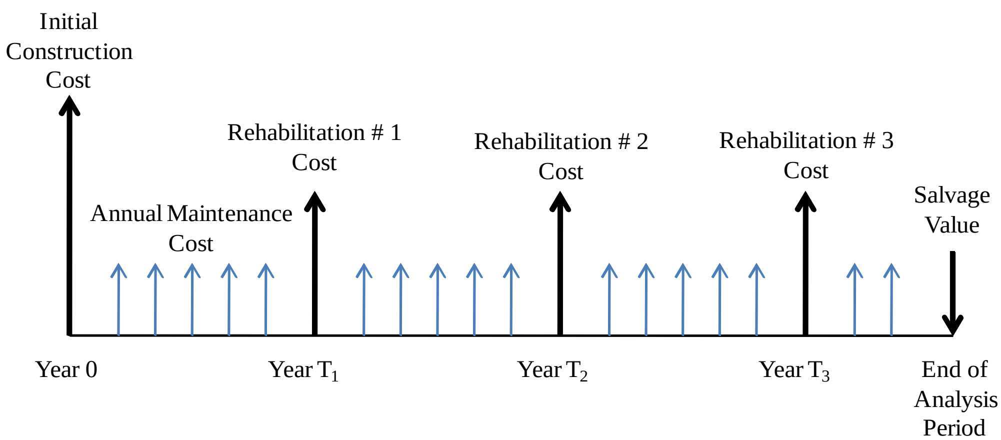

Figure B2: Cash flow diagram.

Initial construction costs include all costs related to the construction and/or rehabilitation of each pavement alternative. Construction cost estimates will vary from region to region due to material availability, project scope and applicable construction specifications. Construction cost estimates can be based on previous history or current construction projects utilizing bid item tabulations or engineering judgment in the case of new materials or techniques.

Rehabilitation costs include all costs related to future rehabilitation costs. Similar to construction costs, estimates can be based on bid item tabulations or engineering judgment in the case of new materials or techniques.

[1] Pavement Preservation Compendium website - http://www.fhwa.dot.gov/Pavement/preservation/ppc0302.cfm

Maintenance costs that are unique to each pavement alternative (e.g., crack sealing and patching for HMA pavements; joint sealing and patching for PCC pavements) should also be included. These costs are typically represented as an annual cost for the routine maintenance of the pavement surface.

Salvage Value is the value of the strategy or treatment at the end of the analysis period. The use of a salvage value implies that the strategy or treatment has either not reached its useable life by the end of the analysis period or that the roadway materials provide value (e.g. recycling) for future work. Estimation and use of salvage value varies widely among highway agencies. One method for characterizing the salvage value is by multiplying the last treatment construction cost by the ratio of the treatments remaining service life to the treatments expected service life (Equation 1).

$$\text{Salvage Value} = \text{Treatment cost} \times \frac{\text{Treatment remaining life}}{\text{Treatment expected life}} \qquad \text{(Equation 1)}$$

As an example, assume that treatment A has a construction cost of $2,000,000 with an expected life of 10 years. At the end of the analysis period, treatment A has only reached an age of 6 years; therefore, treatment A has 4 more years of remaining service life. Using equation 1, the salvage value for treatment A is $800,000 ($2M x 4 years/10 years) .

User costs are costs that are incurred by the users of the facility related to increased vehicle operating costs, costs due to speed changes, delays and detours caused by construction, rehabilitation and maintenance activities, or crash costs. User costs are one of the more difficult costs to determine primarily since they are non-agency costs. Though not commonly incorporated into the life cycle cost analysis (AASHTO, 2007), state highway agencies that either include or are in the process including user costs do so in relation to user delay through the construction zone. Of those states incorporating user costs into the LCCA process, the majority have adopted the procedures outlined in the FHWA RealCost program[2].

4. **Compute life cycle costs**. Since the above described costs can occur at different times and the value of money varies according to the year in which it occurs, the construction, rehabilitation and maintenance costs cannot be simply added together for determination of life cycle costs. To incorporate the time value of money, an economic analysis must be conducted to convert future anticipated costs into current dollars so that a direct comparison of alternatives can be conducted. The following describes the required inputs and methods for conducting the economic analysis.

   Analysis Period is the length of time over which the life cycle cost analysis is based. An analysis period should be of a sufficient span of time to include initial construction or major rehabilitation and at least one additional rehabilitation treatment for each alternative (FHWA, 2002); however, it is not necessary for each alternative to have the same number of rehabilitation treatments. Many state highway agencies (AASHTO, 2007) have adopted analysis periods ranging from 28 to 50 years.

[2] FHWA RealCost software - http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm

Discount Rate is the interest rate used to convert future costs to present dollars, and may be determined in a number of different ways. Many transportation agencies estimate the discount rate as the difference between the interest rate and the inflation rate. Discount rates ranging from 3 to 5 percent are typically used, which are based on the returns of U.S. Government Treasury Notes and future forecasts of inflation. Many state highway agencies determine the appropriate discount rate as reported in the OMB Circular A-94 (OMB, 2006).

The LCCA results are very sensitive to the discount rates that are used in the analysis. Generally speaking, the use of lower discount rates favor projects with higher initial costs but lower future (i.e., maintenance and rehabilitation) costs, whereas the use of higher discount rates favor projects with lower initial costs but higher future costs.

Net Present Value method involves the conversion of current and future expenses, which typically occur during different time periods, into a single amount, generally in today's costs. Future costs are converted into present value by applying a discount factor based on the timing that the cost is incurred. The general form of the net present value equation is as follows:

$$NPV = F \frac{1}{(1+i)^n} \tag{Equation 2}$$

where,

NPV	=	Net Present Value
F	=	Future sum of money at the end of n years
n	=	Number of years
i	=	Discount rate

Equivalent Uniform Annual Cost is an economic procedure that converts present and future costs (represented as present value) into a uniform annual cost. The annualized cost is determined as follows:

$$A = PV \frac{i(1+i)^n}{(1+i)^n - 1} \tag{Equation 3}$$

where,

A	=	Annualized cost
PV	=	Present value
n	=	Number of years
i	=	Discount rate

There are two approaches used to determine life cycle costs: deterministic and probabilistic. By far, the more common approach used by state highway agencies is the deterministic method; however, increased usage of the probabilistic method is anticipated in the near future. These two approaches are more fully described as follows:

Deterministic Analysis. In a deterministic analysis each input variable (e.g. construction cost, service life and discount rate) used in the LCCA is assigned a discrete value. Any consideration for input variability is not taken into account. This analysis produces a single discrete value for the present worth (or equivalent uniform annual cost) of the life cycle cost for each alternative. An example of a deterministic analysis is shown in Figure B3. The deterministic approach, though appropriate, does not take into consideration the possibility of uncertainty of inputs, such as construction cost estimates, pavement service lives, or discount rate.

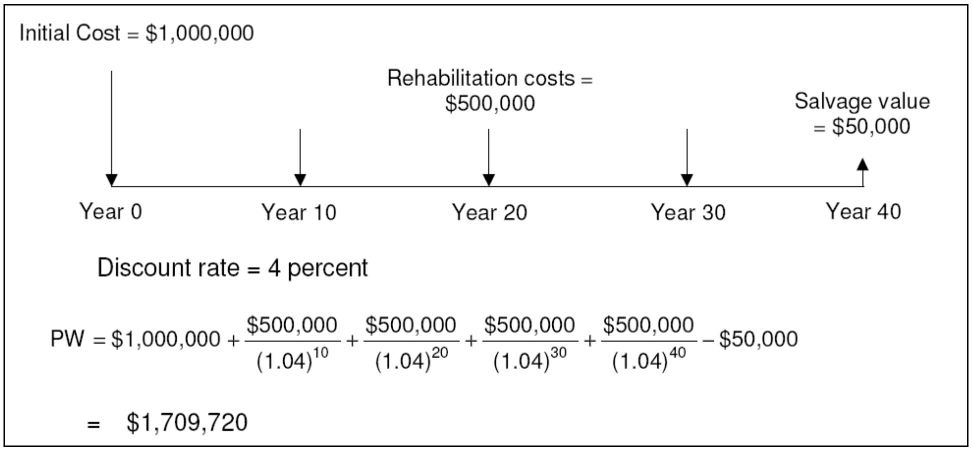

Figure B3: Deterministic life cycle cost analysis example (WSDOT, 2005).

Probabilistic Analysis. A probabilistic approach to life cycle cost analysis has the ability to incorporate uncertainty in the input variables, through the use of Monte Carlo simulation. “The Monte Carlo Simulation is a computerized procedure that takes each input variable, assigns a range of values (using the mean and standard deviation), and runs multiple combinations of all inputs and ranges to generate a life cycle cost probability distribution (WSDOT, 2005).” The use of a probabilistic distribution allows for the determination of the variability in the life cycle cost analysis, and therefore the associated risk. Figure B4 represents a typical probabilistic distribution. FHWA’s RealCost computer program has the capability of conducting a probabilistic life cycle cost analysis.

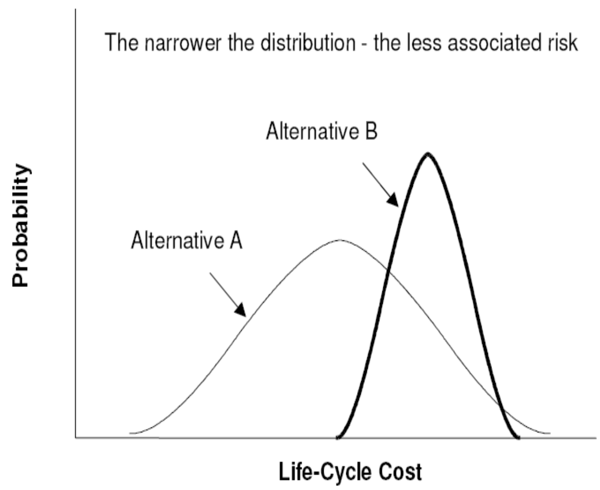

Figure B4: Probabilistic distribution.

SUMMARY

LCCA can be used as an analytical tool to provide a structured approach in the selection of competing strategies for new and/or rehabilitated pavement structures. LCCA should include all costs associated with the construction, maintenance, and rehabilitation of the roadway segment. The incorporation of user costs should be considered especially in areas where construction, maintenance and rehabilitation activities greatly impact the traveling public. In general, two approaches to LCCA are used: deterministic and probabilistic. Currently, the majority of agencies incorporate the deterministic approach in the LCCA; however, as agencies become more experienced, it is envisioned that the probabilistic analysis will gain in popularity.

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APPENDIX C

APPLICATION OF LCCA TO HYPOTHETICAL HIGHWAY NOISE ABATEMENT CASES

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APPLICATION OF LCCA TO HYPOTHETICAL HIGHWAY NOISE ABATEMENT CASES

INTRODUCTION

In order to illustrate how Life Cycle Cost Analysis (LCCA) can be used to evaluate the economic features of pavement and barrier strategies for highway noise abatements, several abatement scenarios for a hypothetical Type 1 highway project were evaluated. The project is a new 6-lane highway (3 lanes in each direction) in an area of sensitive noise receptors. Two different pavement alternatives are considered, one portland cement concrete (PCC) and one hot mix asphalt (HMA) along with a 12 ft sound wall.

For the LCCA analysis, the FHWA *RealCost* software (*1*) was used to evaluate barrier and pavement treatment scenarios. Although *RealCost* was specifically developed for the evaluation of pavement strategies, its application to this project is appropriate as long as similar input requirements (e.g., initial costs, maintenance costs, performance life, and so on) are met when considering different barrier scenario strategies.

RealCost is a Microsoft Excel®-based software tool that is based on the FHWA's technical bulletin on LCCA *(2)*. The program allows for the inclusion of agency and user delay costs in relation to new construction, reconstruction, rehabilitation, and maintenance activities, and presents the LCCA results in both tabular and graphical formats *(1)*. Moreover, *RealCost* includes both deterministic (in which each key input variable [such as costs, performance period, and discount rate] are fixed) and probabilistic (which incorporates uncertainty in the input variables by assigning a range of values) LCCA procedures.

With some additional considerations, LCCA can be used to analyze pavement and barrier strategies for noise abatement. For quieter pavement options, the rehabilitation cycle needs to account for acoustic longevity. Depending on the pavement, the cycle may need to be shortened to ensure that an acceptable level of noise reduction performance is maintained over the entire pavement life. For sound walls, initial construction costs as well as wall maintenance and graffiti removal will also need to be included in the analysis.

On the surface, implementing noise abatement options in the LCCA appears to be relatively straightforward. However, there are several issues to be considered. For example, LCCA results are only as good as the input data, so successful implementation requires the availability of valid data in sufficient quantities in order to be certain that an assumed level of noise reduction can be achieved with a given pavement design and construction. In addition, the acoustic longevity of the specific design would also need to be determined for use in defining the rehabilitation cycle, and the acoustic performance of the pavement or surfacing used for rehabilitation would also have to be known.

In the example cases to follow, it should be noted that the cases are completely fictitious and only designed to illustrate the use of the LCCA tool in evaluating the economic aspects of evaluating pavement and barrier noise abatement strategies. The inputs were generated and developed based on the research team's past experience and information available in the literature and are not specific to any one actual project. The results developed are not intended to suggest that one approach is "better" than the other. Actual cases need to be based on data generated by the state agencies.

NOISE SCENARIO

Traffic noise levels resulting from the new freeway were determined with the Federal Highway Traffic Noise Model (TNM®) using a uniform vehicle speed of 65 mph for all vehicle types. For simplicity, the traffic was assumed to have a daytime hourly average in each direction of 4000 vehicles/hr with 3% medium trucks, 3% heavy trucks and, otherwise, light vehicles. Medium and heavy trucks were distributed in the two outside lanes with the light vehicle uniformly distributed across all three lanes in each direction of travel. The terrain was taken as flat with a lawn ground type. With these assumptions, the worst hour levels at residences up to 250 ft from the center of the nearest lane of travel are predicted. At 100 ft, the traffic noise level was modeled to be 73.4 dBA using TNM average pavement. For residences at this distance, the level exceeds the Federal Highway Traffic (FHWA) Noise Abatement Criteria (NAC) *(3)* and those established by individual state agencies. These range between 64 and 67 dBA. Because the NAC are exceeded, noise abatement should be considered.

In the analysis, the PCC pavement option is considered to have a longitudinal tine texture producing an on-board sound intensity of 103½ dB based on levels measured on the Mojave Bypass, State Route 58 in Kern County, California *(4)*. From measurements conducted over a nine year period since new construction, this pavement has been found to increase with time at a rate of about 0.09 dB/year *(5)*. The HMA pavement option has a 1 inch thick asphalt rubber friction coarse (ARFC) producing typically OBSI levels of about 97 dBA when new and increasing in level at a rate of about 0.33 dB/year *(6)* as documented for the ADOT Casa Grande HMA test surfaces on I-10 south of Phoenix. Based on the research conducted in the NCHRP 1-44 project *(7)* and other statistical pass-by to OBSI comparsions, TNM average pavement corresponds to an OBSI level of about 102½ dBA. Under the assumption that the traffic noise is dominated by tire/pavement noise, these source levels would result in estimated traffic noise levels of 74.4 dBA and 67.9 dBA at 100 ft. After 7 years, the AFRC performance will drop 2.3 dBA producing a level of 70.2 dBA. The PCC will drop by 1.8 dB in 20 years, or to an increased level of 76.2 dBA. The 12 ft high concrete sound wall was determined to produce a 10.7 dB reduction at 100 ft resulting in levels of 63.7 dBA and 59.5 dBA for the new PCC and HMA cases, respectively. For the PCC after 20 years, a diamond grinding treatment would drop the OBSI level to 100.5 dBA or traffic noise level of 60.7 dBA.

LCCA ANALYSIS

The project scenario used in the LCCA includes a new highway facility 1 mile in length with six 12-ft wide lanes (3 lanes in each direction), a 12-ft wide outside shoulder, and an 8-ft wide inside shoulder. Two primary alternatives were evaluated, including:

- New hot mix asphalt (HMA) pavement with an asphalt rubber friction course (ARFC). Future rehabilitation includes a 2 in. HMA dense-graded mill and overlay every 18 years and a 3/4 in. ARFC overlay placed every 7 years to maintain acoustical qualities. The acoustic longevity of the ARFC is based on an initial OBSI level of 97 dB, which degrades to 99.3 dB after 7 years when acoustic rehabilitation is required (i.e., 2.3 dB acoustic degradation).

- New portland cement concrete (PCC) pavement with an initial longitudinally tined surface. Future rehabilitation includes diamond grinding on a 20-year cycle. This scenario results in an initial noise quality level of 103.5 dBA, which degrades to 105.3 dBA after 20 years and will be restored to 100.5 dBA following diamond grinding. This scenario includes the use of a 12-ft high concrete noise wall to provide the noise abatement.

Sub-cases of these include the HMA with the AFRC overlay with longer rehabilitation schedules of 8 and 9 years and the 7-year HMA cases with the same 12 ft barrier used in the PCC case.

As previously noted, *RealCost* is capable of conducting both a deterministic and probabilistic LCCA. Since a more extensive data set would be required to conduct a probabilistic analysis (i.e., average and standard deviation or minimum and maximum cost and/or performance life data), the analysis conducted under this task only includes deterministic inputs for barrier and pavement treatment costs and performance lives.

The *RealCost* software requires a number of inputs related to analysis options, traffic, and treatment strategies. Additional discussion on each of these inputs is further described in the following sections.

Analysis Options

Analysis options are typically selected in accordance with agency policy and include project level data that will be applied to all alternatives in the LCCA. Table C1 summarizes the analysis options used in this evaluation.

Traffic Inputs

Traffic inputs are used exclusively in *RealCost* to calculate costs associated with user delay due to construction activities. Traffic data inputs used in this analysis include:

- Average annual daily traffic (AADT) – 8,000 vehicles per hr (both directions).
- Single unit trucks – 3 percent of AADT.
- Combination trucks – 3 percent of AADT.
- Annual growth rate of traffic – 1.5 percent.
- Speed limit under normal operating conditions – 65 mph.
- Lanes open in each direction under normal conditions – 3. Free flow capacity – 2136 vehicles per hour per lane (vphpl). Free flow capacity was calculated within

RealCost. The free flow capacity calculation was based on a lane width of 12 ft, zero percent grade, and 8 ft to the nearest obstruction (inside shoulder).

- Queue dissipation capacity – 1800 vphpl.
- Maximum AADT – 140,000 vehicles per hour (vph), both directions.
- Maximum queue length – 10 miles.
- Rural or urban hourly traffic distribution – urban
- Value of user time (in 2011 dollars) due to construction delay includes (*8*):
  - Passenger cars: $15.50 per hour.
  - Single unit trucks: $24.80 per hour.
  - Combination trucks: $29.85 per hour.
- Traffic hourly distributions were based on *RealCost* default values.
- Added time and vehicle stopping costs were based on *RealCost* default values.

Table C1: Summary of analysis options

Input	Description[1]	Value
Analysis period	Number of years over which the strategies are compared.	50 years
Discount rate	Rate future expenditures are discounted to present value.	4 percent
Beginning of analysis period	First year of the analysis period.	2011
Include agency cost remaining service life	Include a prorated value of original agency cost when a treatment life extends beyond the analysis period.	Yes
Include user costs in analysis	Include user costs in the analysis.	Yes
User cost computation method	User costs based on *RealCost* calculation or user input values.	*RealCost*
Traffic direction	User costs based on AM peak hour, PM peak hour, or both.	Both
Include user cost remaining service life	Include a prorated value of user costs when a treatment life extends beyond the analysis period.	Yes
Number of Alternatives	Number of alternatives used in the analysis.	2

[1] Based on FHWA *RealCost User Manual* descriptions (*1*).

Pavement Strategy

As listed above, the assumed traffic level on this roadway section is 8,000 AADT with 6 percent trucks. From this, the pavement sections shown in Figure C1 and Figure C2 were determined to be appropriate for a 50-year pavement section. The proposed pavement thicknesses were used to estimate initial construction cost for the HMA and the PCC pavement alternatives. Pavement sections shown in Figure C1 and Figure C2 are based on

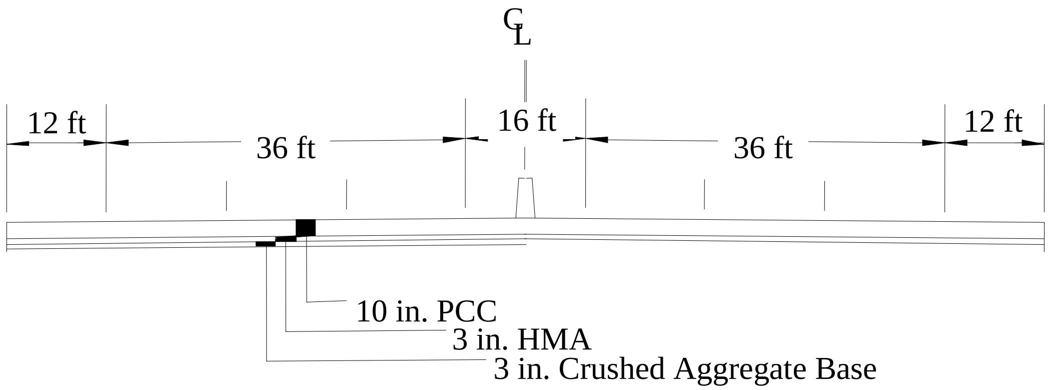

Figure C1: HMA pavement cross-section

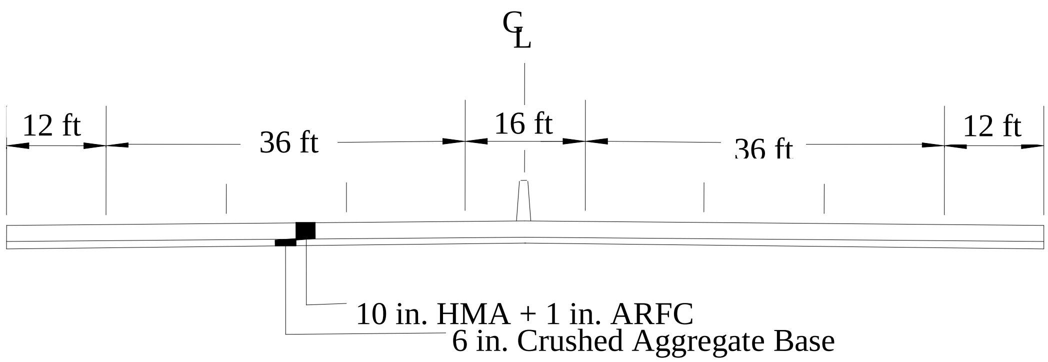

Figure C2: PCC pavement cross-section

thicknesses from the Washington State Department of Transportation (DOT) *Pavement Policy Manual* (*9*). The resulting construction costs are shown in Table C2.

Table C2: Summary of pavement costs, work zone duration, and performance life

Treatment	Total Project Cost[1]	Work Zone Duration (days)	Life (years)
New construction – HMA	$5,781,000	-[2]	50
New construction – PCC	$7,124,000	-[2]	50
ARFC	$1,118,000	7	7
HMA mill and overlay and ARFC	$1,985,000	12	14
Concrete – diamond grinding	$1,348,000	13	20

[1] Costs are based on a pavement type selection report obtained from the Washington State DOT *(8)*. Cost includes all agency costs including traffic control, mobilization, sales tax, engineering, and contingencies. Costs shown are in 2011 dollars.

[2] Work zone duration for initial construction is assumed to be the same for both the HMA and PCC options; therefore initial construction user costs are excluded from the analysis.

Sound Wall Strategy

While information is generally available related to the construction costs of sound barriers, the documentation of such information is often inconsistent in terms of what items are and are not included in recorded construction costs. While resolution of this issue is an important matter, it is beyond the scope of this project. As such, the average construction costs from the FHWA were used in this effort (see Table C3). Since data in the FHWA inventory does not show an overall trend of increasing costs per year, no cost escalation from 2007 to 2011 were assumed in this evaluation.

A variety of sources were used in an attempt to determine sound wall maintenance costs. These sources included:

- Literature searches – via internet and available reports.
- Telephone contacts with State highway personnel.
- Telephone contacts with barrier manufacturers.
- Personal experiences associated with barrier design, construction, and maintenance.

Table C3: Summary of concrete sound wall cost (10)

Year	Cost (sq ft)
1963 - 96	$26
1997	$27
1998	$24
1999	$30
2000	$25
2001	$26
2002	$35
2003	$28
2004	$23
2005	$30
2006	$29
2007	$34
Average	$27

Although a review of these sources provided valuable information related to the maintenance-related factors associated with sound walls, little, if any, information was found related to actual historical maintenance-related costs. Less information was found related to the incorporation of actual life cycle costs in the sound wall selection process.

