Designing Sustainable Concrete Pavements using the Pavement-ME Mechanistic Empirical Pavement Design and Life Cycle Analysis

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ABSTRACT:

Increasing the sustainability of our infrastructure is accomplished in ways other than just developing better materials and using recycled materials: it is also about employing the right designs. For concrete pavements, overdesign and use of poor features causes excess materials to be used during construction, leading to higher economic costs and environmental impacts. Optimizing pavement designs for prescribed service lives, climates, and traffic conditions allows pavement engineers to create structures that have low initial costs and CO_2 emissions as well as low life cycle costs and CO_2 emissions.

This paper shows how design optimization can lower costs and CO_2 emissions by balancing:

1. The initial costs and CO_2 emissions of a pavement, which are primarily a function of the thickness and specific design features used, and
2. The rehabilitation costs and CO_2 emissions, which are a function of the pavement's estimated service life and required rehabilitation activities

To do this, a case study for a California highway is analyzed where the conventional designs are compared against optimized designs from the AASHTOWare Pavement – ME Mechanistic Empirical Pavement Design *(Pavement-ME).* Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) are used to quantify the costs and environmental impacts of the different alternative pavement scenarios and to compare the trade-off between the initial costs and CO_2 emissions and successive rehabilitation activities in order to find the "optimized design."

INTRODUCTION:

Historically, pavement designs have been based on an engineering analysis where the pavement layer thickness and features are developed for the given traffic level, environmental conditions, and subgrade properties of the project. While it has been long recognized that different pavement designs will perform differently (longer or shorter initial performance periods), state Departments of Transportation (DOTs) and other transportation agencies have tended to rely on designs with assumed design lives and standard rehabilitation strategies.

When there are competing designs, Life Cycle Cost Analysis (LCCA) is often used to compare the competing pavement designs to determine which pavement provides the best value. LCCA is an economic procedure that compares the tradeoffs of cost and performance for the different designs and features, considering all significant costs expressed in equivalent net present value dollars (NPV), over the defined analysis period.

While in the past, only costs and performance have been assessed, the environmental impacts of pavement choice are also starting to be looked at in greater details. The reason for this is that