One exception to this is a 1999 report titled "Evaluation of Service Life of Barrier Walls in Illinois" prepared by the Southern Illinois University at Edwardsville for the Illinois Department of Transportation (*11*). The Illinois Department of Transportation report documents extensive surveys, considerations, evaluations, and life cycle cost analyses calculation conducted for a variety of sound walls in Illinois. While actual data were utilized related to construction costs, the lack of actual historical data associated with maintenance-associated factors required assumptions related to types, frequencies, and costs associated with such factors.

Table C4 provides a summary of associated costs and application frequency for the concrete sound wall. Table C4 may be further refined in subsequent tasks if additional and more detailed information becomes available. The approach assumes the aforementioned FHWA initial construction costs and what is believed to be reasonable assumptions related to initial construction and maintenance costs. In addition, service lives for the concrete sound wall is based on the research team's opinions and supported by information in the IDOT Report. Additional assumptions used in developing the sound wall cost estimate include:

- 12 ft sound wall height.
- Initial sound wall construction is conducted within the roadway right-of-way.
- Future sound wall surface maintenance, graffiti removal, and impact damage repair is conducted during pavement rehabilitation and has no additional impact to user delay.
- No special provisions (e.g., moving utilities, absorptive linings, extra drainage) are required during sound wall construction.

Table C4: Summary of concrete sound wall cost and performance life

Treatment	Total Project Cost	Life (years)
Initial construction	$3,421,000	50
Surface Maintenance	$253,000	15
Graffiti Removal[1]	$5,000	1
Impact Damage Repair[2]	$26,000	5

[1] Assumes 1 percent of total wall area.

[2] Assumes repair of two panels (480 sq. ft) due to vehicle impact.

Scenario Cost Summary

As described previously, the two primary pavement options evaluated were: (1) a "quieter" HMA pavement without sound walls and a 7 year rehabilitation cycle, and (2) a conventional PCC pavement with sound walls. Both options include pavement rehabilitation activities and the PCC option also includes the construction and maintenance of a sound wall. Figures C3, C4, and C5 summarize the cash flow diagrams for both the HMA and PCC alternatives, respectively. The salvage value included at the end of the analysis period is based on an internal RealCost calculation. The salvage value calculation considers a depreciation approach for pavement service life remaining at the end of the.

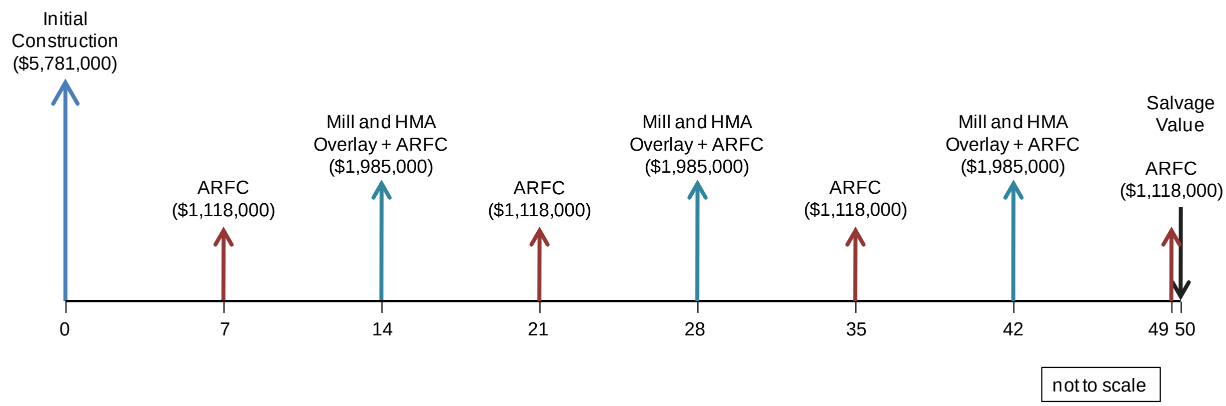

Figure C3: HMA/ARFC pavement cash flow diagram

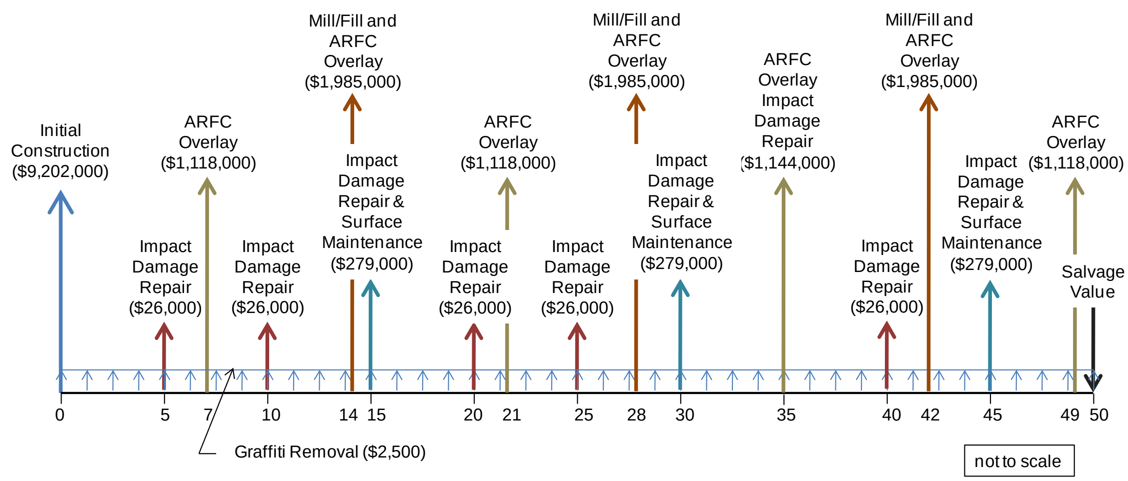

Figure C4: HMA pavement/sound wall cash flow diagram

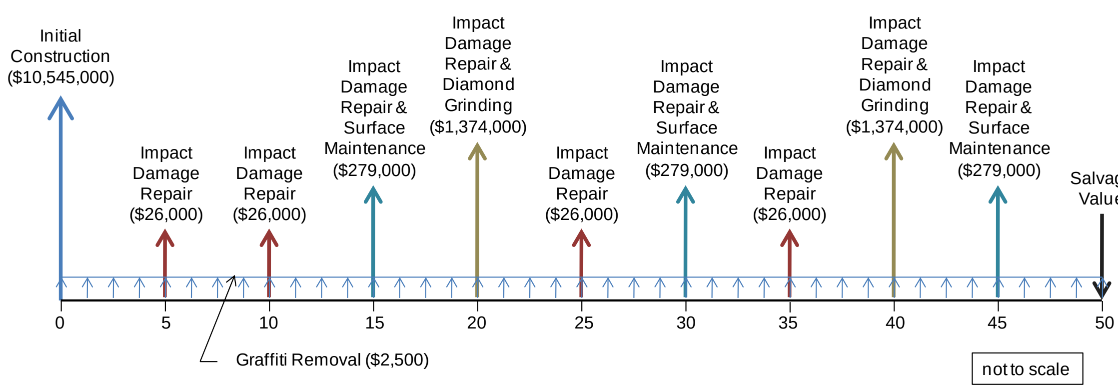

Figure C5: PCC pavement/sound wall cash flow diagram

analysis period (1). Details of the LCCA for these two primary cases are provided in the Attachment

LCCA RESULTS AND DISCUSSION

Table C5 provides the results of the LCCA for the two primary cases, ARFC with a 7 year rehabilitation and PCC with a 12 ft sound wall. In this table, Undiscounted Sum refers to the total agency costs across the complete 50 year project span as shown in Figures C3,C4, and 5 less the Salvage Value in today's dollars. The Present Value or alternatively, the EUAC (equivalent uniform annual cost) are the figures in constant dollars that would be used by an agency to evaluate the cost of each scenario. Based on the assumptions used in this example, the alternative with the lowest present value of agency costs is the HMA alternative, while the PCC alternative has the lowest present value of user costs. The additional cases that were considered included the above HMA 7-year cycle case but with a 12 ft sound wall and HMA cases with 8 and 9-year rehabilitation cycles. The LCCA results for these cases are shown in Table C6. As would be expected, with the longer rehabilitation cycles, the present value of the 8 and 9-year scenarios are less than the 7-year alternative, with the 9-year alternative being the lowest case. With the sound wall added to the 7-year cycle alternative, this becomes the highest cost alternative. It should also be considered that present values for the alternatives are functions of the assumed project life. With a shorter project life assumption, Alternative 1 becomes even lower compared to Alternative 2.

Table C5: Summary of deterministic LCCA results for the primary HMA and PCC alternatives

Total Cost	**Alternative 1: HMA (7-year overlay cycle)**		**Alternative 2: PCC (with sound wall)**	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$15,249.71	$66.34	$14,357.50	$31.47
Salvage Value	$958.29	$9.53	$0	$0
Present Value	$8,962.99	$20.17	$11,582.97	$7.62
EUAC	$490.96	$1.10	$634.48	$0.42

Table C6: Summary of deterministic LCCA results for the secondary HMA alternatives

Total Cost	**Alternative 1a: HMA (8-year overlay cycle)**		**Alternative 1b: HMA (9-year overlay cycle)**		**Alternative 1c: HMA (7-year overlay cycle with noise wall)**	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$13,601.25	$54.59	$12,608.11	$54.59	$19,787.07	$66.34
Salvage Value	$1,488.75	$14.09	$496.89	$14.09	$960.43	$9.53
Present Value	$8,430.12	$16.87	$8,049.76	$16.87	$12,721.25	$20.17
EUAC	$461.77	$0.92	$440.94	$0.92	$696.83	$1.10

To go along with the range in present value project costs, there is also a range in the noise abatement performance of these five alternatives. In comparison to the PCC alternative with a sound wall, the three HMA alternatives without a sound wall all provide less reduction at moderate distances from the highway (e.g. 100 ft). On the other hand, the HMA case with the 7-year rehabilitation cycle and the sound wall provide the greatest amount of noise abatement as shown in the summary provided in Figure C6. From Figure C6, all of the noise abatement alternatives initially satisfy a 5 dB improvement criterion compared to the TNM average pavement prediction, however, for the HMA alternatives, this is maintained only for the first years of the initial project and for the first years after each rehabilitation. Depending on the length of the cycle, the improvement over the TNM prediction falls to about 3 to 3½ dB just prior to rehabilitation. Relative to the PCC without a barrier, the HMA alternatives without a barrier range from being 5 to 8 dB lower for the first 20 years of the project. After the rehabilitation grinding of the PCC, the HMA alternatives provide levels only 1½ to 2½ dB lower than the PCC without a sound wall. For the two cases with a sound wall, the alternative with the HMA pavement is more "effective" at providing lower traffic noise levels however it increases the present value by about $1,034,670. Using a 9-year rehabilitation cycle for the HMA (Alternative 1b) and the sound wall would drop this difference to about $121,000 which might make this alternative more reasonable without sacrificing much acoustic performance.

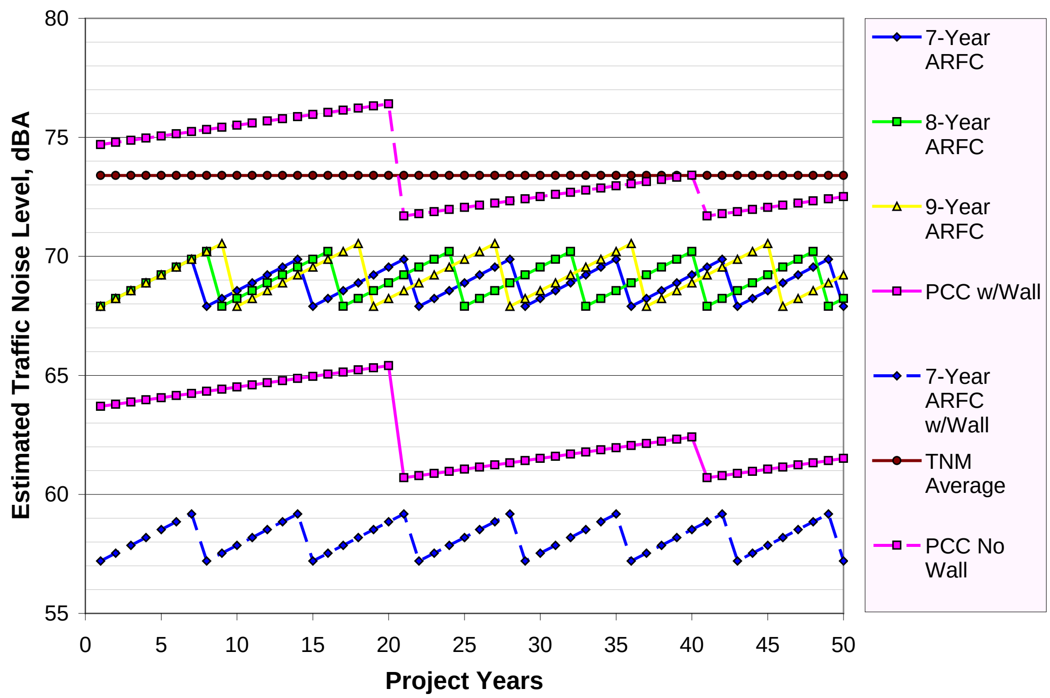

Figure C6: Estimated acoustic performance of alternative traffic noise abatement methods

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ATTACHMENT

PAVEMENT AND BARRIER COST ESTIMATING WORKSHEETS AND *REALCOST* REPORT

Pavement Cost Estimate

HMA Initial Construction

Detail: HMA Initial Construction - 10 in. HMA over 6 in. crushed aggregate base

Quantity	Unit	Bid Item	Unit Price	Amount	Quantity Per Day	Days
		Construction Items				
20,262	Ton	Crushed Surfacing Base Course	$19	$379,305		
3,600	Ton	ARFC	$135	$486,720		
24,014	Ton	HMA (Lanes)	$78	$1,873,092		
13,342	Ton	HMA (Shoulder and Median)	$78	$1,040,676		
37,356	Ton	Anti Stripping Additive	$1	$38,850		
$1,873,092	2%	Compaction Price Adjustment	2%	$38,960		
$3,400,488	3%	Job Mix Compliance	3%	$106,095		
		Traffic Control				
		Assume the intial construction traffic control equal value for both alternatives.		N/A		
			Items Subtotal	$3,963,698		
			Mobilization (5% of Items Subtotal)	$206,112		
			Contract Items Subtotal (Items Incl Mobilization)	$4,169,810		
			Sales Tax (8.3% of Contract Items Subtotal)	$359,938		
			Contract Subtotal (Contract Items Incl Sales Tax)	$4,529,748		
			Engineering and Contingencies (15% of Contract Subtotal)	$706,641		
			Total Construction Subtotal (Contract Incl Engineering and Contingencies)	$5,236,389		
			Preliminary Engineering (10% of Total Construction Subtotal)	$544,584		
			Total Project Cost (Total Construction Incl Preliminary Engineering)	**$5,781,000**		

Rehabilitation - ARFC

Detail: 3/4 in. ARFC

Quantity	Unit	Bid Item	Unit Price	Amount	Quantity Per Day	Days
		Construction Items				
65,706	SY	Planning Bituminous Pavement	$2.60	$170,836	12,000	5
3,600	Ton	ARFC (Lanes and shoulders)	$135	$486,720	3,000	2
3,600	Ton	Anti Stripping Additive	$1	$3,744		
$486,720	3%	Job Mix Compliance	3%	$15,186		
		Days Construction Time				**7**
		Days Construction Time (HRS) @ 10 Hrs per Day				**70**
		Traffic Control				
280	Hr	Other Traffic Control Labor (4 Laborers)	$47	$13,104		
70	Hr	Traffic Control Supervisor	$62	$4,368		
420	Hr	Flaggers and Spotters (6 flaggers)	$47	$19,656		
140	Hr	Sequential Arrow Sign	$5	$728		
140	Hr	Operation of Portable Changeable Message Sign	$6	$801		
2	Each	Portable Changable Message Sign	$6,240	$12,480		
2	Each	Truck-Mounted Impact Attenuator	$9,360	$18,720		
140	Hr	Operation of Truck-Mounted Impact Attenuator	$57	$8,008		
800	SF	Construction Signs Class A	$16	$12,480		
		Items Subtotal		$766,831		
		Mobilization (5% of Items Subtotal)		$39,875		
		Contract Items Subtotal (Items Incl Mobilization)		$806,706		
		Sales Tax (8.4% of Contract Items Subtotal)		$69,635		
		Contract Subtotal (Contract Items Incl Sales Tax)		$876,341		
		Engineering and Contingencies (15% of Contract Subtotal)		$136,709		
		Total Construction Subtotal (Contract Incl Engineering and Contingencies)		$1,013,050		
		Preliminary Engineering (10% of Total Construction Subtotal)		$105,357		
		Total Project Cost (Total Construction Incl Preliminary Engineering)		**$1,118,000**		

Rehabilitation - HMA and ARFC

Detail: Mill & overlay full-width - 2 in. HMA and 3/4 in. ARFC

Quantity	Unit	Bid Item	Unit Price	Amount	Quantity Per Day	Days
		Construction Items				
65,706	SY	Planning Bituminous Pavement	$2.60	$170,836	12,000	5
6,752	Ton	HMA	$78	$526,656	1,500	5
3,600	Ton	ARFC	$135	$486,720	3,000	2
10,352	Ton	Anti Stripping Additive	$1	$10,766		
$526,656	2%	Compaction Price Adjustment	2%	$10,954		
$1,013,376	3%	Job Mix Compliance	3%	$31,617		
			Days Construction Time			**12**
			Days Construction Time (HRS) @ 10 Hrs per Day			**120**
		Traffic Control				
480	Hr	Other Traffic Control Labor (4 Laborers)	$47	$22,464		
120	Hr	Traffic Control Supervisor	$62	$7,488		
720	Hr	Flaggers and Spotters (6 flaggers)	$47	$33,696		
240	Hr	Sequential Arrow Sign	$5	$1,248		
240	Hr	Operation of Portable Changeable Message Sign	$6	$1,373		
2	Each	Portable Changable Message Sign	$6,240	$12,480		
2	Each	Truck-Mounted Impact Attenuator	$9,360	$18,720		
240	Hr	Operation of Truck-Mounted Impact Attenuator	$57	$13,728		
800	SF	Construction Signs Class A	$16	$12,480		
			Items Subtotal	$1,361,226		
			Mobilization (5% of Items Subtotal)	$70,784		
			Contract Items Subtotal (Items Incl Mobilization)	$1,432,010		
			Sales Tax (8.4% of Contract Items Subtotal)	$123,611		
			Contract Subtotal (Contract Items Incl Sales Tax)	$1,555,621		
			Engineering and Contingencies (15% of Contract Subtotal)	$242,677		
			Total Construction Subtotal (Contract Incl Engineering and Contingencies)	$1,798,298		
			Preliminary Engineering (10% of Total Construction Subtotal)	$187,023		
			Total Project Cost (Total Construction Incl Preliminary Engineering)	**$1,985,000**		

PCC Initial Construction

Detail: Full Depth Lane and Shoulder 12 in. PCCP over 3 in. HMA base over 3 in. crushed aggregate base

Quantity (Eng)	Unit	Bid Item	Unit Price	Amount
		Construction Items		
10,130	Ton	Crushed Surfacing Base Course	$18.72	$189,634
18,178	CY	Cement Concrete Pavement	$208.00	$3,781,024
25,344	EA	Corrosin Resistant Dow el Bars	$15.00	$380,160
$3,781,024	CALC	Ride Smoothness Compliance Adjustment	1%	$39,323
11,254	Ton	HMA	$78.00	$877,812
11,254	Ton	Anti Stripping Additive	$1.00	$11,254
$877,812	3%	Job Mix Compliance	3%	$27,388
		Traffic Control		
		Assume the intial construction traffic control equal value for both alternatives.		N/A
		Items Subtotal		$5,306,595
		Use HMA's Initial Mobilization Cost		$206,112
		Contract Items Subtotal (Items Incl Mobilization)		$5,512,707
		Use HMA's Initial Sale Tax Cost		$359,938
		Contract Subtotal (Contract Items Incl Sales Tax)		$5,872,645
		Use HMA's Initial Construction Engineering and Contingencies Cost		$706,641
		Total Construction Subtotal (Contract Incl Engineering and Contingencies)		$6,579,286
		Use HMA's Initial Construction Preliminary Engineering Cost		$544,584
		Total Project Cost (Total Construction Incl Preliminary Engineering)		**$7,124,000**

Rehabilitation - Diamond Grinding

Detail: Diamond Grind PCC Lanes and Clean and Reseal Joints

Quantity	Unit	Bid Item	Unit Price	Amount	Quantity Per Day	Days
		Construction Items				
65,706	SY	Portland Cement Concrete Pavement Grinding	$11.44	$751,677	5,000	13
751,677	Calc	Ride Smoothness Compliance Adjustment	1%	$7,817		
		Days Construction Time				**13**
		Days Construction Time (HRS) @ 10 Hrs per Day				**130**
		Traffic Control				
5,280	LF	Removing and Resetting Existing Permanent Barrier	$6.50	$34,320		
520	Hr	Other Traffic Control Labor (4 Laborers)	$47	$24,336		
130	Hr	Traffic Control Supervisor	$62	$8,112		
780	Hr	Flaggers and Spotters (6 flaggers)	$47	$36,504		
260	Hr	Sequential Arrow Sign (2 Signs, 1 NB and 1 SB)	$5.20	$1,352		
260	Hr	Operation of Portable Changeable Message Sign	$5.72	$1,487		
2	Each	Portable Changable Message Sign	$6,240	$12,480		
2	Each	Truck-Mounted Impact Attenuator	$9,360	$18,720		
260	Hr	Operation of Truck-Mounted Impact Attenuator	$57	$14,872		
800	SF	Construction Signs Class A	$16	$12,480		
		Items Subtotal		$924,157		
		Mobilization (5% of Items Subtotal)		$48,056		
		Contract Items Subtotal (Items Incl Mobilization)		$972,213		
		Sales Tax (8.4% of Contract Items Subtotal)		$83,921		
		Contract Subtotal (Contract Items Incl Sales Tax)		$1,056,134		
		Engineering and Contingencies (15% of Contract Subtotal)		$164,757		
		Total Construction Subtotal (Contract Incl Engineering and Contingencies)		$1,220,891		
		Preliminary Engineering (10% of Total Construction Subtotal)		$126,973		
		Total Project Cost (Total Construction Incl Preliminary Engineering)		**$1,348,000**		

Barrier Cost Estimate

YEAR	PRECAST CONCRETE BARRIER					
	INITIAL COST	MAINTENANCE COSTS				YEARLY COST
		SURFACE MAINTEN-ANCE[1]	GRAFITTI REMOVAL[2]	IMPACT DAMAGE	DISPOSAL AND SALVAGE	
1	$3,421,440		$5,069			$3,426,509
2			$5,069			$5,069
3			$5,069			$5,069
4			$5,069			$5,069
5			$5,069	$25,920		$30,989
6			$5,069			$5,069
7			$5,069			$5,069
8			$5,069			$5,069
9			$5,069			$5,069
10			$5,069	$25,920		$30,989
11			$5,069			$5,069
12			$5,069			$5,069
13			$5,069			$5,069
14			$5,069			$5,069
15		$253,440	$5,069	$25,920		$284,429
16			$5,069			$5,069
17			$5,069			$5,069
18			$5,069			$5,069
19			$5,069			$5,069
20			$5,069	$25,920		$30,989
21			$5,069			$5,069
22			$5,069			$5,069
23			$5,069			$5,069
24			$5,069			$5,069
25			$5,069	$25,920		$30,989
26			$5,069			$5,069
27			$5,069			$5,069
28			$5,069			$5,069
29			$5,069			$5,069
30		$253,440	$5,069	$25,920		$284,429
31			$5,069			$5,069
32			$5,069			$5,069
33			$5,069			$5,069
34			$5,069			$5,069
35			$5,069	$25,920		$30,989
36			$5,069			$5,069
37			$5,069			$5,069
38			$5,069			$5,069
39			$5,069			$5,069
40			$5,069	$25,920		$30,989
41			$5,069			$5,069
42			$5,069			$5,069
43			$5,069			$5,069
44			$5,069			$5,069
45		$253,440	$5,069	$25,920		$284,429
46			$5,069			$5,069
47			$5,069			$5,069
48			$5,069			$5,069
49			$5,069			$5,069
50			$5,069		$633,600	$638,669
TOTALS	$3,421,440	$760,320	$253,440	$233,280	$633,600	$5,302,080

AMOUNT OF AREA	100%	1%	4 panels (960 sf)	100%
FREQUENCY	Every 15 years	Yearly	Every 5 years	Every 50 years
UNIT COST/SF	$2.00	$4.00	$27.00	$5.00
MAINTENANCE ACTIVITIES				

ASSUMPTIONS:

Barrier Height (ft)	12	
Barrier Length (ft)	10560	
Barrier Surface Area (sf)	126720	Area for each face of barrier
Wood Barrier Cost/sf	$19	Source: FHWA Inventory
Concrete Barrier Cost/sf	$27	Source: FHWA Inventory
Surface Maintenance Cost/sf	$1	Unit cost for general maintenance and restoration of each sf
Graffiti Removal Cost/sf	$2	Unit cost for each sf of surface to remove graffiti and recoat
Wood Disposal and Salvage Cost/sf	$3.75	Source: ILDOT Report
Concrete Disposal and Salvage Cost/sf	$5.00	Source: ILDOT Report

NOTES:

1. Surface maintenance on both surfaces of barriers
2. Graffiti removal on 1% of all barrier surfaces

APPENDIX D

THE EVALUATION OF FEASIBILITY, REASONABLENESS, AND EFFECTIVENESS

TABLE OF CONTENTS

Page

INTRODUCTION

Developing methodologies for evaluating pavement and barrier strategies for noise abatement falls into five topics. These include feasibility, reasonableness, effectiveness, acoustic longevity, and economic issues. In this appendix, the first three of these topics are discussed more detail based on the literature review performed in this research. The remaining two topics are discussed in following successive appendices. Feasibility and reasonableness are already dealt with to some degree in the guidance for 23 CFR 772. In these areas, tailoring the existing approaches for pavement consideration is required. Effectiveness is not covered in the current guidance and it will need to be defined and evaluation methods recommended.

FEASIBILITY

For barriers, the issues for feasibility are well documented in the 23 CFR 722 guidance material *(1)*. The basic questions are: can the barrier physically be built? And will it provide the noise reduction sought in the policy established by the SHA? If one of these criteria cannot be met for specific sections of the project, no abatement is included in the project for those sections regardless of the predicted noise levels. Whether the barrier can be built is an engineering assessment and noise reduction potential is obtained using TNM. For noise abatement through quieter pavement, it is envisioned that the acoustical feasibility of quieter pavement would be assessed in a similar manner to barriers. Using a modified version of TNM, the predicted noise levels with the quieter pavement would be compared to either the TNM average pavement or TNM results calibrated to an existing pavement. The amount of the noise reduction indicated by such analysis would be compared to an abatement threshold to determine if a minimum amount of performance is achieved. As discussed previously, it is anticipated that this would be accomplished using OBSI data, although other means, such as more pavement specific REMEL data could be used. Although this approach may appear to be straightforward, there are a number of open issues to be considered. For acoustic feasibility, some of these include: what is the range of noise reduction that can be expected with quieter pavements, how to reconcile TNM average pavement and existing pavement performance, should different level criterion be used to assess feasibility when pavement is involved, how should combined effects of pavement barriers be considered, how should acoustic longevity be included? In addition to acoustic issues, the use of quieter pavement also adds dimensions of feasibility for other pavement performance issues such as safety, climate susceptibility, and durability.

Acoustic Feasibility

An initial question in regard to quieter pavement is what is the amount of traffic noise reduction that can be expected? For barriers, this is loosely quantified in the 23 CFR 772 guidance document where 5 dB reduction is considered to be “simple” to obtain, 10 dB is “attainable”, and 15 dB is “very difficult”. The actual reductions clearly depend on the geometry, however these guidelines support the notion of a 5 to 10 dB insertion loss (noise reduction) criteria used by the SHAs. Although the performance is geometry dependent, it is not strongly dependent on pavement. The noise reduction attained with pavement is, however, strongly dependent upon the performance of the initial pavement.

Continuous flow time integrated method (CTIM) cases

For tire/pavement noise, range in source level has been documented to be on the order of 13 dB going from transversely tined PCC to quieter OGAC and rubberized AC pavements *(2)*. In some situations, traffic noise reductions close to this amount can be measured such as at Site 3D in the Arizona QPPP where the reduction in OBSI level was virtually matched by the reduction in wayside level *(3)*. However, in this case, not only was the source level reduction large, the traffic was dominated by light vehicles. Light vehicles typically display an almost 1 to 1 relationship between reduction in tire/pavement noise source levels and pass-by levels *(4)*. For trucks, reductions in tire/pavement noise source levels often do not produce a 1 to 1 reduction in passby noise level, but rather a slightly less amount *(5)*. As a result, depending on the traffic mix, smaller amounts of traffic noise reduction may occur than would be predicted from tire source levels. For more moderate pavement cases, such as that reported for I-80 Davis, the reduction produced going from an older DGAC to new OGAC was initially about 6 dB while relative to new DGAC, the reduction was only slightly more than 2 dB.

TNM Test Cases

In implementing the consideration of quieter pavement through TNM using OBSI, the relationship between source levels and predictions based on average pavement also needs to be examined. One approach to this was recently reported using measured CTIM sound levels from three sites with ARFC, longitudinally tined PCC and transversely tined PCC *(6)*. In this study, OBSI averages for each pavement type relative to DGAC averages were used to adjust the ground level (tire noise) source strength in the model for comparison to TNM average pavement results and the measured data. As may be expected, the average pavement predicted levels exceed the measured levels for the ARFC site by 5.0 dB. For the two PCC sites, the measured levels exceed the predicted level by 1.1 and 3.5 dB for the longitudinal and transverse tined pavements, respectively. Adjusting the TNM predictions with the pavement specific source levels brought the PCC predictions down to being just 0.3 dB greater than the measured, while the over prediction of the ARFC was lowered to 1.8 dB. This example demonstrated that a 5 dB noise reduction criteria could be achieved relative to average pavement with pavement specific implementation in TNM. With adjustment to the specific pre-project OBSI levels for measurement sites, the reduction relative to TNM average pavement should be even greater than 5 dB based on the CTIM results. From these results and those from the I-80 Davis study, it appears that a 5 dB reduction over TNM average pavement may be achievable, at least for newer, quieter pavements.

REMELs and OBSI

Another approach to relating TNM average pavement predictions to OBSI levels is to develop relationships between OBSI levels and statistical pass-by (SPB) measurements. These can then be used for comparison to REMEL values defining average and other pavements used in TNM. To apply this approach, statistical pass-by data from a number of studies have been processed to compare to OBSI data. In each case, corresponding OBSI data for the SRTT were measured at or close to the same time as the SPB measurements. In a few cases, OBSI levels were estimated for older Goodyear Aquatred 3 data using defined relationships *(7).* The data sources included 12 sites from the NCHRP 1-44 project (6 AC and 6 PCC sites) *(4)* and 7 PCC sites from REMELs studies sponsored by the American Concrete Pavement Association *(8).* Data from the AC pavement research work sponsored by Caltrans on LA 138 *(9, 10)* as measured in different years over the multi-year project were also used yielding a total of 32 data points. For the analysis of the SPB data, a logarithmic regression was fit to the passby level versus vehicle speed data for each site for comparison to the average pavement REMEL data. An example of this is presented in Figure D1 for data obtained at the longitudinal tine PCC site from the NCHRP 1-44 project. From these curves, the SPB values at 60 mph were to match the OBSI data also measured

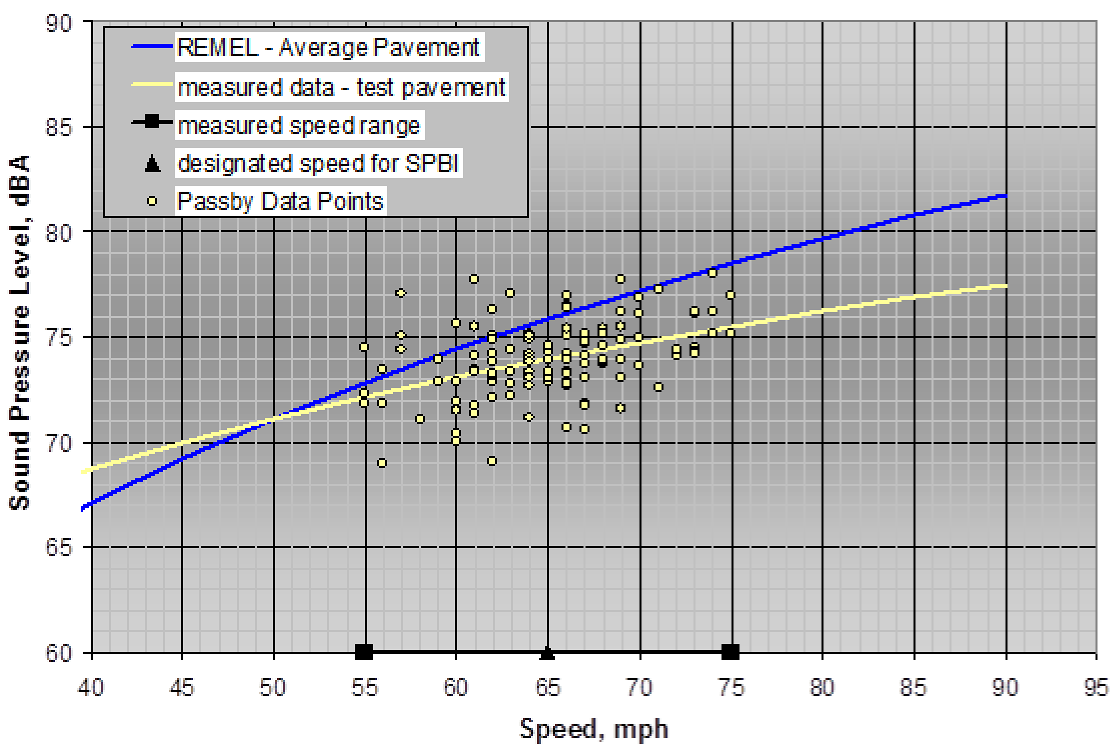

Figure D1: Maximum overall sound pressure levels from statistical passby events for light vehicles versus speed for longitudinal tine PCC

at 60 mph. The cross-plot of the SPB and OBSI data at 60 mph is presented in Figure D2 along with a line of slope 1 fit to the data and a linear regression of the data points. There is some scatter in the slope 1 fit (standard deviation = 1.6 dB), however the R^2 of the linear regression is greater than 0.8. For the NCHRP 1-44 data included in this plot, the scatter was reduced from a standard deviation of 1.7 to 1.0 by normalizing the data for site

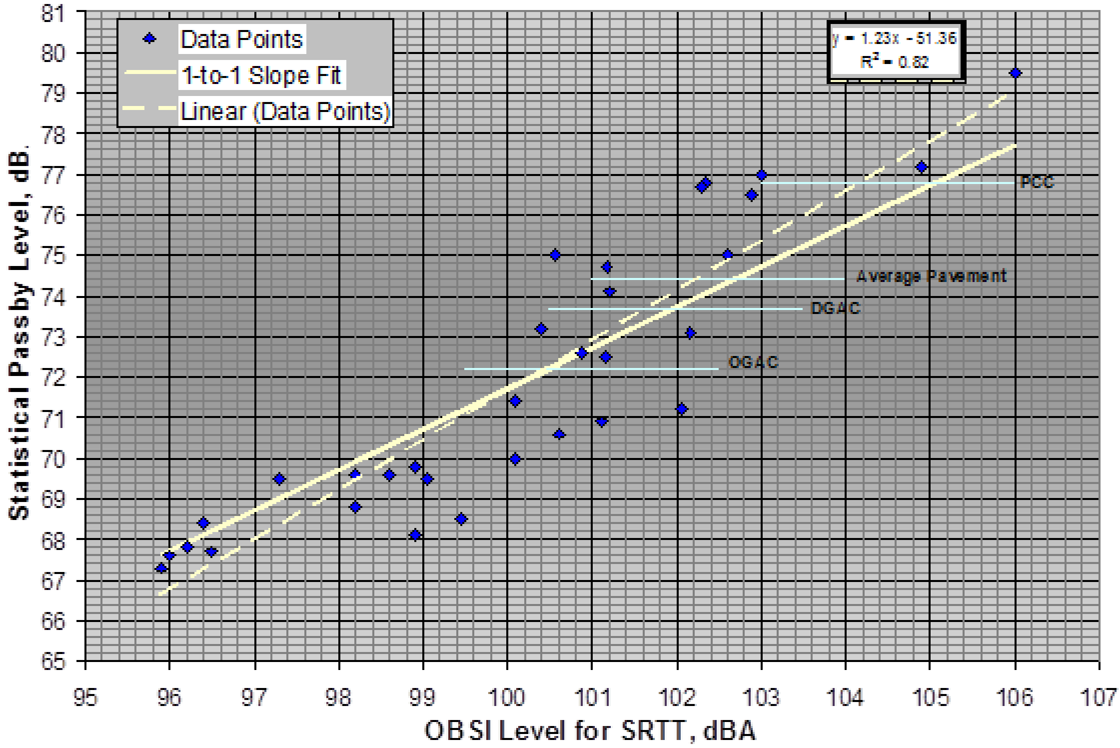

Figure D2: Overall OBSI level versus statistical passby level at 60 mph for 32 sites and various AC and PCC pavements with REMELs averages indicated

variation *(4)*. If such data (CPB with SRTTs) were available for the other sites in Figure D2, the standard deviation of all 32 point might be similarly reduced.

To compare to the REMELs data, the light vehicle value for 60 mph and average pavement (74.4 dBA) is indicated in the Figure D2. This corresponds to an OBSI level of 102.7 dBA based on the slope 1 fit. The REMELs values for DGAC, PCC, and OGAC can also be shown based on the offsets of -0.7, 2.4, and -2.2 for each respectively. These correspond to OBSI levels of about, 102.0, 105.1, and 100.5 dB, respectively. In examining these results, it is apparent that some pavements are capable of producing REMELs and OBSI levels 5 dB below that of TNM average pavement, consistent with theresults discussed above comparing TNM and measured CTIM results. However, the pavements that are actually below OBSI levels 97.7 dBA are from the quieter test sections of LA 138 measured when the pavements were one year old or less. After 6 years, these same pavements have increased in noise level to the 98 to 99 dBA range. The ARFC in the Arizona QPPP has also increased in noise performance reaching to the same 98 to 99 dBA range after about 4 years.

Noise Reduction with Distance

From barrier theory, it is well understood that the amount of noise reduction provided decreases with increasing distance *(11)*. For quieter pavement, it is often assumed that by reducing the tire/pavement noise source levels, the noise reduction is provided at all distances. Wayside data provided from the Arizona QPPP *(12)* and the Caltrans I-80 Davis *(13)* studies indicate that this is not necessarily the case. For the five wayside sites in the QPPP, although there is some variation, the reduction provided by the ARFC does generally decrease with distance (Figure D3). This is consistently seen for the data at

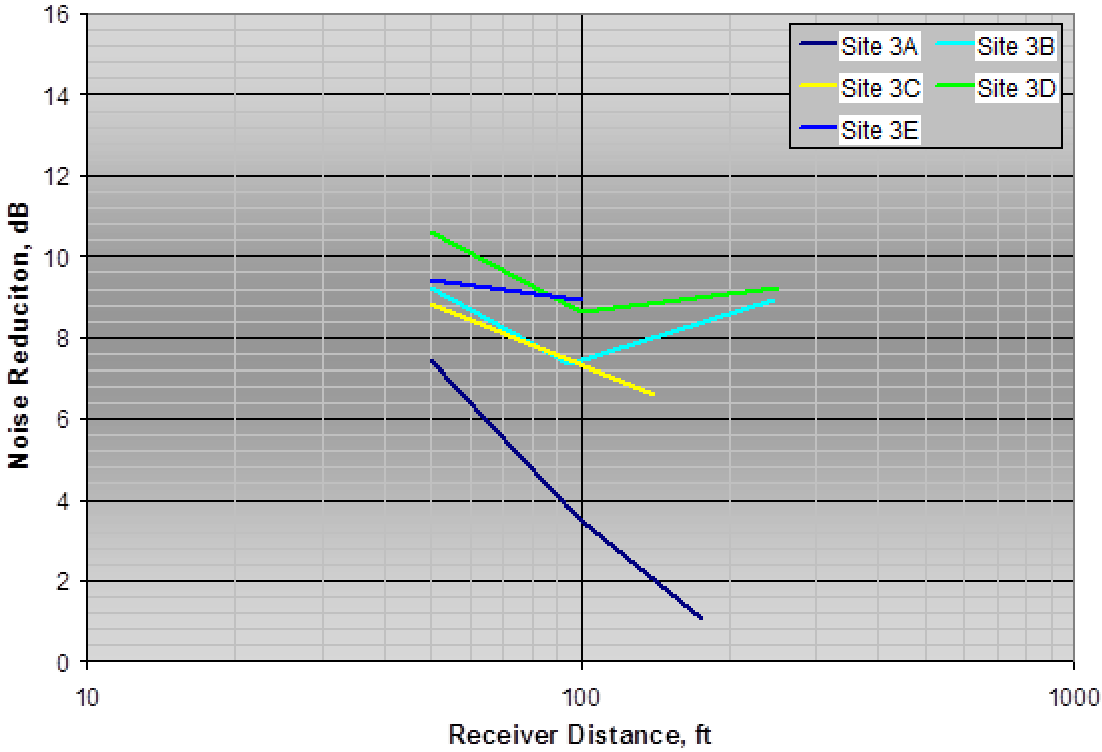

Figure D3: Change in noise reduction between transverse tine PCC and ARFC as a function of distance from the highway for ADOT QPPP test sites

distances from 50 to 100 ft: however, in the range of 100 to about 250 ft, the results are mixed. In two cases, the noise reduction increases with distance and in two, they decrease. This variation may be due to differences in ground type and site geometry or other issues such as background noise level. The reason for the decreased performance of quieter pavement with distance has to do with spectral shape. As shown in Figure D4, quieter pavements typically produce the largest reduction in one-third octave bands of 800 Hz and above. These frequencies are also attenuated at a higher rate than those below 800 Hz. As a result, these lower frequencies become more important in determining the overall A-weighted level at longer distances. A similar result was seen in the I-80 Davis results. In this case, wind conditions added significant scatter in the noise reductions measured at the 475 ft distance microphone location: however, noise reductions were typically about 1 dB less than those measured at the 66 ft reference microphone location.

This effect can be studied using TNM to predict noise level versus distance for quieter pavement, barriers, and combined barriers and quieter pavement. The approach used was as discussed earlier in which the TNM ground level source strength was adjusted to that of ARFC relative to TNM average pavement. Placing a barrier optimally close to the near lane of vehicle travel, calculations were performed using different barrier heights

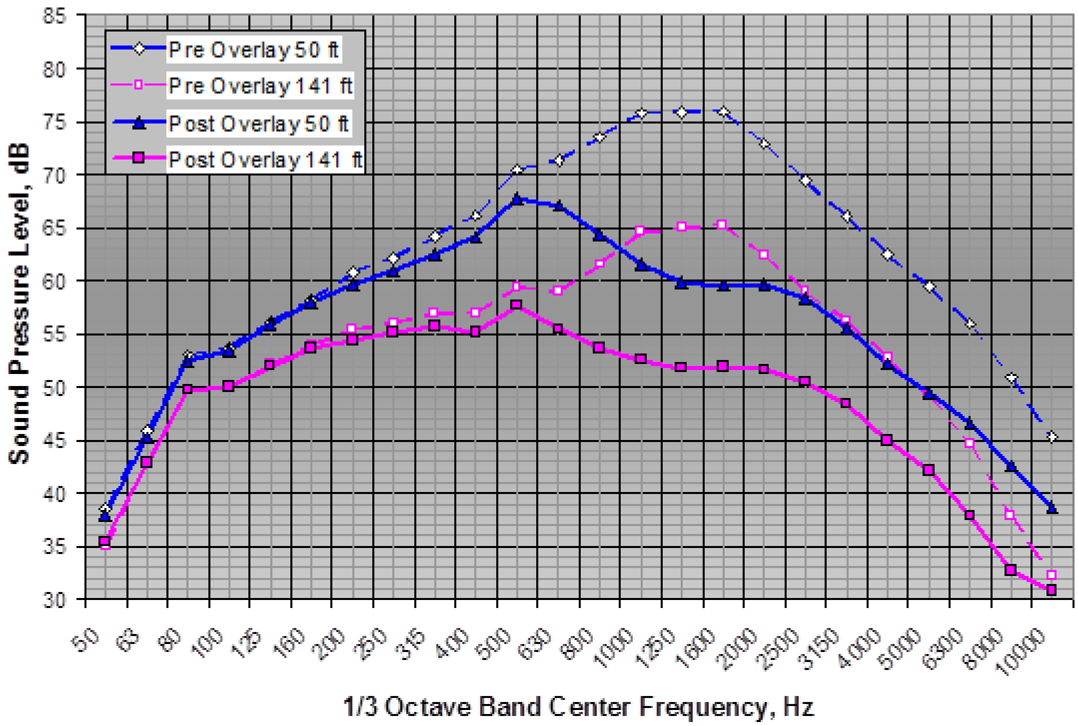

Figure D4: Differences in spectrum at two distances from the highway for original transverse tine PCC and ARFC overlay at ADOT QPPP Site 3C

with average pavement, no barrier with quieter pavement, and then with quieter pavement and barriers of different heights. The mix of trucks in the traffic flow was also varied and included 0%, 5%, and 10% trucks. Also, two-lane and eight-lane highways were considered with acoustically hard or soft ground between the highway and the receiver location and with background noise levels of 0, 45, and 60 dBA. An example of a two-lane highway case with 5% trucks, soft ground, no background noise, and barrier heights of 8 and 16 ft is shown in Figure D5. In this particular example, the ARFC provides a fairly constant reduction of about 4 dB over a distance up to 500 ft. As expected, for the 8 ft barrier alone, the noise reduction falls quickly from 50 to 100 ft, decreases more gradually out to about 400 ft, and decreases more rapidly beyond 500 ft. With both 8 ft barriers and the AFRC, the fall-off is similar to that of the barrier alone: however, the amount of reduction provided increases by about 2 to 3 dB out to 400 ft. For a higher, 16 ft barrier, the noise reduction provided is about 7 dB greater than the 8 ft barrier: however, the effectiveness of the quieter pavement on the combined performance is less (only 1 to 2 dB). This trend was found throughout the analysis cases, that is, the less effective (shorter) the barrier, the more the quieter pavement contributes to noise reduction. Further, barrier height could be reduced by 4 to 6 ft when quieter pavement is added to the noise abatement strategy. It was also observed that dropping the percentage of trucks from 5 to 0 significantly improved the barrier performance (~ 7 dB) while the pavement noise reduction only increased a few tenths of a decibel.

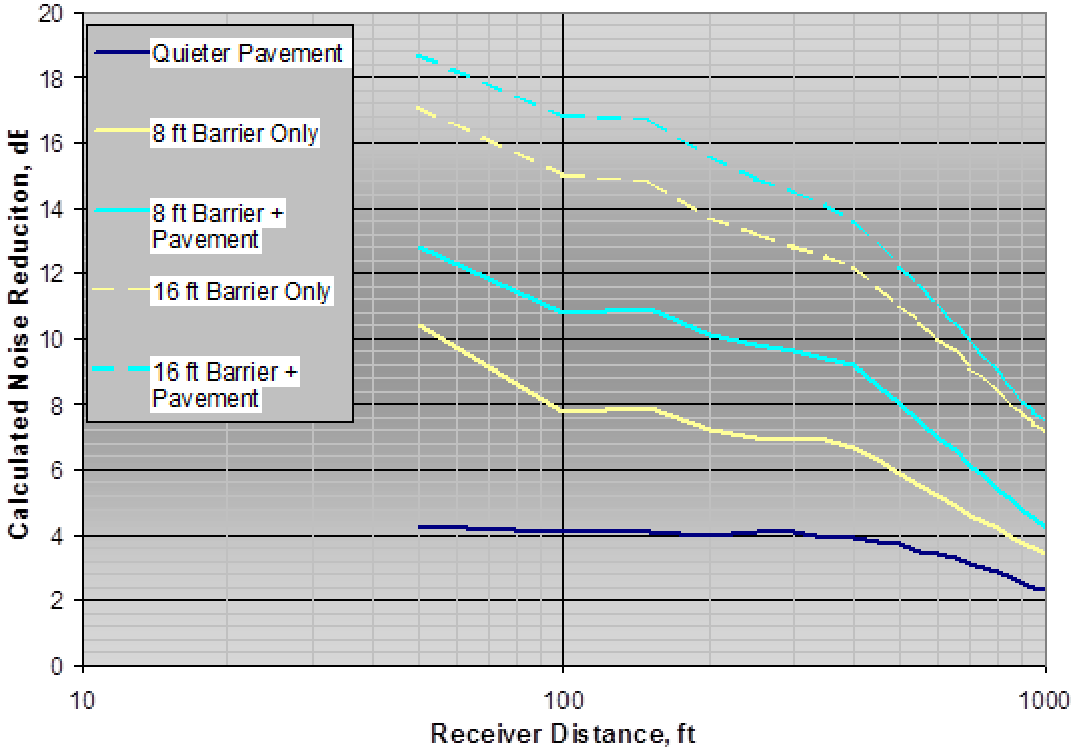

Figure D5: Traffic noise reduction as function of distance for barrier and pavement scenarios for 2-lane highway, soft ground, and 5% trucks

Summary

The level of "feasibility" for quieter pavement depends largely on the noise performance of the pavement used in the comparison. Using TNM average pavement as a comparison point, traffic noise reductions up to about 6 dB have been achieved. However, to sustain the reduction over time, the achievable range may more likely be 3 to 4 dB out to distances of about 500 ft, at least based on current quieter pavement research and TNM simulation. For starting points based on existing pavement, the level of feasibility could be greater depending on the noise performance of the existing pavement. In these cases, reductions of 8 to 9 dB may achievable initially and 5 to 7 dB sustainable over time.

Some applications of quieter pavement may also lead to a consideration of a level lower than 5 dB for noise reduction feasibility. In situations where barriers are not possible due to geometry or other constraints, it may be desirable to attain at least some noise reduction of an amount less than 5 dB, particularly if the predicted levels well exceed the NAC. Also, some consideration of the feasibility of combined barrier and pavement noise reductions should be given. In particular, in these cases, is the feasibility based on each element, the barrier and the pavement, or on the combined barrier/pavement system? Answers to these feasibility questions may become apparent if the reasonableness calculations include accounting for residences benefitted down to 3 dB, possibly on a sliding scale for reductions between 5 and 3 dB. In Phase II of this project, different scenarios of feasibility and benefitted residences will be considered in actual project contexts working with several SHAs. These will be considered both by how they effect the analysis of feasibility and how receptive the SHAs and FHWA are to lower criteria.

Other Feasibility Considerations

Any pavement design considered for noise abatement purposes is subject to the requirements established in 23 CFR 626, General Pavement Design Considerations which states that "Pavements shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost-effective manner" *(14)*. As a result, quieter pavement designs may not be feasible if they do not meet a SHA's criteria for safety and durability. In regard to safety, the primary concern is with skid resistance. It is stated that a SHA should have historical performance information to be certain that a proposed design is capable of providing a satisfactory skid resistance over the expected life of the pavement. For a quieter pavement to be an option for noise abatement, this implies that either an "off-the-shelf" design is used or that other convincing historical information is available. For pavement rehabilitation, it is also stated that for safety reasons, traffic disruption should be minimized and that adequate protection of motorists and workers should be considered. Concerning durability, the pavement design decision needs to consider traffic by vehicle classification and cumulative loading, and a foundation design that is stiff, and moisture and frost resistant. These durability issues may influence whether a quieter pavement design is feasible or not in a particular application.

In addition to the safety and durability issues that impact quieter pavement feasibility, it should also be noted that weight limitations on structures can be an issue. This applies both to quieter pavement overlays of the structure and to barriers added to the structure. If either of these noise abatement possibilities are included in the initial design phase, they may be feasible to implement as the project progresses. However, if considered after the structural design, neither of these may be feasible.

Relative to the feasibility of achieving a defined level of noise reduction performance, of the issues cited for barriers, some do and some do not apply to quieter pavements *(1)*. Issues such as topography, access for driveways and ramps, presence of cross streets, drainage, barrier maintenance, and utilities should not restrict or compromise the performance of quieter pavements. However, noise from other sources present in the area could affect the ability of a quieter pavement to reduce noise.

In Phase II of this project, any other issues affecting the ability of a quieter pavement to achieve a set level of feasibility will be sought. These may be constraints on the pavement itself, such as safety and durability or application constraints regarding the ability of the quieter pavement to achieve a given level of noise reduction performance.

REASONABLENESS

In considering the use of quieter pavements to reduce traffic noise levels, the general principles of the Highway Traffic Noise Analysis and Abatement Policy and Guidance are applicable. However, admittedly in the document itself, the considerations presented are intended for noise barrier use *(1)*. One significant factor in barrier reasonableness is the cost of the barrier versus the benefit of those affected. This becomes a "go or no go" question with the cost of any feasible barrier being relatively large. Unlike barriers, pavement is integral to the project itself. The cost for a quieter pavement option is incremental, such as adding a final layer of rubberized AC or OGAC on a HMA base or initially grinding a PCC surface. In these cases, the reduction over DGAC or longitudinally tined PCC may be only 2 to 4 dB, but the nearby residents will receive some incremental benefit that could last for the life of the pavement compared to the noisier alternative. Some method of accounting for this type of "reasonableness" should be captured in methodologies for evaluating pavement strategies.

For considering reasonableness of pavement strategies and barriers for noise mitigation, three scenarios can be considered that include pavements. These are the incremental reduction provided by quieter pavements alone, quieter pavements versus noise barriers, and quieter pavements and barriers in combination.

Quieter Pavement Strategies

Quieter Pavements Alone

There are a number of situations in new highway projects where it may be desirable to consider the use of quieter pavements alone to achieve some level of traffic noise reduction. One situation is when the use of noise barriers is not feasible due to either physical or performance constraints when a normally sufficient number of the impacted residences are identified and the NAC are exceeded. Another situation is when a barrier may not be reasonable due to the high cost of relocating major utilities such as gas lines or when highway widening is planned in less than 15 years. In these situations, it might be considered a "prudent expenditure of public funds" to consider quieter pavements even though the "substantial" noise reduction of 5 dB or more may not be met particularly if the cost of the quieter pavement alternative can be implemented at a fractional cost of a barrier. In situations where a 5 dB reduction or more can be achieved by the pavement, the existing application of reasonableness could be invoked. In situations where this is not the case, methodologies that allow the further consideration of quieter pavement would be useful. This could be accomplished by a set of new pavement thresholds for noise reduction, such as 2 or 3 dB. This may be further supported by a cost/residence/dB reduction approach already used by some states or a prorated cost/residence for reductions less than 5 dB. With these adjustments, the process for determining cost reasonableness would be essentially the same as in the 23 CFR 772 Policy and Guidance Document *(1)*.

Another situation where quieter pavement options could be considered is for Type 1 highway expansion projects. In these cases, the addition of an HOV lane or even a normal through lane of traffic may produce virtually no increase in noise or increases up to something on the order of 3 dB. In these cases, the SHA is required to complete a noise assessment and consider noise abatement if the levels exceed the NAC. In these situations, it may be very difficult to demonstrate that the cost of new barriers or even adding height to existing barriers is reasonable from a cost perspective. With the ability to consider quieter pavement and using a cost reasonableness methodology as described above, some level of noise abatement may be achieved that would not otherwise be reasonable.

The consideration of quieter pavement as an alternative in Type II projects could also improve the frequency with which these projects occur. In cases where the existing pavement is particularly noisy, substantial (5 dB) reductions may be readily achievable and using the existing cost reasonableness approach may very well support the use of quieter pavements. With the expected lower cost of using quieter pavement than building noise barriers, this could also modify the priority rating systems that are employed by some states, where the priority factor is inversely related to barrier cost. Utilizing a revised cost reasonableness methodology as described above, may also increase the occurrence of Type II projects.

The consideration of pavement as a means of reducing traffic noise may also have applications outside of the existing scope of 23 CFR 772. With the development of cost reasonableness analysis methodology tailored to quieter pavements, noise could also be introduced into pavement rehabilitation projects at the option of the SHA. This may require additional adjustment to the cost/residence or cost/residence/dB values to account for the life-cycle duration of the rehabilitation. With this methodology, it may be possible to justify the incremental cost of using a quieter pavement option in performing the LCCA for the rehabilitation.

Quieter Pavements versus Noise Barriers

With the ability to consider quieter pavement as a noise abatement option, there may be situations in which a SHA could consider using one or the other. In these cases, the methodologies for assessing reasonableness could remain similar to what is currently described in the 23 CFR 772 Policy and Guidance Document *(1)*. To be comparable, both quieter pavement and noise barriers would both need to be physically feasible and feasible in meeting the defined substantial noise reduction criterion. In regard to cost reasonableness, both options would require a LCCA over the project life which includes all of the initial and ongoing maintenance/rehabilitation costs so that the noise reduction performance is achieved in perpetuity. In addition to addressing feasibility and reasonableness in this manner, the magnitude of the reduction also should be taken into account. As discussed previously, except in extreme cases, such as the Arizona QPPP where some locations achieved reductions of 10 dB, the maximum reduction achievable by a quieter pavement maybe limited to 5 or 6 dB. In cases of severe impact (e.g. hourly L_{eq} values of 75 dBA or greater), the additional reduction of 10 dB or more this is attainable by a barrier should be considered. In the cost reasonableness calculation, this could be accounted for by using the cost/residence/dB approach or by subdividing the cost/residence values into two or more brackets depending on the noise level as is currently done by some SHA.

Combined Barriers and Quieter Pavement

There may also be situations where a combination of the barriers and quieter pavements are worthy of consideration as an overall noise reduction strategy. This could be the case when neither a barrier nor quieter pavement alone can achieve a substantial noise reduction. It could also occur when a feasible barrier is not reasonable due to cost. In these cases, the incremental increase in noise reduction performance provided by quieter pavements may be sufficient to make the system feasible while the incremental pavement cost keeps the cost reasonable using a shorter barrier. Also in situations where barrier height is constrained (e.g. for earthquake considerations), the incremental improvement afforded by the quieter pavement may make the system feasible.

The methodologies for evaluating these combined systems for reasonableness follow from those discussed above for quieter pavement versus barriers. The overall cost of the noise abatement would be developed using LCCA applied to both elements of the system so that the initial and on-going costs are both captured properly. The criterion of substantial noise reduction would also be applied to the complete system. It may be appropriate to consider an additional adjustment for the magnitude of the noise impact in cases where the barrier height is lowered solely to reduce costs.

Other Reasonableness Issues

The reasonableness considerations beyond the cost and benefit of noise abatement as outlined in the 23 CFR 772 Policy and Guidance Document *(1)* are also appropriate in considering quieter pavement. These include the views of the impacted residents, the absolute noise levels, the change in noise levels, development along the highway, and environmental impacts of abatement construction. Although these issues are not strictly cost issues, the manner in which SHAs evaluate trade-offs between abatement and no abatement may have the anticipated cost of barriers implicitly imbedded. In considering quieter pavement as an alternative to barriers, it becomes important to the have LCCAs done first for each of several abatement strategies so that these other factors can be adequately considered. It should also be noted that as the public becomes more aware of quieter pavements, there may be increased pressure for SHAs to consider this as an option particularly when there are aesthetic and view obstruction issues with barriers. As a result, having a thorough cost and performance analysis of the abatement strategies will be important in communicating with the public.

EFFECTIVENESS

In 23 CFR 772 and the accompanying Policy and Guidance document, there is no mention of the term "Effectiveness" of the noise abatement. In the context of traffic noise reduction, the ability to produce a decided, decisive, desired effect can take on both an objective side and a subjective side. Objectively, it can often be taken as how effective is the noise abatement in producing a predicted dB reduction in noise. Subjectively, it may be considered how effective is the noise abatement in reducing complaints regarding traffic noise.

Objective Effectiveness

For highway noise abatement, effectiveness is typically considered as how closely does the actual noise reduction performance or predicted overall noise level match that which is expected on a decibel basis. In regard to 23 CFR 772, the prediction is generated by TNM. One class of circumstance in which expected performance is not matched by the actual is when pavement type is a factor. Currently, TNM is limited to predicting traffic noise levels using average pavement. From OBSI data, the actual range in tire/pavement noise source strength can be as large as 13 dB or greater *(2)*. Without the ability to account for this range, predictions can often not be fulfilled, particularly when the upper range of levels is not represented. The Ohio Department of Transportation (ODOT) has recently reported cases in which an existing asphalt pavement was replaced with transversely tined PCC *(15)* and unexpected noise impacts occurred. Although it is not known what level of tire/pavement noise these surfaces actually produced, judging by published levels for transversely tined PCC, the OBSI levels could have been on the order of 109 to 112 dBA *(16, 17)*. Using the relationship shown in Figure 11, this may have generated vehicle noise source levels 7 to 10 dB greater than what would be predicted for light vehicles. Using average pavement in TNM, sound walls were built that did not take into account this additional source level and as a result, the “noise barriers were not working as designed”, the public complained, and the barriers were deemed “ineffective” *(18)*. In reality, the barriers were likely completely effective in providing a predicted amount of noise reduction: however, with the increased source levels, the system was truly ineffective in abating noise. In a more hypothetical case, using the calculated results of Figure 14, in a situation where a quieter pavement was already in place producing the 4 dB reduction at 100 ft, the addition of an 8 ft barrier would not be as effective in producing a noise reduction as it would without the quieter pavement. That is, using average pavement, the reduction would be predicted to be about 8 dB. When the barrier is inserted with quieter pavement in place, the reduction would be only 7 dB.

Both of the cases discussed above could be improved for determining effectiveness if pavement type and performance were taken into account. In principle, this could be done by using the three different pavement categories already imbedded in TNM. However, the total range is limited to 4.6 dB reflecting the difference between a national average for OGAC and PCC. Although this would help in better assessing this type of effectiveness, given the much larger range of OBSI levels reported in the literature, this is probably insufficient. As a result, implementing the use of actual OBSI measurements for the pavements involved appears to be the best direction for addressing this issue.

It is clear that implementing explicit OBSI data or some other specific accounting for pavement in noise prediction is critical to addressing the effectiveness of overall noise abatement. However, this must be done across the board in all noise assessments. That is, the pavement levels need be used regardless of whether or not the proposed pavement for a project is quieter or noisier than TNM average pavement. This may be somewhat problematic as the use of actual performance of a noisier pavement may increase cost for noise abatement by indicating the need for barriers where it might not otherwise be considered resulting in higher sound walls.

In addition to actual pavement performance, there are environmental factors not accounted for in TNM that could influence effectiveness. Although it is arguable that these time varying effects should not be included in the impact assessment, by at least considering them, there may be some implications on the effectiveness of the noise abatement design. In the case of prevailing downwind conditions (wind from the highway to the receiver), noise levels will increase due to refraction *(11)* and as illustrated in the results of the Caltrans I-80 Davis study at distances of 475 ft even under light wind conditions (2 to 5 mph) *(19).* Downward refraction will tend to reduce the effectiveness of a barrier making consideration of quieter pavements, alone or in conjunction with a barrier, appropriate. Even though the downwind condition will still produce higher noise levels, the reduction provided by the quieter pavement would remain the same in comparison to the same prevailing wind condition. A similar consideration might be made in cases where temperature inversions occur and are known to generate noise complaints by the public. In these cases, quieter pavements alone may not be *the* solution, but quieter pavements in combination with a noise barrier maybe the most effective solution.

Subjective Effectiveness

The somewhat more subjective side of effectiveness deals with two aspects. The first might be termed "sufficiency" of the noise abatement. This can be considered in terms of absolute level. In the case cited above for ODOT, the barriers constructed along the transversely tined PCC highway were almost certainly "feasible" and the performance of the barriers "effective" in achieving the predicted reduction. However, the overall solution was not effective in the public view, likely because the absolute values remained high and/or were higher than the pre-project case. Concern over "unacceptably high" absolute level is discussed in the 23 CFR 772 Policy and Guidance document addressed through the NAC. It is also recommended that SHAs establish an absolute level at which more consideration is given to noise abatement. For the SHAs that have identified such a level, the range is from 70 to 80 dBA with 75 dBA being the most common (see Appendix B). In some cases, these higher levels are also used to increase the cost/residence in the reasonableness calculation. Out of the 51 states and districts, only 18 have identified levels for which more consideration is given. With apparently little attention paid to absolute noise levels, it is more than conceivable that a noise abatement approach could be reasonable, feasible, effective in producing an anticipated noise reduction, but still notprovide an effective solution in the public view due to the final absolute level of traffic noise.In order to put the issue of absolute level into perspective, it is useful to consider traffic noise in terms of L_{dn} (day/night equivalent noise level). The bulk of the research to establish annoyance response relationships for transportation noise sources is based on this metric in which the nighttime hours are penalized by 10 dB before (energy) averaging hourly L_{eq} levels over a 24-hour period *(20, 21).* Estimating L_{dn} from worst hour L_{eq} has been attempted by a number of researchers based on measured diurnal traffic noise patterns such as that shown in Figure D6 *(22, 23).* The average results obtained in these studies indicate that about 2½ dB to 4 dB need to be added to the highest hourly value to estimate

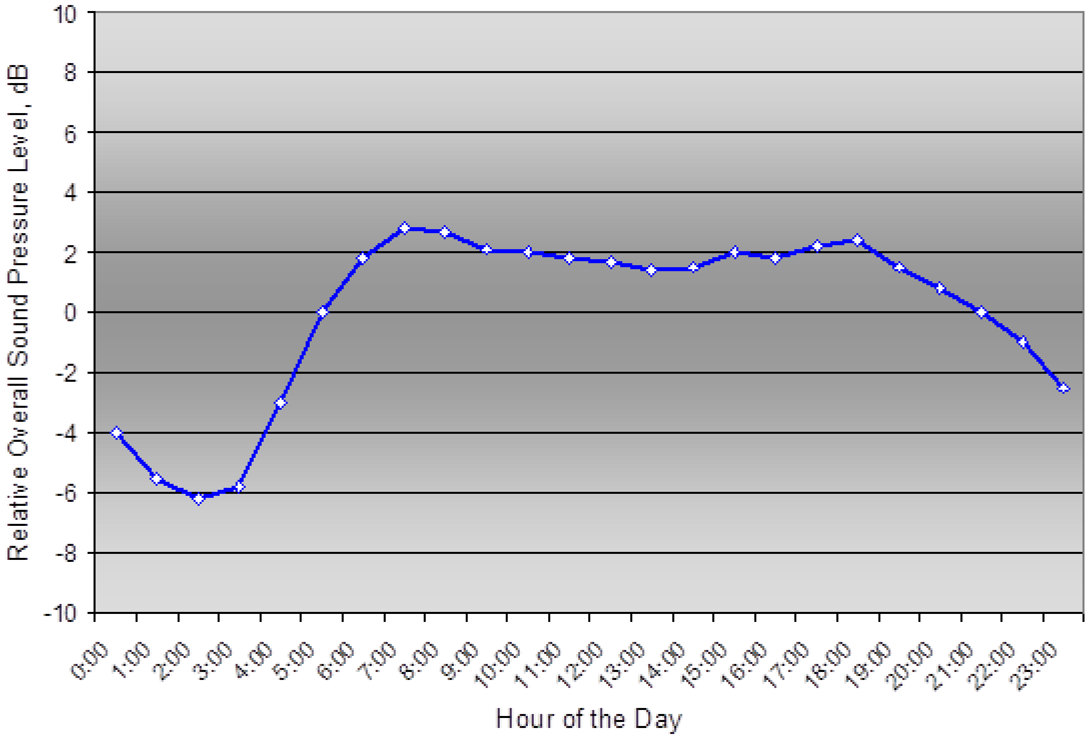

Figure D6: Typical diurnal traffic noise pattern for metropolitan areas with levels expressed to the 24-hour level

L_{dn}. Taking 3 dB as typical number, a 75 dBA level for additional consideration translates to 78 dBA. The number of people expected to be highly annoyed by this level of traffic noise varies: however, typically the percentage is on the order of 40%. For the NAC of 67 dBA, the estimated L_{dn} is about 70 dBA which produces high annoyance in the range of 20 to 30%. It is not being advocated that L_{dn} criterion be implemented, however, it is useful to consider these annoyance relationships in assessing how effective a predicted and achieved absolute L_{eq} may be in meeting the expectations of the SHA for public reaction to a project. L_{dn} is also useful in relating values to the criteria used for other transportation noise sources, such as aircraft and trains (impact thresholds at 65 L_{dn}) and to land use planning documents at the local level.

There is some evidence that subjective effectiveness in terms of positive public response may occur when relatively small changes in overall A-weighted level are produced. In California, there have been two cases involving grinding of PCC surfaces in which reductions on the order of 3 dB have produced favorable public response *(17, 24)*. Given a SHA's experience with small changes and their ability to produce positive response, it may be appropriate to consider these small changes as "effective" in assessing noise control options.

Summary

Effectiveness is a new dimension to be considered in evaluating pavement and barrier solutions for traffic noise mitigation. Ultimately, it may be considered along with feasibility and reasonableness in assessing noise abatement options. Several key aspects of the effectiveness have been identified and should be considered. The first of these is the use of specific pavement tire/noise sources in TNM preferably through the use of OBSI data. This will greatly enhance the ability of SHAs to accurately predict traffic noise levels necessary for the evaluation of noise abatement options in terms of effectiveness as well as feasibility and reasonableness. The second key aspect is some consideration of absolute level in terms of understanding public response to highway projects. Other aspects that should be considered are 24-hour metrics or, at least, understanding the cycle of hourly L_{eq} levels throughout the day and night; the potential influence of prevailing meteorological conditions; and recognizing the potential of smaller changes in overall noise level in regard to producing effective, positive public response. In the second phase of this project, these aspects will be explored further in order that recommendations can be developed and advanced.

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APPENDIX E

PAVEMENT ACOUSTIC LONGEVITY

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INTRODUCTION

In the 23 CFR 772 Policy and Guidance document, there are basically two reasons provided why pavement "must not be considered as a noise abatement measure". The first is uncertainty in the role of tire pavement noise in overall traffic noise. Since the document was written in 1995, there has been a significant amount of research done in the US relating tire-pavement noise to overall vehicle noise both for trucks and light vehicles. In the NCHRP 1-44 project, relationships between OBSI level and statistical passby results were developed for both trucks and light vehicles (10). In Caltrans sponsored research and the NCHRP 8-56 project, acoustic beam forming has been used to localize noise sources on trucks under normal operation on highways indicating that tire/pavement noise is the major source (43, 44). Further, by taking into account differences in tire/pavement noise by modifying the ground level source strength in TNM, rather than overall vehicle emissions, the influence of pavement should be properly allocated in the predicted results.

The second reason for not considering tire pavement noise is the uncertainty of the tire noise performance of the pavement over time. Also since 1995, the acoustic longevity has been further investigated. It is now understood that a 2 to 4 dB reduction in noise level will not be lost in a 6 to 12 month time period except possibly under very unusual circumstances such studded tire damage (45). However, it has been shown in more recent research that noise reduction performance of a pavement, particularly HMA pavements, will degrade over time. As a result, acoustic life-cycle needs to be considered when using pavement as a feature of a noise abatement strategy.

Although there has been research done recently on pavement acoustic longevity, generally the time periods are still too short to capture noise performance over the usable life of a quieter pavement. There is some potential error in judging the lifetime performance based on the first several years of a pavement. For non-porous HMAs, it is generally thought that the noise will increase on the order of 1 to 2 dB in the first several years, stabilize, and then, toward the end of the pavement life, increase again when raveling, cracks, and unevenness occur (11). For porous pavements, clogging of the pores can also degrade performance with time. Although these trends have been observed, the understanding of the increases in noise for HMA pavements, particularly in the early degradation, is unknown (11). An alternative approach for assessing longevity is to measure the performance of a number of pavements built to the same specification and spanning a wide range of build dates. This was the primary approach taken in the Arizona QPPP for examining the acoustical longevity of the ADOT ARFC (3).

The primary tool considered here for assessing acoustic longevity of pavements used as noise abatement is the use of OBSI measured on a regular basis throughout the life-cycle of the pavement. These levels would be used in TNM to calculate traffic noise levels for a constant set(s) of traffic and site geometry data. If the TNM calculations exceed a predetermined level, then the pavement would be rehabilitated to reduce the OBSI level accordingly. For implementing this approach in LCCA, noise would be treated as any other pavement performance parameter that would generate a need for rehabilitation. Ideally, the rehabilitation cycle for noise would correspond to that required for other purposes. If shorter, then the LCCA would reflect more rehabilitation events over the life-cycle. Simplistically, if a life-cycle was assumed to be 36 years and rehabilitation for noise alone was required every 9 years instead of

12 years, then the cost of one additional rehabilitation in the 36 year life-cycle would be included in the analysis. Added to this would be any incremental cost for the quieter pavement relative to a lower cost, higher noise pavement option. Before using a quieter pavement for noise abatement, an agency would need some applicable information on, or estimate of, its acoustic longevity.

A discussion of studies on the acoustic longevity of different pavements is summarized in the remainder of this appendix. This is basically for information in regard to how the quieter pavement methodologies would perform in the area of longevity and LCCA. Prior to attempting to use quieter pavement for noise abatement, each SHA would need to quantify both the initial reduction provided by the pavement and to have some understanding of its acoustic longevity specific to their own application. Generally, the results of this appendix indicate that AC surfaces can increase in noise level at rates of about 0.3 to 0.8 dB/year assuming linear trend lines and the absence of studded snow tire usage. PCC pavements increase at lower rates, typically just 0.1 or 0.2 dB/year based on the more limited, available data.

SUMMARY OF ACOUSTIC LONGEVITY STUDIES

The longest, ongoing study of the acoustic performance of a quieter pavement in the US is that sponsored by the California Department of Transportation (Caltrans) *(1)*. This project began in 1998 with an application of a one inch OGAC overlay used to replace an existing older DGAC surface. The 5.6-mile stretch of pavement is along a high volume, multi-lane section of Interstate I-80 near the city of Davis, CA. On a daily basis, trucks make up about 7.6% of the total traffic volume. From 1998 through 2009, time averaged noise levels (CTIM) have been measured three times per year on either side of the roadway at a reference distance 65-feet from the center of the outside lane of travel. Beginning in 2002, on-board sound intensity (OBSI) tire/pavement noise measurements were added to the data acquisition program. In the earlier stages of this investigation (through 2007), both the wayside levels and the OBSI increased at a rate of about 0.1 dB/year. Through 2009, the wayside levels show rate of increase of about 0.2 dB/year and the OBSI levels about 0.3 to 0.4 dB/year with a more rapid increase in the last two years. Initially, the CTIM levels were 6 dB below those predicted by TNM and after ten years still remain 4 dB lower than the TNM predictions.

In 2002, Caltrans initiated another quieter research project that monitored the initial and subsequent performance of five AC overlays on State Route LA 138. These sections have been monitored using a variety of methods including statistical passby (SPB) measurements *(2)* and controlled passby (CPB) and OBSI measurements *(3)*. Other properties of these pavements including durability, permeability, and friction performance have also been documented *(4)*. The five test pavements were constructed on a new HMA leveling course and consisted of a one-inch thick DGAC, two overlay sections of OGAC of three-inch and one-inch thicknesses, a rubberized asphalt concrete open graded (RAC[O]) one-inch thick, and a bonded wearing course (BWC) also one-inch thick. The nominal maximum aggregate size for all pavements was ½-inch, with the exception of the three-inch thick OGAC measuring ⅜-inch *(4)*. Over the four-year span of the SPB measurements, the DGAC pavement produced an average 1.1 dB increase in level (0.30 dB/year), the three-inch thick OGAC a 1.2 dB increase (0.30 dB/year), the one-inch thick OGAC a 0.18 dB increase (0.04 dB/year), and the RAC(O) a 1.5 dB increase (0.38

dB/year) for light vehicles. Similar rates were measured for heavy trucks with the exception of the three-inch thick OGAC that increased only 0.3 dB over the four years *(5)*. Over the period from October 2002 to October 2008, OBSI levels for the OGAC and RAC(O) pavements increased at rate of about 0.3 dB/year while the DGAC was about 0.1 dB/year and the BWC 0.2 dB/year *(3)*. From the controlled passby tests all five pavements increased at about the same rate of 0.2 dB/year.

In 2003, Caltrans initiated a research project to examine different PCC texturing methods on State Route 58 bypassing the town of Mojave in Kern County. The textures included typical California longitudinal tining (LT), burlap drag, longitudinally broomed, grooving, and grinding *(6)*. From March 2003 to October 2008, the LT section increased in OSBI level by 0.2 dB (less than 0.1 dB/year), the burlap drag by 0.9 dB (~0.2 dB/year) and the broomed by 1.1 dB (~0.2 dB/year). For the ground and grooved surfaces from June 2003 to October 2008, the four ground only surfaces increased typically 0.8 to 0.9 dB (~0.2 dB/year) with one increasing only 0.2 dB for the whole period, the three grooved only surfaces ranged from 0.2 dB to 1.0 dB (~0.2 dB/year) and one grooved and ground surface increasing 0.7 dB (~0.2 dB/year).

Results from a number of smaller project studies in California have also been monitored and reported over time. One case was a rehabilitation project completed on I-280 in San Mateo County in November 2002. In this project, an older, faulted PCC was initially ground over the length of the project. The majority of the project was ground a second time while the remainder was overlaid with RAC(O) in the travel lanes and OGAC on the shoulders. The pavement was retested in June of 2005 using the same OBSI procedures. Over this relatively short period, the PCC was an average of 0.3 dB noisier (average rate of ~0.1 dB/year), the RAC(O) was 0.8 dB noisier in the southbound direction and 1.8 dB in the northbound direction (average rate of ~0.5 dB/year). The OGAC shoulder increased in level by 2.1 dB (~0.8 dB/year) with virtually no traffic.

In another project on I-5 in Sacramento County, Caltrans had identified a section of suburban freeway for a Type 2 noise abatement project. However, it was determined that increasing the height of the existing sound walls was not feasible in terms of providing sufficient noise reduction. As a result, Caltrans decided on overlaying the existing PCC pavement with RAC(O) using state funds. Wayside and OBSI measurements were made prior to the overlay and afterwards beginning in December 2004. The measurements were repeated annually through August of 2008. Over this time period, the average OBSI levels increased about 0.2 dB (less than 0.1 dB/year), wayside levels close to the freeway increased an average of 0.7 dB (~0.2 dB/year), and levels in the community displayed no increase over the measurement period.

Prior to the QPPP in Arizona, a series of AC test sections were constructed on the interstate highway in the state. One set of these pavements located I-10 near Casa Grande has been measured using OBSI from May 2002 through October 2008. These included two asphalt rubber-asphalt concrete friction course (AR-ACFC) pavements with ½-inch and ¾-inch maximum aggregate size, a ¾-inch stone matrix asphalt (SMA) pavement, a ¾-inch porous-ACFC (P-ACFC) pavement, a 1¼-inch porous European mixture (PEM) pavement, and a ¾-inch ACFC pavement. Over this time period, the level of the ½-inch AR-ACFC increased 2.0 dB (~0.3 dB/year), the ¾-inch AR-ACFC 1.7 dB average (~0.3 dB), the SMA 1.7 dB, the P-ACFC

4.7 dB (~0.7 dB/year), the PEM did not change, and the ACFC increased 2.4 dB (~0.4 dB/year). These sections were placed in succession and, accordingly, subject to the same traffic. Of these sections, the AR-ACFC was the quietest and was similar to that used in the QPPP.

Longevity was also evaluated by ADOT by measuring the on-board CPX noise levels of ARFC pavements throughout the state constructed in different years. Initial results from this type of evaluation indicated that the noise level increased at about a ½ dB/year with some scatter (R^2 ~ 0.4 to 0.6 dB) for pavements up to 12 years old *(7, 8)*. Measurements were later measured up to 17 years in age producing a trend of about a ⅓ dB/year using both CPX and OBSI measurements *(9)*. These latter data also demonstrated that the ARFC was capable of provided a 4 to 5 dB reduction over the ADOT standard uniform transverse tined PCC for periods up to 14 years *(10).*

In the QPPP itself, results up 3½ years have been obtained for the 1-inch ARFC overlay placed on PCC. These results indicated both in wayside, CTIM measurements and OBSI measurements that the performance fell fairly rapidly in the first year or two of the overlay and has appeared to maintain a consistent level of performance after 1½ to 2 years. Over the 3½ year period, the rate of decrease in acoustic performance has been about a ½ dB/year *(11).* Given the relatively short length of the monitoring to date, extrapolating such trends may be somewhat misleading.

Contrary to the experiences in California and Arizona, those in Washington State have not been so successful. WSDOT has constructed two sets of three experimental pavements in the Seattle that have been monitored over time using OBSI. The pavements include a conventional (dense grade) asphalt as a control section, a OGFC with rubber, and a OGFC modified with polymer *(12).* Initially, reductions of 4 dB and 2 dB were measured for the OGFC with rubber and the polymer modified, respectively relative to the DGAC. From August 2006 to January 2009, the first sections produced increases in noise level of 5 dB, 10 dB, and 7 dB for the DGAC, OGFC-R, and OGFC-P, respectively, and now with the levels of all three being within a dB range of 2 dB. The second set of sections produced increases in level of 4 dB, 8 dB, and 5 dB, respectively in the period from July 2007 to January 2009. The rapid deterioration in performance, especially in late 2008, was found to be due to unusual amounts of snow and the resultant high usage of studded snow tires. Along with this loss of performance, differences in OBSI level in and out the wheel path were found to be quite large (2 to 6 dB) even after one year for the 2006 sections *(13).* The WSDOT experience makes it very clear of the benefit of conducting quieter pavement research prior to considering the use of pavement for noise abatement. At this point, both of the OGFC pavements are producing noise levels exceeding that of TNM average pavement (refer to Figure 11 in main body).

European experience in quieter pavement acoustic longevity also indicates the necessity of documenting the performance of the specific pavement being considered for noise abatement. In the EU project SILENCE, the experience in a number of European countries covering a wide of range of pavements concluded that on average, dense asphalt performance decreased at a rate of 0.1 dB/ year while porous asphalt had a rate of 0.4 dB/year for higher speed light vehicles *(14).* For heavy vehicles, the rate was 0.1 dB/year and 0.2 dB for the two pavement categories, respectively. There was considerable scatter within each category depending on pavement specifics. As an example, dense asphalt concrete (DAC) and SMA ranged from -0.1 dB to 0.37 dB/year at higher speed. The French data for a variety of quieter pavement types produced an average rate of 0.5 dB/year while German porous sections were 0.32 dB/year. In a recent review of the AC pavements in California and Demark, it was concluded that deterioration rate for DGAC was 0.40 dB/year, OGAC was 0.41 dB/year, thin open layers was 0.84 dB/year, and porous AC was 0.53 dB/year *(15)*. However, these averages were somewhat bipolar with the rates in California typically in the range of 0.2 to 0.3 dB/year, while those from Denmark were more typically in the range from 0.5 to 0.9 dB/year.

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APPENDIX F

EVALUATION OF COST BENEFIT ANALYSIS TO HIGHWAY NOISE ABATEMENT

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INTRODUCTION

Within the scope of 23 CFR 772, economic features are dealt with through the assessment of noise abatement reasonableness based on assigning a dollar figure per noise impacted residence. In considering pavement and barrier alternatives, a broader consideration of Cost-Benefit Analysis (CBA) could be applied. With the 23 CRF 772 approach, the benefit is monetized with a cost per benefited receiver applied state-wide assigned by the SHA within a range set in the 23 CRF 772 Guidance Document of $15,000 to $50,000. In the State of California, Caltrans uses a cost that is based on the state-wide average cost to build a barrier to block an average lot width *(1)*. It is suspected, but not confirmed, that other SHA use similar methods. In considering the economic features of quieter pavement and barriers, one plausible direction would be to essentially leave the benefit side of the equation as it is currently defined by the SHA under 23 CFR 772 and concentrate only on the cost side. This would assume that the monetized benefit is independent of the type of abatement. One of the issues in developing methodologies for evaluating pavement strategies and barriers for noise mitigation is to determine if the current methods of assessing economic features is sufficient or if other CBA are appropriate.

COST-BENEFIT ANALYSIS

In the broadest sense, CBA seeks to balance the “winners” and “losers” in any particular public decision by developing monetary values assigned to each group *(2)*. In the case of highway noise, the winners can be both the driving public for improved transit performance or residents benefiting from noise abatement. The losers can be both the general public in terms of the direct cost of noise abatement funded ultimately by taxpayers or residents alongside a highway exposed to higher levels of noise. CBA then attempts to define these in terms of direct and indirect costs to society. Direct costs, such as the cost of building a sound wall or selecting a quieter pavement, are in principle straightforward to define. Indirect costs, such as the benefit of reduced noise levels, are much harder to determine. If a link between the increased cost to society for health and welfare effects of exposure to increasing levels of traffic noise could be made, this would provide some method of assigning a monetary value to the level of exposure. However, more commonly considered is the use of damage valuation methods of Revealed Preference and Stated Preference which are used to estimate “willingness to pay” (WTP) for lower noise levels *(3)*. Of the WTP methods, the most commonly considered for traffic noise is Hedonic Property Values *(4)*. The effects on health and welfare and the application of Hedonic methods are discussed in the remainder of this subsection.

Health and Welfare Effects

Ideally, a CBA for highway noise would capture all negative effects of not mitigating the noise and assign some monetary amount to each effect. However, some aspects such as health effects, annoyance, and reductions in economic productivity are difficult to quantify. In the area of health effects, noise is reported to produce stress and effects on the cardiovascular system. However, identifying the precise impact of noise is difficult because it is only one factor among many that affect cardiovascular health. Related to cardiovascular effects is the effect of traffic noise on sleep disturbance. In the nighttime hours, as the traffic density typically is reduced, the impacts of the distinct (passby) events from louder vehicles become the more dominant feature in regard to sleep disturbance *(5)*. As a result, much of the research on sleep disturbance from traffic noise has concentrated on single event maximum level and temporal pattern. With respect to awakenings, it has been found that maximum (passby) levels of about 55 dBA result in about a 10% risk factor for awakening and at 65 dBA, this risk factor increases to about 18% *(5)*. Cardiac arousals during sleep due to vehicle (passby) events have also been documented and found to persist up to 40 seconds after the onset of the passby event. There is also evidence that people do not necessarily habituate to cardiac arousal or awakenings even over periods of years or decades. As a result, there is some evidence of a greater level of hypertension for people who suffer from sleep disturbance induced by road traffic noise. However, this linkage is still somewhat tentative and not developed well enough to be used in CBA.

Noise can also affect job performance in a number of ways. It may slow communication between co-workers, decrease worker's ability to carry out multiple tasks simultaneously, increase error rates, and increase the tendency of workers to make quick decisions. These productivity effects are likely to affect work quality rather than a raw measure of output. Also, reduction in traffic noise will only impact workplaces that are otherwise quiet. Workplaces that produce more noise than is produced by roads, such as automobile manufacturing plants, will not benefit from reduced road noise. It is likely that such productivity improvements would be difficult to measure empirically since the effects on each workplace will be small and affect subjective quality rather than easily measurable output. However, the accumulation of small improvements in worker productivity over all workplaces affected by traffic noise may result in a large total benefit of reduced road noise. In regard to children's education, noise is more likely to have adverse effects on children than adults. Disruption of speech and communication may affect children's language development in addition to the temporary inconvenience of disrupting their immediate attempts at communication.

In addition to affecting health, productivity and learning, noise impacts subjective well-being. Subjective well-being is difficult to measure because individuals have different expectations and their stated annoyance is measured relative to these expectations. The European Union has quantified some of the above effects for road noise on an interim basis with a sliding scale that assigns a dollar (euro) amount to L_{den} levels in the range from 50 to 75 Dba *(6)*. At 65 L_{den}, the cost in US dollars is slightly over $200 per person per year. With this valuation, it becomes feasible to do CBA that actually takes into account some of the effects that are not really quantified. In the US, such analysis has not been done and as a result there is no basis for assigning a dollar per dB amount for use in CBA.

Hedonic Analysis

In order to compare the costs and benefits of noise abatement projects, it is necessary to state costs and benefits in a common unit. A monetary unit is almost universally applied for this purpose in economic analysis. The costs discussed above are largely non-quantifiable. Only a few of these costs can be directly expressed in monetary terms. Therefore, economists have devised methods to infer the value of noise abatement from existing market transactions. The most common method requires a hedonic analysis of real estate transactions.

The logic of the hedonic approach is simple. Homebuyers consider a number of factors when purchasing a home. If they are considering two homes that are otherwise identical except for a difference in the neighborhood noise level, homebuyers will be willing to pay less for the home in the noisier neighborhood. This difference in willingness to pay will be reflected in sales prices. If sales prices did not account for noise levels, homes in noisy neighborhoods would sit empty while homebuyers flocked to purchase homes in quieter neighborhoods. While market prices do not work perfectly, they do provide some indication of the benefits of noise abatement. The argument is that homebuyers will consider the health and annoyance effects of noise when purchasing a home. While homebuyers probably do not fully understand the health effects of noise, they are probably better able to account for them than researchers. Therefore, hedonic valuation of residential home price depreciation is argued to be the preferred measure of total health costs and annoyance costs. While parents may take their children's ability to learn at home into consideration when purchasing a house, noise levels at schools are not likely to be incorporated into housing prices and thus represent a cost that must be accounted for elsewhere. Likewise, the cost to workplace productivity would not be incorporated into residential housing prices. A hedonic analysis of office buildings could conceivably estimate this value, but such studies are rare due to difficulties in constructing an adequate dataset.

In a recent study conducted in Maryland, the impact of proximity to highways was assessed in regard to noise as well as other aspects of houses sold such as number of bedrooms, bathrooms, and levels, days on the market, size, and whether or not it included a fireplace. Overall, it was found that while noise is likely the largest component of decreased property values adjacent to highways, other factors also appear to be important *(7).* Just being adjacent to a highway was found to reduce property values by 3 to 10% depending on which model was used. On the other hand, the presence of a barrier was found to improve property value by 3%. Being able to see the highway was also found to have a negative effect of 4% that may also be related to noise. The only other negative effect on value of all other variables besides those associated with noise was the number of days on the market. Although this study made progress on disentangling some of the variables associated with determining effect of highway noise on property values, it also re-enforced that these studies can be confounded by a number of factors not necessarily directly related to noise.

One of the shortcomings of hedonic analysis is that it only measures the cost of noise to homeowners. Drivers and pedestrians are also impacted by noise. Cost-benefit analysis should account for benefits that are not captured by hedonic valuation. Consideration of all the potential beneficiaries of noise mitigation is especially important when comparing noise barriers to quieter pavement. Hedonic valuation is largely adequate for measuring the benefits of noise barriers, because the bulk of noise barriers accrue to homeowners. Quieter pavement can benefit a broader range of people, including drivers and pedestrians. For vehicle occupants, a typical range of interior noise exposure due to various pavement types can be considered from data obtained as part of the Caltrans Quieter Pavement Research work. In Figure F1, overall A-

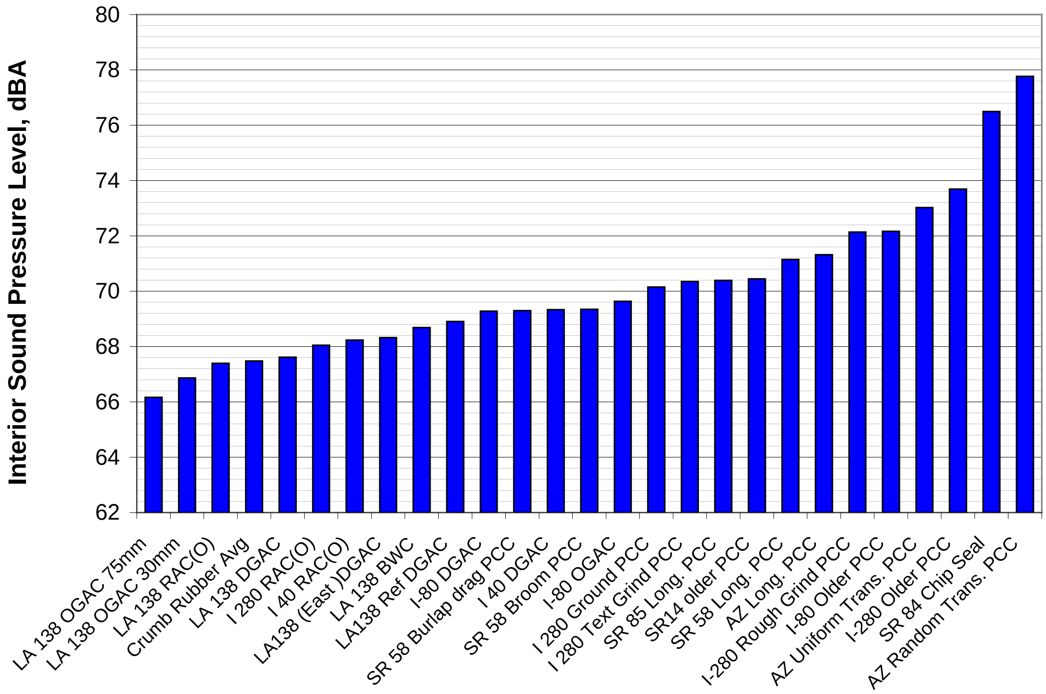

Figure F1: Overall interior sound pressure levels for a range of AC and PCC pavements from California and Arizona (same vehicle and tires)

weighted interior noise levels are presented as measured with a common vehicle and tires on a range of highways in California and Arizona at a speed of 60 mph. The range in interior levels is almost 12 dB mirroring the range seen in the OBSI levels for these same pavements *(7)*. The extremes of this range, more than 10 dB, would be considered to be more than a doubling of the interior loudness of tire-pavement noise *(9)*. It is also anticipated that these higher noise levels could degrade speech communication inside the vehicle. With the aging driving population in the US, this will be become an increasing problem as difficulty with speech perception among older persons with typical amounts of hearing loss are commonly cited in passenger cars *(10)*. However, this area of concern has not been researched sufficiently to begin to quantify and assign costs to higher noise levels in vehicles due to road noise and pavement type.

Other Potential Costs

There are a number of incidental impacts of road-noise which should be considered. Safety may be impacted due to the characteristics of certain pavements. Certain pavements may encourage drivers to adjust their speed which would entail both costs (in terms of safety) and benefits (in terms of time saved). Elvik and Greibe *(11)* reviewed 18 studies for a meta-analysis and found no statistical evidence of changes in road safety on tire-noise reducing pavements. Absent further evidence, safety and speed impacts may be excluded from the CBA.

More significant impacts of noise-reducing pavements are the environmental effects. The increased porosity of some noise-reducing pavements allows the road to absorb some of the rainfall which would otherwise be washed into nearby streams. This reduces flooding and the amount of sediment and heavy metals that are washed in local bodies of water. This is likely to be a significant ancillary benefit of quieter pavements. A search of the literature did not reveal any economic valuations of this impact on human health. However, the US EPA has conducted an experiment that measures the cost of obtaining similar reductions in storm water runoff through the construction of rain gardens and rain barrels. Data from an experiment such as this could be used to estimate the avoided cost of storm water retention. However, avoided cost is not an ideal measure of storm water retention benefits because such costs are not regularly incurred at present. An avoided cost valuation of the storm water retention benefits of noise-reducing pavements requires the assumption that the benefits of the US EPA project exceeded the costs, an assumption that is not verifiable at present.

Another environmental impact results from the increased energy and material required to meet the quieter pavement repaving schedule. The external costs of energy and materials use can be obtained from the literature. This is likely to be a small fraction of the construction costs that result from increased repaving

COST COMPARISONS FOR PAVEMENT STRATEGIES AND BARRIERS FOR NOISE MITIGATION

From the discussion above, completing a societal CBA analysis of traffic noise mitigation either by quieter pavement or barriers would be a large undertaking. For the purposes of this project, the emphasis is more focused to examine methods of completing true direct cost comparisons for pavements and barriers for the life-cycle of the highway. For assigning cost benefit, the existing method of using the cost per benefitted receiver as described in the 23 CFR 772 Guidance Document will be assumed as the standard for assessing cost reasonableness. The cost comparison will be done with LCCA for all mitigation scenarios. Even with this seemingly straightforward approach, there are several issues that require some discussion and would ultimately end up as policy issues. These are discussed in the remainder of this subsection.

Barrier Costs

Although it would seem that determining the cost of a barrier for noise mitigation would be straightforward, there can be some variation in the manner in which individual SHAs determine barrier cost*(12)*. The cost of the material is typically the majority of the cost of the barrier and this alone varies substantially. According to the recently published barrier inventory data collected by FHWA *(13)*, the average cost for earth berm barriers is $6/sq ft, while for wood, concrete, and brick, it is $19, $27, and $31/sq ft, respectively. Besides material cost, a number of other items may or may not be included in the cost estimate used in the reasonableness assessment. These include items such as grading, excavation, site preparation, right-of-way costs, drainage provisions, safety measures, utility work and relocation, traffic control, landscaping and visual issues, and effects of combined features such as berms and walls. Some of these are reflected in the range of state average costs of $6 to $42/sq ft *(13)*. Specific SHA protocols will also affect the estimated barrier cost. In California, the additional cost for transparent sound walls is not counted as part of noise mitigation, but rather as visual mitigation *(14)*. Also visual aesthetics is typically not included and is paid for through local jurisdiction based their requirements. Ultimately, barrier costs should be determined as project cost with the barrier versus the project cost without the barrier. However, this distinction is not always able to be made.

In terms of doing a LCCA for noise mitigation, barriers may need some attention in comparison to what might not be considered currently. Depending on the protocol of the SHA, maintenance and replacement costs may or may not be included in the cost estimate used for reasonableness. Currently in California, any maintenance costs associated with barriers as noise mitigation are not included in the cost analysis *(1)*. Other SHAs may include some provision for maintenance such as graffiti removal, barrier repair (depending on the material used), or maintenance of landscaping (if considered as part of the noise mitigation). In order to do a thorough LCCA for barriers relative to pavement, these costs will need to be estimated and considered. Also, an expected barrier life-cycle will need to be considered if it is less than the highway life-cycle.

Pavement costs

The primary issue for applying LCCA is accounting for the rehabilitation cycle for maintaining the acoustic performance of the pavement especially if it is shorter than that required for other pavement performance properties. There may also be added costs attributed maintaining the acoustic performance of pavement such as a need to clean porous pavements. As in the case of barriers, establishing the additional cost for a quieter pavement may not be as straightforward as it appears. Every project already includes some cost for pavement and a quieter pavement maybe selected for other reasons regardless of it acoustic performance. As example, a LCCA has been reported for the ARFC used in the Arizona QPPP versus conventional hot mix asphalt (HMA). ARFC was first used in Arizona due to its ability to reduce reflective cracking as an overlay of PCC and was found to also reduce maintenance cost and provide a smooth riding surface *(15)*. With a life-cycle of 25 years, the use of ARFC was found to produce a net savings over HMA for initial reconstruction due to the sub-layer construction and life-cycle maintenance costs. For use as a ½-inch overlay, the ARFC is shown to be more expensive initially, but the life-cycle costs are about the same due to the improved maintenance and user costs. For these examples, the use of the ARFC would be supported regardless of any consideration of noise. It also turns out that from the Casa Grande test sections, the HMA is about 3 dB louder than the ARFC even after six years of testing. In this case, there is no added cost for the noise mitigation benefit of the ARFC. However, other scenarios are likely to have added initial cost of a quieter pavement that may not be offset over the life-cycle and there would be a cost associated with noise mitigation.

Similar scenarios can be conceived for PCC pavements. If the decision is made to use PCC for non-noise related reasons, the choice of texturing can have a large impact on the resultant noise level, e.g. random transverse versus burlap drag. However, the texturing method has virtually no impact on the cost of the project. In principle, the burlap drag surface could produce light vehicle passby levels about 3 dB lower than TNM average pavement (see Figure 11) assuming its safety related performance was deemed acceptable, while the transverse tine could be 4 to 6 dB higher. If a burlap drag were used, it would not be accounted for as noise mitigation cost although it is supplying that benefit. On the other hand, if the higher levels of the transverse tined texture were used and properly included in the noise impact assessment, it would likely add cost to the project in terms of more and higher barriers. With the burlap drag texture, it could be decided for safety reasons to groove the pavement longitudinally. This would add cost to the project, but provides no acoustic benefit *(16).* The grooving may or may not be considered as noise abatement cost depending on the accounting.

To complete the cost analysis for pavements and barriers, the nature of the two mitigation methods need to be considered, particularly in the way that policy exists under 23 CFR 772. In considering barriers, the mitigation is basically to build or not to build one. Performance and cost is judged on the basis of barrier insertion loss and is essentially independent of pavement. As a result, the final traffic noise levels are left to float with pavement characteristics over a range possibly larger that the noise reduction of the barrier. For pavement, its performance can range from creating no need for a barrier based on the NAC to needing a high barrier to achieve the same overall noise performance. The challenge from a cost benefit perspective is to affect both the barrier decision and the pavement decision to achieve a similar benefit. As an example, assume a barrier is designed and determined to be reasonable providing an 8 dB insertion loss. However, the choice of pavement is a transverse tined PCC producing an OBSI level of 108 dBA and the as-build level turns out to be 74 dB behind the wall. If a different pavement texture were selected such as burlap drag or diamond ground, the OBSI level would likely be 100 dBA or less. This would provide a level of about 66 dBA behind the wall. In terms of real benefit to the residents, in the first case, they are "benefitted" by the barrier, not nearly as much as those benefited by the combination of the barrier and the quieter pavement. Without some accounting of the absolute noise level, this combined benefit would not be captured and likely not implemented.

Another cost benefit issue for pavements is its use in the close vicinity of multi-story buildings. This situation is becoming more common with the revitalization of urban areas throughout the U.S. as well as the scarrcity of developable land. In most analyses, only the receptors at the height of the first floor of building are considered and primarily for backyard exposure, although in some states, some consideration is given to the second floor spaces *(1)*. For multi-storied, multi-occupant residential buildings, outdoor living space may include balconies and terraces. With barriers as the only mitigation, people on the lowest level would realize the benefit on their patios, while those above would not. In terms of sleep disturbance, without the 8 to 10 dB barrier benefit experienced for bedrooms located on the first floor, it would be expected that risk for awakenings would be on the order of 5 to 8% greater on the upper floors *(17)*. In these types of situations, the aggregate benefit may be better served by mitigation that affects more receivers to a lesser amount than mitigation that affects a limited number of receivers by a greater amount.

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APPENDIX G

LIFE CYCLE COST ANALYSIS FOR CALIFORNIA I-580 HOV LANE PROJECT EXAMPLE

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PROJECT DESCRIPTION

The project consists of adding a high-occupancy vehicle (HOV) lane in both directions to an existing eight-lane interstate highway. The HOV lane will be constructed at the outside edge of the existing roadway, replacing the existing shoulder with the new HOV lane and shoulder.

The current two-way traffic volume on I-580 is 167,000 vpd with 8.375 percent trucks (assumed to be 5 percent single unit trucks and 3.375 percent combination trucks). The current lane configuration for I-580 is shown in Figure G1.

Figure G1: Current configuration of I-580

LIFE CYCLE COST ANALYSIS ALTERNATIVES

For this section of I-580 a total of five alternatives have been evaluated. The LCCA alternatives include:

1. Construct added HOV lane and shoulder with PCC. The PCC surface of the added lane will be longitudinally tined to match the similar surface texture of the existing pavement. The existing pavement is in good condition and does not require rehabilitation at the time of the HOV lane construction. Diamond grinding of all lanes (for noise and other

considerations) is conducted 10 years after the addition of the HOV lane construction and every 20 years thereafter.

2. Construct added HOV lane and shoulder with PCC and diamond grind all lanes to reduce the tire/pavement noise levels. Diamond grinding of all lanes is then conducted on a 20-year cycle thereafter.
3. Construct added HOV lane and shoulder with PCC and overlay all lanes and shoulders with a 1-in. RAC(O) overlay. To ensure noise performance, the RAC(O) overlay is milled and replaced every 9 years.
4. Construct added HOV lane and shoulder with HMA and overlay all lanes and shoulders with a 1-in. RAC(O) overlay. To ensure noise performance, the RAC(O) overlay is milled and replaced every 9 years.
5. Construct added HOV lane and shoulder with HMA and overlay existing lanes and shoulders with a 5-in. HMA overlay. Future rehabilitation includes a 2-in. mill and HMA overlay applied on a 12-year cycle.

REALCOST ANALYSIS

The *RealCost* analysis includes the use of deterministic inputs for all pavement treatment costs and performance lives. In addition, the *RealCost* software requires a number of inputs related to analysis options, traffic, and treatment strategies. Additional discussion on each of these inputs is further described in the following sections.

Analysis Options

Analysis options are typically selected in accordance with agency policy and include project level data that will be applied to all alternatives in the LCCA. Table G1 summarizes the analysis options used in this evaluation.

Table G1. Summary of Analysis Options.

Input	Value
Analysis period	50 years
Discount rate	4 percent
Beginning of analysis period	2011
Include agency cost remaining service life	No
Include user costs in analysis	Yes
User cost computation method	*RealCost*
Traffic direction	Both
Include user cost remaining service life	Yes
Number of Alternatives	5

Traffic Inputs

Traffic inputs are used exclusively in *RealCost* to calculate costs associated with user delay due to construction activities. Traffic data inputs used in this analysis include:

- Average annual daily traffic (AADT) – 167,000 vehicles per day (both directions).

- Single unit trucks – 5 percent of AADT.
- Combination trucks – 3.375 percent of AADT.
- Annual growth rate of traffic – 1.5 percent.
- Speed limit under normal operating conditions – 65 mph.
- Lanes open in each direction under normal conditions – 4 (initial construction of added lane) and 5 (during rehabilitation treatments).
- Free flow capacity – 2,136 vehicles per hour per lane (vphpl). Free flow capacity was calculated within *RealCost*. The free flow capacity calculation was based on a lane width of 12 ft, zero percent grade, and 8 ft to the nearest obstruction (inside shoulder).
- Queue dissipation capacity – 1,800 vphpl.
- Maximum AADT – 280,000 vehicles per day, both directions.
- Maximum queue length (which models the effects of self-imposed detours) – 10 miles.
- Rural or urban hourly traffic distribution – urban.
- Value of user time (in 2011 dollars) due to construction delay includes:
  - Passenger cars: $15.50 per hour.
  - Single unit trucks: $24.80 per hour.
  - Combination trucks: $29.85 per hour.
- Traffic hourly distributions were based on *RealCost* default values.
- Added time and vehicle stopping costs were based on *RealCost* default values.

Pavement Strategies

Figures G2 through G6 illustrate the pavement alternatives and thickness evaluated as part of this LCCA.

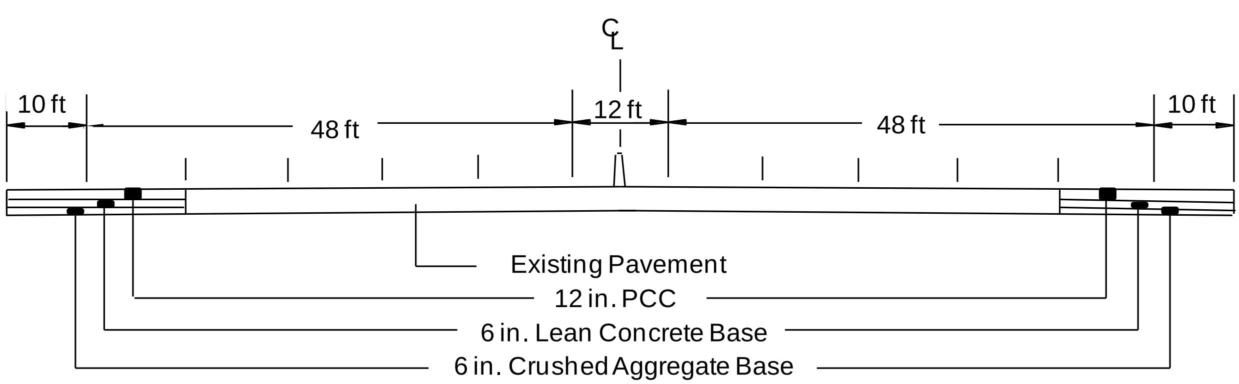


Figure G2. PCC added lane—Alternative 1.

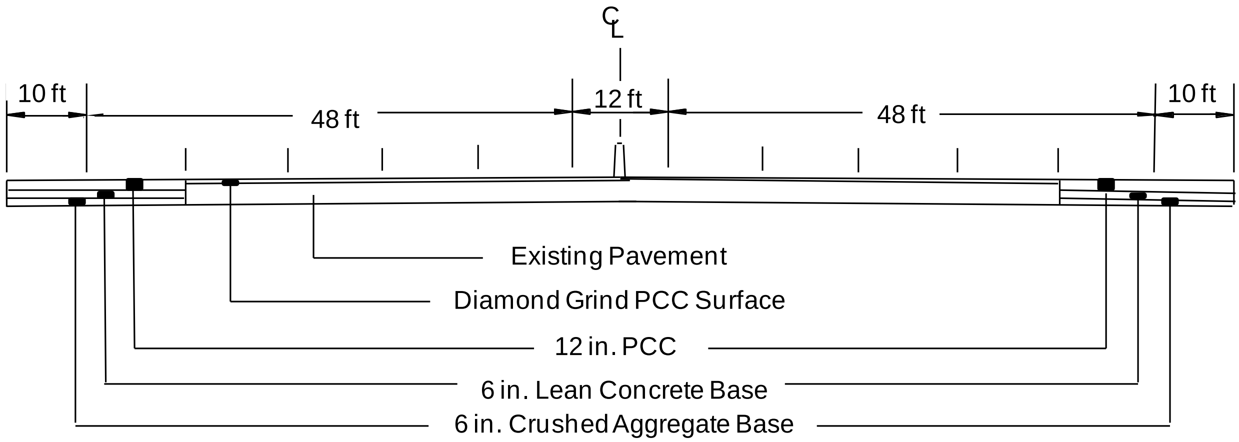


Figure G3. PCC added lane and diamond grind existing—Alternative 2.

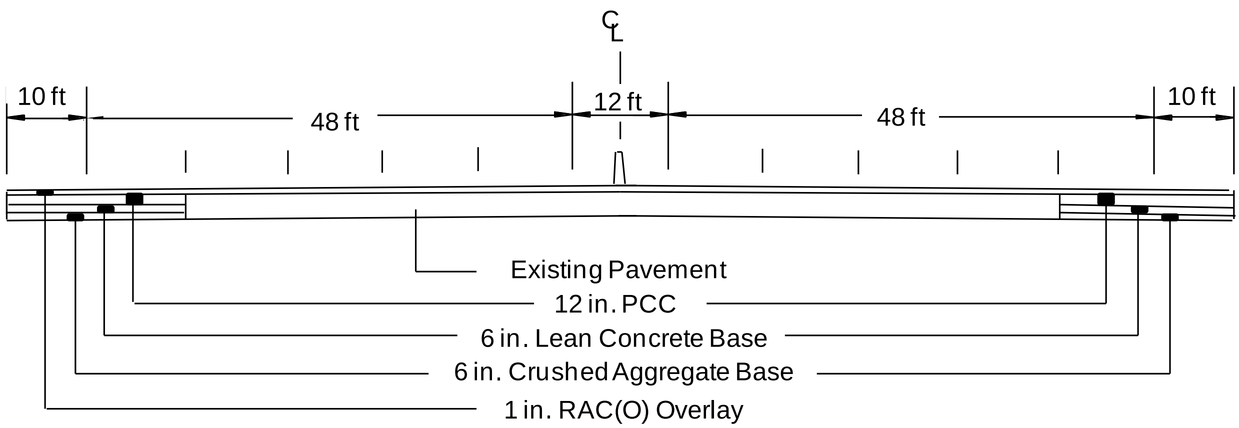


Figure G4. PCC added lane and 1-in. RAC(O) overlay of all lanes—Alternative 3.

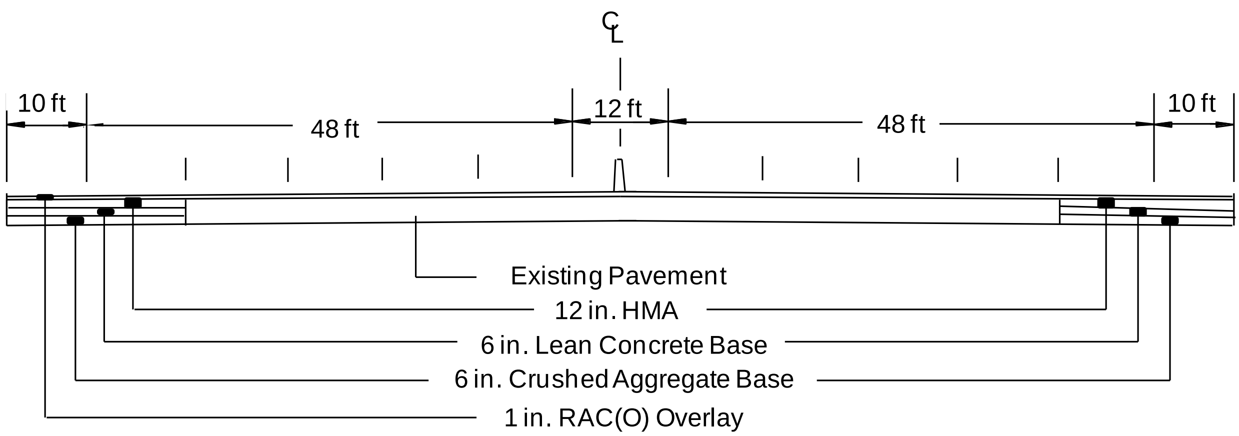


Figure G5. HMA added lane and 1-in. RAC(O) overlay of all lanes—Alternative 4.

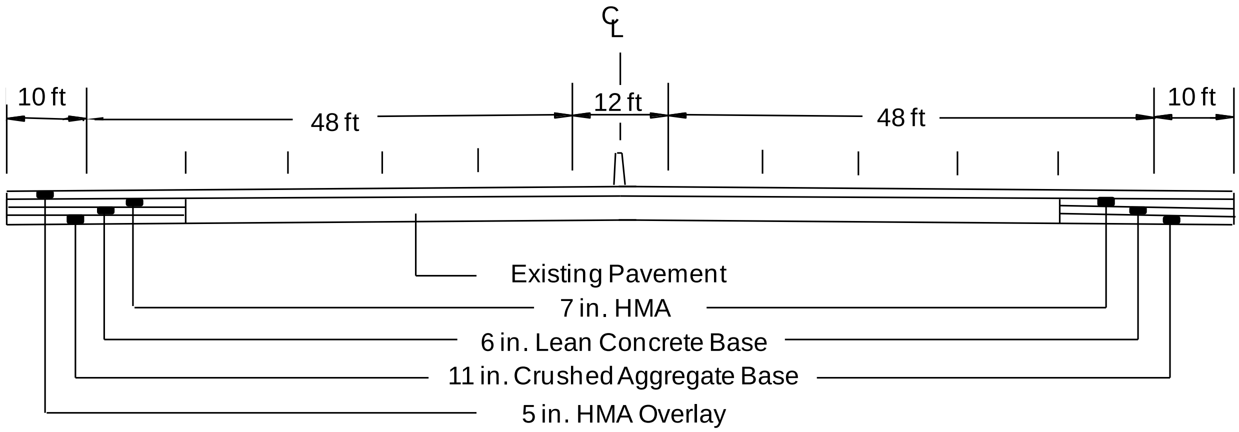


Figure G6. HMA added lane and 5-in. HMA overlay of all lanes—Alternative 5.

Construction costs associated with the five alternatives are summarized in Table G2. Construction costs are based on the bid tabulations of similar projects constructed by the California Department of Transportation (Caltrans). However, for uniformity, similar bid items and costs are used for each alternative (where applicable). Details of the cost calculations are included in Attachment 1.

Table G2. Summary of pavement costs, work zone duration, and performance life.

Treatment	**Total Project Cost**	**Construction Duration (days)**	**Life (years)**
Construct HOV lane with PCC	$1,484,000	59	see diamond grinding
Construct HOV lane with PCC and diamond grind existing lanes	$3,727,000	71	see diamond grinding
Construct HOV lane with PCC and overlay all lanes with 1-in. RAC(O)	$2,202,000	87	see RAC(O) overlay
Construct HOV lane with HMA and overlay all lanes with 1-in. RAC(O)	$2,887,000	82	see RAC(O) overlay
Construct HOV lane with HMA and overlay all lanes with 5-in. HMA	$3,680,000	172	12
Diamond grinding all lanes	$2,243,000	12	20
1-in. mill and RAC(O) overlay all lanes	$1,301,000	28	9
2-in. mill and HMA overlay all lanes	$1,381,000	46	12

Construction duration was based on the estimated total volume of PCC or HMA tonnage for each alternative in relation to the actual project duration and PCC volume or HMA tonnage placed. For example, an actual Caltrans project constructed an HMA overlay, placing 5230 tons in 30 working days. Therefore, for the 5-in. HMA overlay, approximately 22,500 tons are estimated for Alternative 5 resulting in a construction duration of 172 working days (30 days/5230 tons x 22,500 tons).

To further illustrate both the initial and future rehabilitation costs and associated timing of each application, Figures G7 through G11 illustrates the cash flow diagrams for each of the five alternatives.

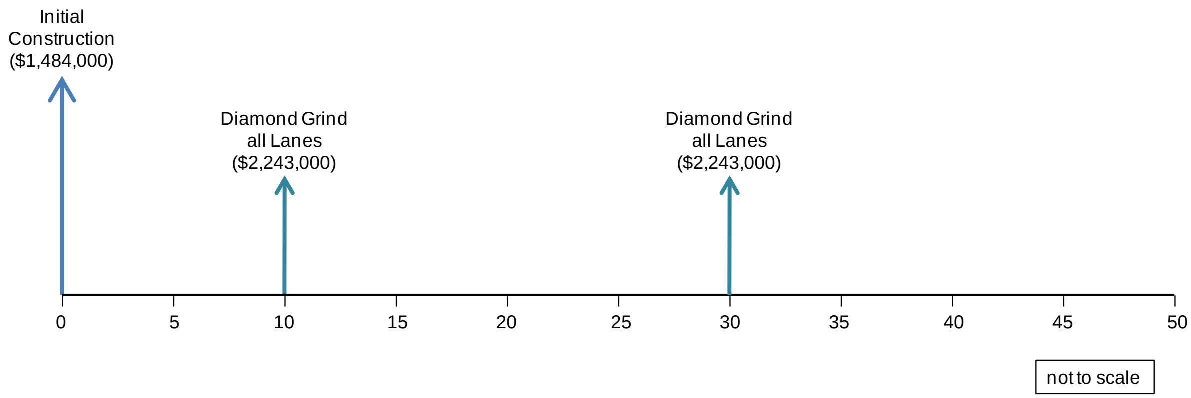


Figure G7. Cash flow diagram—Alternative 1.

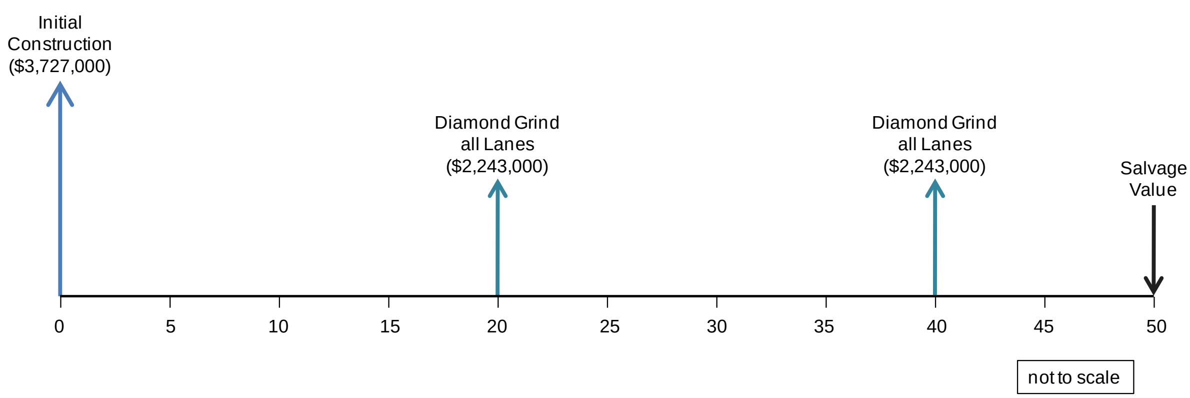


Figure G8. Cash flow diagram—Alternative 2.

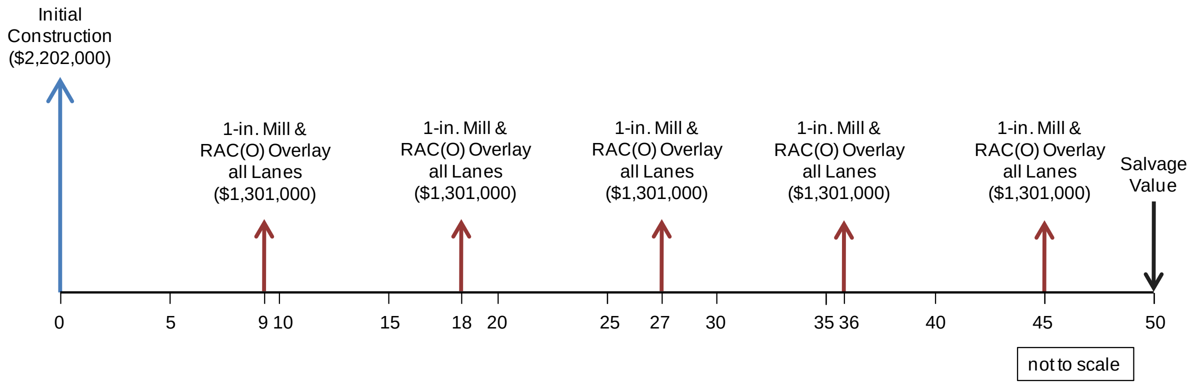


Figure G9. Cash flow diagram—Alternative 3.

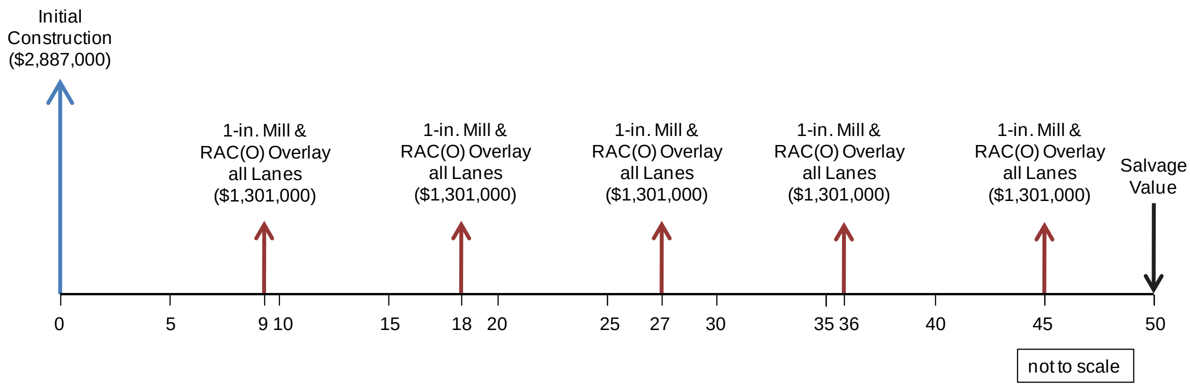


Figure G10. Cash flow diagram—Alternative 4.

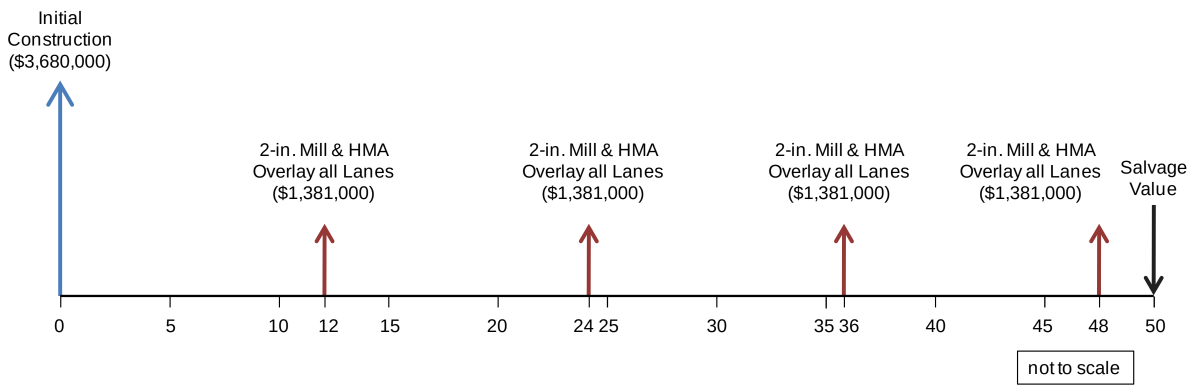


Figure G11. Cash flow diagram—Alternative 5.

LCCA RESULTS

Table G3 (and illustrated in Figure G11) provides the results of the LCCA in relation to total cost, present value, and equivalent uniform annual cost (EUAC). In addition, alternative costs are shown in relation to both agency and user costs. The salvage value included at the end of the analysis period is based on the internal *RealCost* calculation (see Table G3). *RealCost* results are included in Attachment 2.

Table G3. Summary of results for deterministic LCCA.

	Alternative 1		Alternative 2		Alternative 3	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$5,970	$15,673	$7,092	$17,821	$8,129	$95,656
Present Value	$3,691	$8,405	$5,060	$9,420	$4,668	$33,401
Salvage Value	$0	N/A	$1,122	$7,735	$578	$16,043
EUAC	$172	$391	$236	$439	$217	$1,555

	Alternative 4		Alternative 5	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$8,814	$95,308	$8,053	$131,637
Present Value	$5,353	$33,053	$5,466	$50,510
Salvage Value	$578	$16,043	$1,151	$49,419
EUAC	$249	$1,539	$254	$2,351

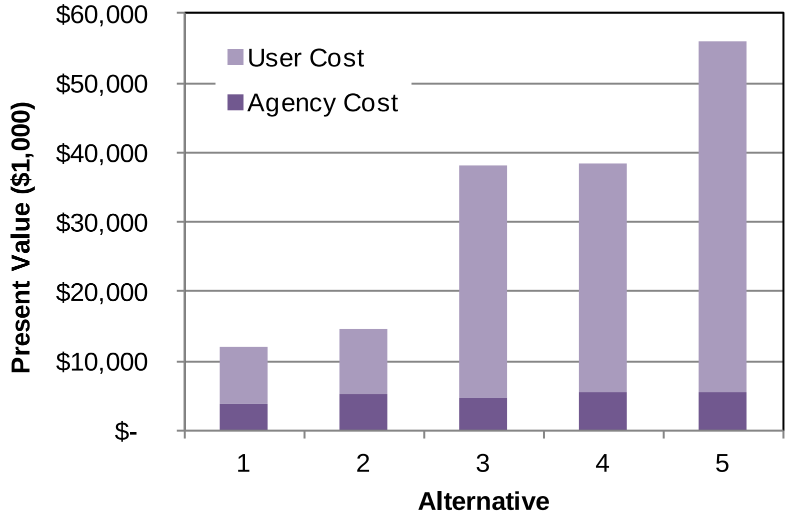


Figure G12. Summary of present value.

Based on the assumptions used in this example, the alternative with the lowest present value of agency costs and the lowest present value of user costs is Alternative 1.

ATTACHMENT 1

PAVEMENT COST ESTIMATES

HOV Lane with PCC – New Construction

12-in. PCC + 6-in. LCB + 6-in. Aggregate Base

Description	Unit	Quantity	Bid	Amount
Roadway Excavation	CY	17,209	$14.00	$240,924.44
Class 2 Aggregate Base	CY	4,302	$11.00	$47,324.44
Lean Concrete Base	CY	4,302	$85.00	$365,688.89
Jointed plain concrete pavement	CY	8,604	$92.00	$791,608.89
Seal Pavement Joint	LF	21,120	$1.80	$38,016.00
				$1,483,562.67

HOV Lane with HMA – New Construction (with 1-in. RAC(O) overlay)

12-in. HMA + 6-in. LCB + 6-in. Aggregate Subbase

Description	Unit	Quantity	Bid	Amount
Roadway Excavation	CY	17,209	$14.00	$240,924.44
Class 2 Aggregate Base	CY	4,302	$11.00	$47,324.44
Lean Concrete Base	CY	4,302	$85.00	$365,688.89
Hot Mix Asphalt	TON	17,680	$77.00	$1,361,360.00
Tack Coat	TON	177	$760.00	$134,368.00
Seal Pavement Joint	LF	10,560	$1.80	$19,008.00
				$2,168,673.78

HOV Lane with HMA – New Construction (with 5-in. HMA overlay)

7-in. HMA + 6-in. LCB + 11-in. Aggregate Subbase

Description	Unit	Quantity	Bid	Amount
Roadway Excavation	CY	17,209	$14.00	$240,924.44
Class 2 Aggregate Base	CY	7,916	$11.00	$87,076.98
Lean Concrete Base	CY	4,302	$85.00	$365,688.89
Hot Mix Asphalt	TON	10,610	$77.00	$816,970.00
Tack Coat	TON	106	$760.00	$80,636.00
Seal Pavement Joint	LF	10,560	$1.80	$19,008.00
				$1,610,304.31

1-in. RAC(O) Overlay – New Construction

Description	Unit	Quantity	Bid	Amount
Construction Site Management	LS	1	$1,500.00	$800.00
Water Pollution Control Program	LS	1	$500.00	$300.00
Construction Area Signs	LS	1	$3,900.00	$2,000.00
Traffic Control System	LS	1	$20,000.00	$10,000.00
Portable Changeable Message Sign	LS	2	$1,000.00	$2,000.00
Remove Yellow Thermoplastic	LF	10560	$0.50	$5,280.00
Remove Thermoplastic Traffic Stripe	LF	10560	$0.35	$3,696.00
Lead Compliance Plan	LS	1	$2,500.00	$1,500.00
Imported Material (Shoulder Backing)	Ton	456	$32.00	$14,598.25
Crack Treatment	LNMI	4	$4,900.00	$19,600.00
Tack Coat	Ton	6	$760.00	$4,640.56
RAC(0)	Ton	6106	$98.00	$598,388.00
Shoulder Rumble Strip	LF	10560	$0.47	$4,963.20
Median Rumble Strip	LF	10560	$0.50	$5,280.00
Thermoplastic Traffic Stripe	LF	1763	$0.24	$423.21
Thermoplastic Pavement Marking	SQFT	1132	$0.80	$905.37
Maintaining Existing Traffic Management	LS	1	$7,422.00	$4,000.00
Mobilization	LS	1	$81,266.00	$40,000.00
				$718,374.59

Mill and 1-in. RAC(O) Overlay – Future Rehabilitation

Description	Unit	Quantity	Bid	Amount
Construction Site Management	LS	1	$1,500.00	$969.48
Water Pollution Control Program	LS	1	$500.00	$323.16
Construction Area Signs	LS	1	$3,900.00	$2,520.64
Traffic Control System	LS	1	$20,000.00	$12,926.34
Portable Changeable Message Sign	EA	2	$2,000.00	$4,000.00
Remove Yellow Thermoplastic	LF	10560	$0.50	$5,280.00
Remove Thermoplastic Traffic Stripe	LF	10560	$0.35	$3,696.00
Cold Plane Asphalt Concrete Pavement	SQYD	89173	$6.00	$535,040.00
Lead Compliance Plan	LS	1	$2,500.00	$1,615.79
Imported Material (Shoulder Backing)	Ton	456	$32.00	$14,598.25
Crack Treatment	LNMI	8	$4,900.00	$39,200.00
Tack Coat	Ton	6	$760.00	$4,640.56
RAC(0)	Ton	6106	$98.00	$598,388.00
Shoulder Rumble Strip	LF	10560	$0.47	$4,963.20
Median Rumble Strip	LF	10560	$0.50	$5,280.00
Thermoplastic Traffic Stripe	LF	10560	$0.24	$2,534.40
Thermoplastic Pavement Marking	SQFT	9968	$0.80	$7,974.40

Description	Unit	Quantity	Bid	Amount
Maintaining Existing Traffic Management	LS	1	$7,422.00	$4,796.96
Mobilization	LS	1	$81,266.00	$52,523.60
				$1,301,270.78

5-in. HMA Overlay – New Construction

Description	Unit	Quantity	Bid	Amount
Construction Site Management	LS	1	$1,500.00	$800.00
Water Pollution Control Program	LS	1	$500.00	$300.00
Construction Area Signs	LS	1	$3,900.00	$2,000.00
Traffic Control System	LS	1	$20,000.00	$10,000.00
Portable Changeable Message Sign	EA	2	$2,000.00	$4,000.00
Remove Yellow Thermoplastic	LF	10560	$0.50	$5,280.00
Remove Thermoplastic Traffic Stripe	LF	10560	$0.35	$3,696.00
Lead Compliance Plan	LS	1	$2,500.00	$1,500.00
Imported Material (Shoulder Backing)	Ton	1825	$32.00	$58,412.14
Crack Treatment	LNMI	4	$4,900.00	$19,600.00
Tack Coat	Ton	24	$760.00	$18,568.32
HMA (Type A)	Ton	24432	$77.00	$1,881,264.00
Shoulder Rumble Strip	LF	10560	$0.47	$4,963.20
Median Rumble Strip	LF	10560	$0.50	$5,280.00
Thermoplastic Traffic Stripe	LF	10560	$0.24	$2,534.40
Thermoplastic Pavement Marking	SQFT	9968	$0.80	$7,974.40
Maintaining Existing Traffic Management	LS	1	$7,422.00	$4,000.00
Mobilization	LS	1	$81,266.00	$40,000.00
				$2,070,172.46

2-in. Mill and HMA Overlay – Rehabilitation

Description	Unit	Quantity	Bid	Amount
Construction Site Management	LS	1	$1,500.00	$800.00
Water Pollution Control Program	LS	1	$500.00	$300.00
Construction Area Signs	LS	1	$3,900.00	$2,000.00
Traffic Control System	LS	1	$20,000.00	$10,000.00
Portable Changeable Message Sign	EA	2	$2,000.00	$4,000.00
Remove Yellow Thermoplastic	LF	10560	$0.50	$5,280.00
Remove Thermoplastic Traffic Stripe	LF	10560	$0.35	$3,696.00
Cold Plane Asphalt Concrete Pavement	SQYD	89173	$6.00	$535,040.00
Lead Compliance Plan	LS	1	$2,500.00	$1,500.00
Imported Material (Shoulder Backing)	Ton	684	$32.00	$21,899.77
Crack Treatment	LNMI	4	$4,900.00	$19,600.00

Description	Unit	Quantity	Bid	Amount
Tack Coat	Ton	9	$760.00	$6,961.60
HMA (Type A)	Ton	9160	$77.00	$705,320.00
Shoulder Rumble Strip	LF	10560	$0.47	$4,963.20
Median Rumble Strip	LF	10560	$0.50	$5,280.00
Thermoplastic Traffic Stripe	LF	10560	$0.24	$2,534.40
Thermoplastic Pavement Marking	SQFT	9968	$0.80	$7,974.40
Maintaining Existing Traffic Management	LS	1	$7,422.00	$4,000.00
Mobilization	LS	1	$81,266.00	$40,000.00
				$1,381,149.37

Diamond Grinding –New Construction and Rehabilitation

Description	Unit	Quantity	Bid	Amount
Construction Site Management	LS	1	$200.00	$800.00
Water Pollution Control Program	LS	1	$500.00	$300.00
Construction Area Signs	LS	1	$4,000.00	$2,000.00
Traffic Control System	LS	1	$41,000.00	$10,000.00
Portable Changeable Message Sign	EA	2	$2,000.00	$4,000.00
Lead Compliance Plan	LS	1	$1,500.00	$1,500.00
Street Sweeping	LS	1	$20,000.00	$7,000.00
Grind Existing Concrete Pavement	SQYD	82133	$25.00	$2,053,333.33
Cold Plane Asphalt (6' shoulders)	SQYD	3520	$15.25	$53,680.00
Tack Coat (6' shoulders)	Ton	1	$760.00	$550.24
Hot Mix Asphalt (Type A) (6' shoulders)	Ton	724	$77.00	$55,748.00
Thermoplastic Traffic Stripe	LF	10560	$0.24	$2,534.40
Thermoplastic Pavement Marking	SQFT	9968	$0.80	$7,974.40
Maintaining Existing Traffic Management	LS	1	$7,500.00	$4,000.00
Mobilization	LS	1	$69,900.00	$40,000.00
				$2,243,420.37

ATTACHEMNT 2
RealCost REPORT

RealCost Input Data

1. Economic Variables	
Value of Time for Passenger Cars ($/hour)	$15.50
Value of Time for Single Unit Trucks ($/hour)	$24.80
Value of Time for Combination Trucks ($/hour)	$29.85

2. Analysis Options	
Include User Costs in Analysis	Yes
Include User Cost Remaining Life Value	Yes
Use Differential User Costs	Yes
User Cost Computation Method	Calculated
Include Agency Cost Remaining Life Value	Yes
Traffic Direction	Both
Analysis Period (Years)	50
Beginning of Analysis Period	2011
Discount Rate (%)	4.0
Number of Alternatives	5

3. Project Details	
State Route	I-580
Project Name	Noise Mitigation Analysis
Region	
County	
Analyzed By	
Mileposts	
Begin	1.00
End	2.00
Length of Project (miles)	1.00
Comments	

4. Traffic Data	
AADT Construction Year (total for both directions)	167,000
Cars as Percentage of AADT (%)	91.6
Single Unit Trucks as Percentage of AADT (%)	5.0
Combination Trucks as Percentage of AADT (%)	3.4
Annual Growth Rate of Traffic (%)	1.5
Speed Limit Under Normal Operating Conditions (mph)	65
No of Lanes in Each Direction During Normal Conditions	4
Free Flow Capacity (vphpl)	2136
Rural or Urban Hourly Traffic Distribution	Urban
Queue Dissipation Capacity (vphpl)	1800
Maximum AADT (total for both directions)	280,000
Maximum Queue Length (miles)	10.0

Alternative 1	Added Lane - PCC	
Number of Activities		4

Activity 1	Initial Construction	
Agency Construction Cost ($1000)	$1,484.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	59	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	10.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 2	Diamond Grinding	
Agency Construction Cost ($1000)	$2,243.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	12	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	20.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 3	Diamond Grinding	
Agency Construction Cost ($1000)	$2,243.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	12	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	20.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 4	Diamond Grinding	
Agency Construction Cost ($1000)	$2,243.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	12	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	20.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Alternative 2	Added Lane - PCC/diamond grind existing	
Number of Activities		3

Activity 1	Initial Construction	
Agency Construction Cost ($1000)	$3,727.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	71	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	20.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 2	Diamond Grinding	
Agency Construction Cost ($1000)	$2,243.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	12	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	20.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 3	Diamond Grinding	
Agency Construction Cost ($1000)	$2,243.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	12	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	20.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Alternative 3	Added Lane - PCC/RAC(O) overlay	
Number of Activities		6

Activity 1	Initial Construction	
Agency Construction Cost ($1000)	$2,202.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	87	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 2	RAC(O) overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 3	RAC(O) overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 4	RAC(O) overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 5	RAC(O) overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 6	RAC(O) overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Alternative 4	Added Lane - HMA/RAC(O) overlay	
Number of Activities		6

Activity 1	Initial Construction	
Agency Construction Cost ($1000)	$2,887.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	82	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 2	RAC(O) Overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 3	RAC(O) Overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 4	RAC(O) Overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 5	RAC(O) Overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 6	RAC(O) Overlay	
Agency Construction Cost ($1000)	$1,301.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	28	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	9.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Alternative 5	Added Lane - HMA/HMA overlay	
Number of Activities		5

Activity 1	Inital Construction	
Agency Construction Cost ($1000)	$3,680.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	172	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	12.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 2	Mill and overlay	
Agency Construction Cost ($1000)	$1,381.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	46	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	12.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

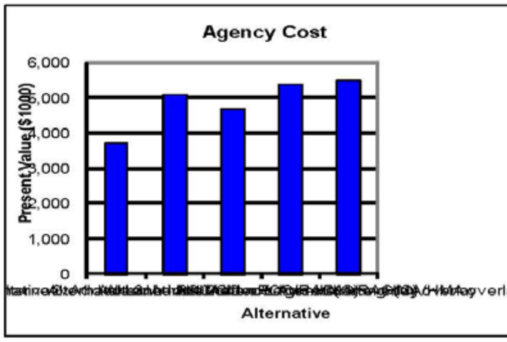
Activity 3	Mill and overlay	
Agency Construction Cost ($1000)	$1,381.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	46	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	12.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

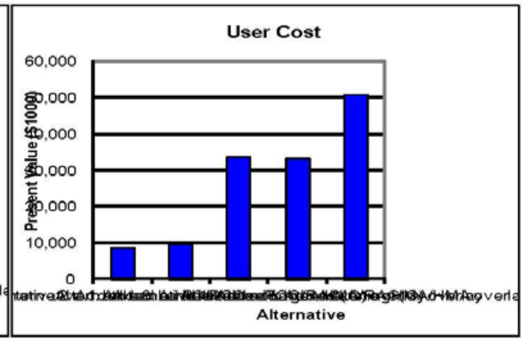
Activity 4	Mill and overlay	
Agency Construction Cost ($1000)	$1,381.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	46	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	12.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Activity 5	Mill and overlay	
Agency Construction Cost ($1000)	$1,381.00	
User Work Zone Costs ($1000)		
Work Zone Duration (days)	46	
No of Lanes Open in Each Direction During Work Zone	3	
Activity Service Life (years)	12.0	
Activity Structural Life (years)		
Maintenance Frequency (years)		
Agency Maintenance Cost ($1000)		
Work Zone Length (miles)	1.00	
Work Zone Speed Limit (mph)	35	
Work Zone Capacity (vphpl)	1490	
Traffic Hourly Distribution	Week Day 1	
Time of Day of Lane Closures (use whole numbers based on a 24-hour clock)		
Inbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		
Outbound	Start	End
First period of lane closure	19	24
Second period of lane closure	0	7
Third period of lane closure		

Deterministic Results

Total Cost	Alternative 1: Added Lane - PCC		Alternative 2: Added Lane - PCC/diamond grind existing		Alternative 3: Added Lane - PCC/RAC(O) overlay		Alternative 4: Added Lane - HMA/RAC(O) overlay		Alternative 5: Added Lane - HMA/HMA overlay	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$5,970.00	$15,673.38	$7,091.50	$17,821.38	$8,128.78	$95,655.52	$8,813.78	$95,307.94	$8,053.17	$131,636.72
Present Value	$3,690.85	$8,405.31	$5,060.06	$9,420.19	$4,667.86	$33,400.54	$5,352.86	$33,052.96	$5,466.08	$50,509.57
EUAC	$171.81	$391.27	$235.55	$438.51	$217.29	$1,554.80	$249.18	$1,538.62	$254.45	$2,351.23





APPENDIX H

LIFE CYCLE COST ANALYSIS FOR NORTH CAROLINA HIGHWAY WIDENING PROJECT EXAMPLES

TABLE OF CONTENTS

I-40 WIDENING LIFE CYCLE COST ANALYSIS

Project Description

The project consists of adding a through lane in both directions to an existing six-lane interstate highway (I-40) in North Carolina. The new through lane will be constructed at the inside edge of the existing roadway, replacing the existing shoulder with the new 12 ft wide through lane and 10 ft wide shoulder.

The current two-way traffic volume on this roadway is 101,000 vpd with 9 percent trucks (4 percent single unit trucks and 5 percent combination trucks).

Life Cycle Cost Analysis Alternatives

For this section of I-40 a total of three alternatives have been evaluated. The LCCA alternatives include:

1. Construct new lane and shoulder with PCC (transverse tined). Future rehabilitation includes diamond grinding all lanes on a 20 year cycle.
2. Construct new lane and shoulder with PCC (transverse tined) and diamond grind existing lanes. Future rehabilitation includes diamond grinding all lanes on a 20 year cycle.
3. Construct new lane and shoulder with PCC and overlay all lanes with 1 inch S9.5 mm HMA. Future rehabilitation includes mill and overlay all lanes with 1 inch S9.5 mm HMA every 9 years.

RealCost Analysis

The *RealCost* analysis includes the use of deterministic inputs for all pavement treatment costs and performance lives. In addition, the *RealCost* software requires a number of inputs related to analysis options, traffic, and treatment strategies. Additional discussion on each of these inputs is further described in the following sections.

Analysis Options

Analysis options are typically selected in accordance with agency policy and include project level data that will be applied to all alternatives in the LCCA. Table H1 summarizes the analysis options used in this evaluation.

Table H1. Summary of Analysis Options

Input	Value
Analysis period	50 years
Discount rate	4 percent
Beginning of analysis period	2011
Include agency cost remaining service life	No
Include user costs in analysis	Yes
User cost computation method	*RealCost*
Traffic direction	Both
Include user cost remaining service life	Yes
Number of Alternatives	5

Traffic Inputs

Traffic inputs are used exclusively in *RealCost* to calculate costs associated with user delay due to construction activities. Traffic data inputs used in this analysis include:

- Average annual daily traffic (AADT) – 101,000 vehicles per day (both directions).
- Single unit trucks – 4 percent of AADT.
- Combination trucks – 5 percent of AADT.
- Annual growth rate of traffic – 1.5 percent.
- Speed limit under normal operating conditions – 65 mph.
- Lanes open in each direction under normal conditions – 4 (initial construction of added lane) and 4 (during rehabilitation treatments).
- Free flow capacity – 2,136 vehicles per hour per lane (vphpl). Free flow capacity was calculated within *RealCost*. The free flow capacity calculation was based on a lane width of 12 ft, zero percent grade, and 10 ft to the nearest obstruction (inside shoulder).
- Queue dissipation capacity – 1,800 vphpl.
- Maximum AADT – 280,000 vehicles per day, both directions.
- Maximum queue length (which models the effects of self-imposed detours) – 10 miles.
- Rural or urban hourly traffic distribution – urban.
- Value of user time (in 2011 dollars) due to construction delay includes:
  - Passenger cars: $15.50 per hour.
  - Single unit trucks: $24.80 per hour.
  - Combination trucks: $29.85 per hour.
- Traffic hourly distributions were based on *RealCost* default values.
- Added time and vehicle stopping costs were based on *RealCost* default values.

Pavement Strategies

Figures H1 through H3 illustrate the pavement alternatives and thickness evaluated as part of this LCCA.

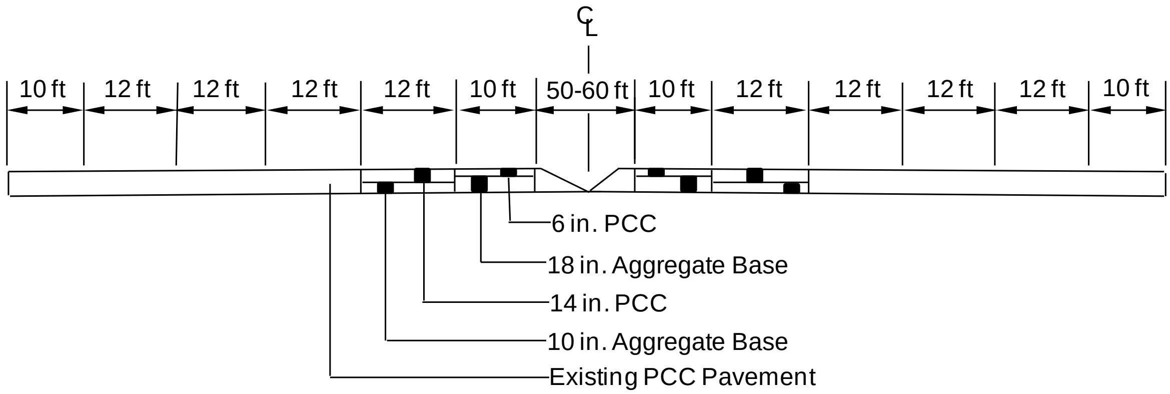


Figure H1. PCC added lane and shoulder—Alternative 1.

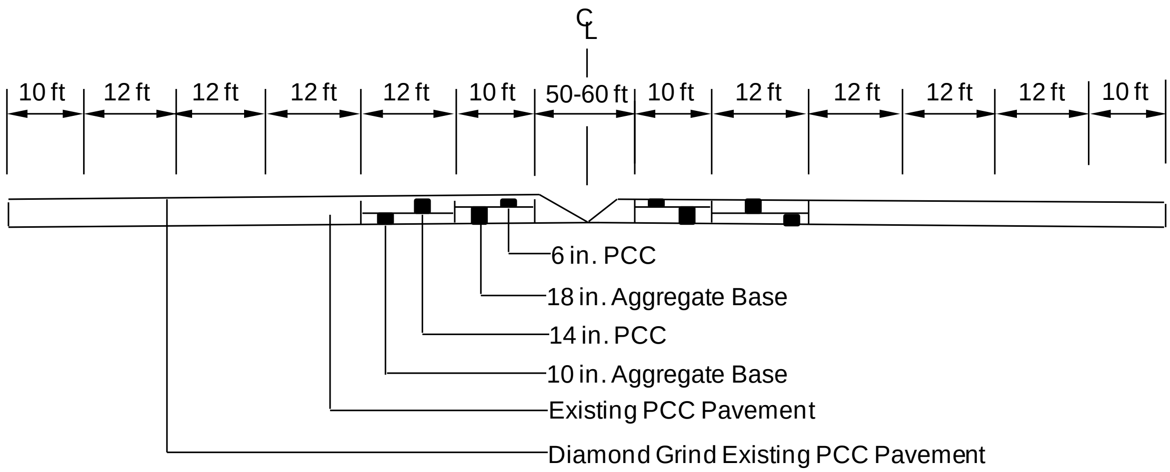


Figure H2. PCC added lane and shoulder and diamond grind existing lanes—Alternative 2.

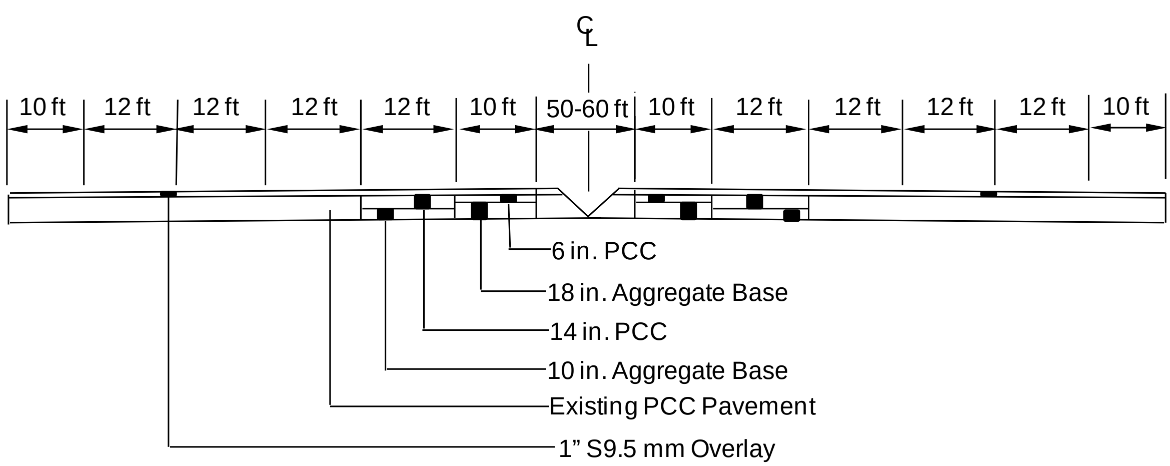


Figure H3. PCC added lane and shoulder and 1-inch S9.5 mm overlay—Alternative 3.

Construction costs associated with the five alternatives are summarized in Table H2. Construction costs were obtained from the North Carolina Department of Transportation.

Table H2. Summary of pavement costs, work zone duration, and performance life.

Treatment	**Total Project Cost**	**Construction Duration (days)[1]**	**Life Until Treatment (years)**
Alternative 1—Construct lane with PCC	$3,202,000	59	20
Alternative 2—Construct lane with PCC and diamond grind existing lanes	$4,443,000	71	20
Alternative 3—Construct lane with PCC and overlay all lanes with 1-in. S9.5mm	$3,584,000	84	9
Diamond grinding left lanes	$1,656,000	16	20
1-in. mill and overlay all lanes and shoulders	$1,244,000	31	9

[1] Based on Caltrans construction duration.

LCCA Results

Table H3 (and illustrated in Figure H4) provides the results of the LCCA in relation to total cost, present value, and equivalent uniform annual cost (EUAC). In addition, alternative costs are shown in relation to both agency and user costs. The salvage value included at the end of the analysis period is based on the internal *RealCost* calculation. *RealCost* results are included in Appendix B.

Table H3. Summary of results for deterministic LCCA

	Alternative 1		**Alternative 2**		**Alternative 3**	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$5,686	$1,994	$6,927	$2,119	$9,251	$9,022
Present Value	$4,186	$1,035	$5,427	$1,160	$5,942	$3,053
Salvage Value	$828	$1,157	$828	$1,157	$553	$2,862
EUAC	$195	$48	$253	$54	$277	$142

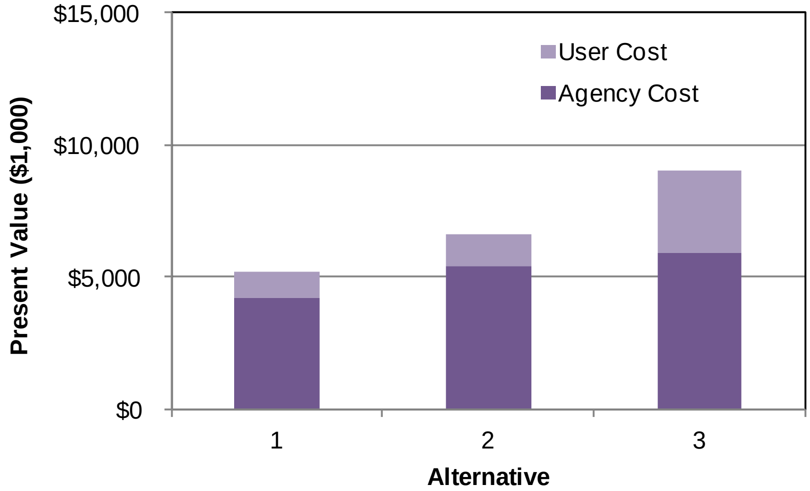


Figure H4. Summary of present value

Based on the assumptions used in this example, the alternative with the lowest present value of agency costs and the lowest present value of user costs is Alternative 1.

I-485 WIDENING LIFE CYCLE COST ANALYSIS

Project Description

The project consists of adding a through lane in both directions to an existing four-lane interstate highway (I-85) in North Carolina. The new through lane will be constructed at the inside edge of the existing roadway, replacing the existing shoulder with the new 12 ft wide through lane and 10 ft wide shoulder.

The current two-way traffic volume on this roadway is 93,000 vpd with 20 percent trucks (5 percent single unit trucks and 15 percent combination trucks).

Life Cycle Cost Analysis Alternatives

For this section of I-85 a total of five alternatives have been evaluated. The LCCA alternatives include:

4. Construct new lane and shoulder with HMA. Future rehabilitation includes mill and overlay all lanes with 1.5 inches of HMA every 12 years.
5. Construct new lane and shoulder with HMA and overlay all lanes with 1-inch S9.5 mm wearing surface. To ensure noise performance, the wearing surface is milled and replaced every 9 years.
6. Construct new lane with PCC (transverse tined) and construct shoulder with HMA. Future rehabilitation includes mill and overlay right two lanes with 1.5 inches of HMA every 12 years and diamond grinding left lane on a 20 year cycle.
7. Construct new lane with PCC, construct shoulder with HMA, and overlay all lanes with 1.5 inches of HMA. Future rehabilitation includes mill and overlay all lanes with 1.5 inches of HMA every 12 years.
8. Construct new lane with PCC, construct shoulder with HMA, and overlay all lanes with S9.5 mm wearing surface. To ensure noise performance, the wearing surface is milled and replaced every 9 years.

RealCost Analysis

The *RealCost* analysis includes the use of deterministic inputs for all pavement treatment costs and performance lives. In addition, the *RealCost* software requires a number of inputs related to analysis options, traffic, and treatment strategies. Additional discussion on each of these inputs is further described in the following sections.

Analysis Options

Analysis options are typically selected in accordance with agency policy and include project level data that will be applied to all alternatives in the LCCA. Table H4 summarizes the analysis options used in this evaluation.

Table H4. Summary of Analysis Options

Input	Value
Analysis period	50 years
Discount rate	4 percent
Beginning of analysis period	2011
Include agency cost remaining service life	No
Include user costs in analysis	Yes
User cost computation method	*RealCost*
Traffic direction	Both
Include user cost remaining service life	Yes
Number of Alternatives	5

Traffic Inputs

Traffic inputs are used exclusively in *RealCost* to calculate costs associated with user delay due to construction activities. Traffic data inputs used in this analysis include:

- Average annual daily traffic (AADT) – 93,000 vehicles per day (both directions).
- Single unit trucks – 5 percent of AADT.
- Combination trucks – 15 percent of AADT.
- Annual growth rate of traffic – 1.5 percent.
- Speed limit under normal operating conditions – 65 mph.
- Lanes open in each direction under normal conditions – 2 (initial construction of added lane) and 3 (during rehabilitation treatments).
- Free flow capacity – 2,136 vehicles per hour per lane (vphpl). Free flow capacity was calculated within *RealCost*. The free flow capacity calculation was based on a lane width of 12 ft, zero percent grade, and 10 ft to the nearest obstruction (inside shoulder).
- Queue dissipation capacity – 1,800 vphpl.
- Maximum AADT – 280,000 vehicles per day, both directions.
- Maximum queue length (which models the effects of self-imposed detours) – 10 miles.
- Rural or urban hourly traffic distribution – urban.
- Value of user time (in 2011 dollars) due to construction delay includes:
  - Passenger cars: $15.50 per hour.
  - Single unit trucks: $24.80 per hour.
  - Combination trucks: $29.85 per hour.
- Traffic hourly distributions were based on *RealCost* default values.
- Added time and vehicle stopping costs were based on *RealCost* default values.

Pavement Strategies

Figures H5 through H10 illustrate the pavement alternatives and thickness evaluated as part of this LCCA.

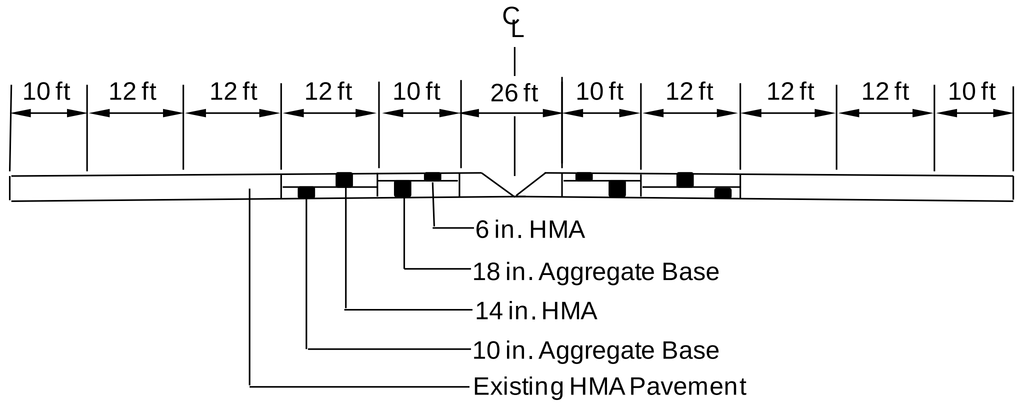


Figure H5. HMA added lane—Alternative 1

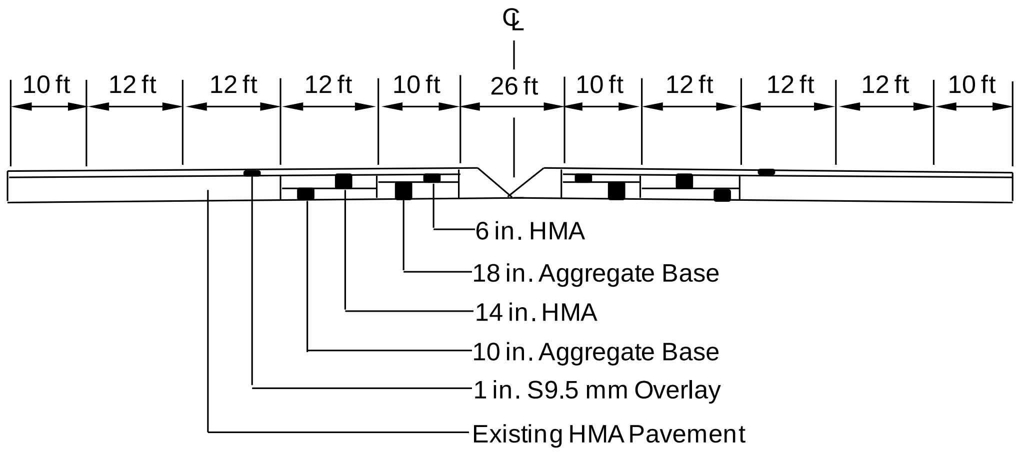


Figure H6. HMA added lane and 1 in. S9.5 mm overlay all lanes—Alternative .

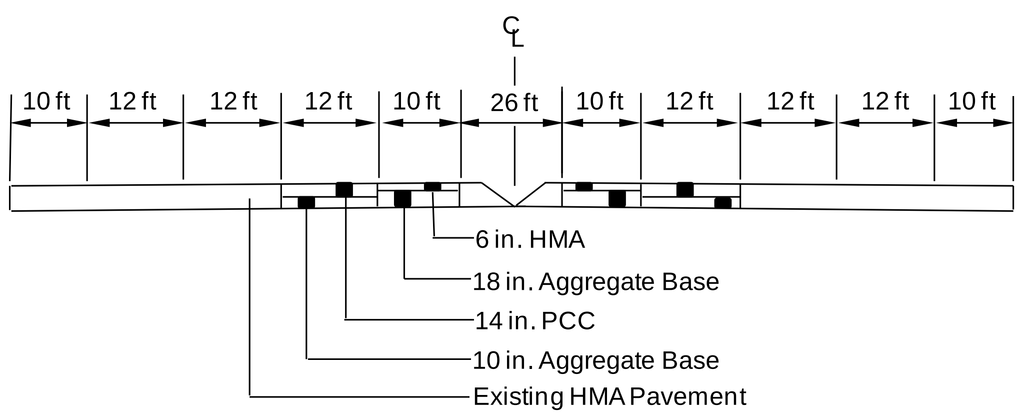


Figure H7. PCC added lane—Alternative 3

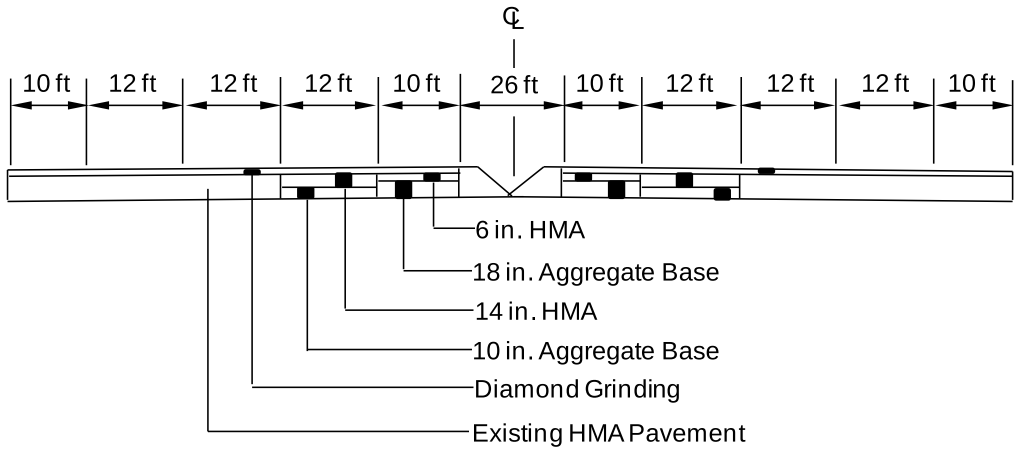


Figure H8. PCC added lane and diamond grind all lanes—Alternative 4

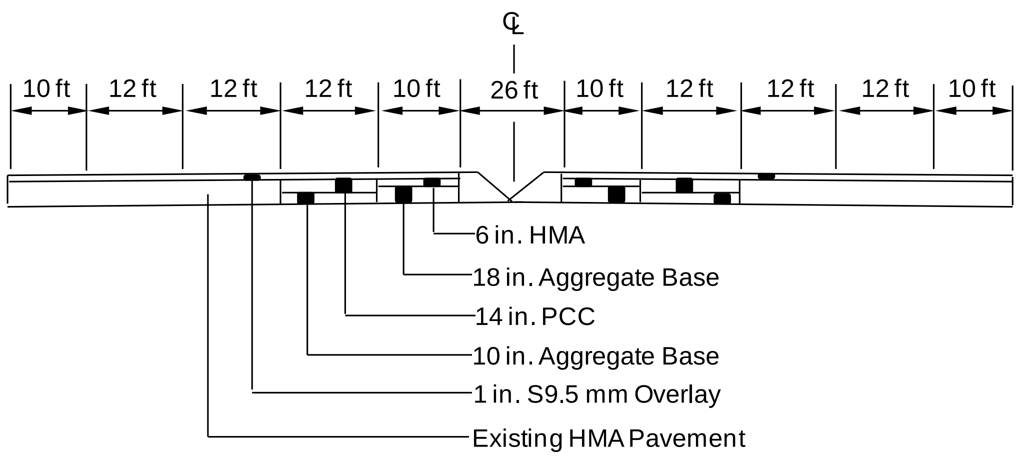


Figure H9. PCC added lane and 1 in. S9.5 mm overlay all lanes—Alternative 5

Construction costs associated with the five alternatives are summarized in Table H5. Construction costs were obtained from the North Carolina Department of Transportation.

Table H5. Summary of pavement costs, work zone duration, and performance life.

Treatment	Total Project Cost	Construction Duration (days)[1]	Life Until Treatment (years)
Alternative 1—Construct lane with HMA	$2,475,000	53	12
Alternative 2—Construct lane with HMA and overlay all lanes with 1 in. S9.5 mm	$3,107,000	69	9
Alternative 3—Construct lane with PCC	$3,592,000	59	20
Alternative 4—Construct lane with PCC and overlay all lanes with 1.5 in. HMA	$4,324,000	89	12
Alternative 5—Construct lane with PCC and overlay all lanes with 1 in. S9.5 mm	$4,224,000	85	9
Diamond grinding left lanes	$414,000	4	20
1-in. mill and overlay all lanes and shoulders	$1,041,000	26	9
1.5-in. mill and overlay right two lanes and shoulders	$948,000	30	12
1.5-in. mill and HMA overlay all lanes and shoulders	$1,206,000	39	12

[1] Based on Caltrans construction duration.

LCCA Results

Table H6 (and illustrated in Figure H10) provides the results of the LCCA in relation to total cost, present value, and equivalent uniform annual cost (EUAC). In addition, alternative costs are shown in relation to both agency and user costs. The salvage value included at the end of the analysis period is based on the internal *RealCost* calculation. *RealCost* results are included in Appendix B.

Table H6. Summary of results for deterministic LCCA.

Total Cost	Alternative 1		Alternative 2		Alternative 3	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$6,294	$11,136	$7,849	$11,669	$7,422	$9,758
Present Value	$4,035	$3,830	$5,080	$3,987	$5,093	$3,427
Salvage Value	$1,005	$10,628	$463	$3,279	$790	$8,175
EUAC	$188	$178	$236	$186	$237	$160

Total Cost	Alternative 4		Alternative 5	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	$8,143	$11,624	$8,966	$11,886
Present Value	$5,884	$4,317	$6,197	$4,203
Salvage Value	$1,005	$10,628	$463	$3,279
EUAC	$274	$201	$288	$196

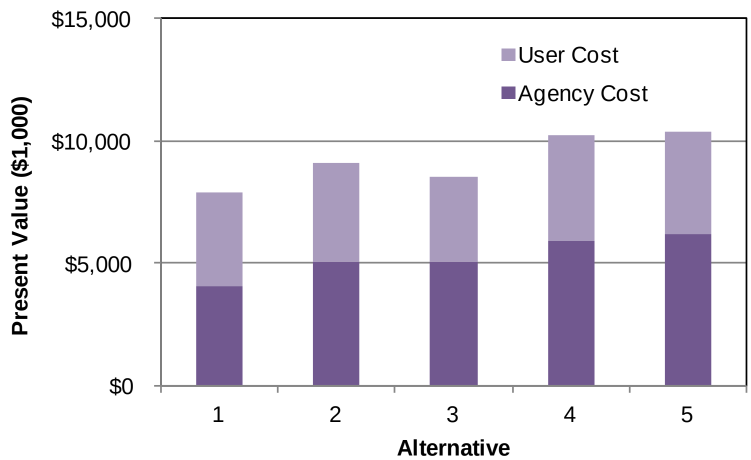


Figure H10. Summary of present value

Based on the assumptions used in this example, the alternative with the lowest present value of agency costs and the lowest present value of user costs is Alternative 1.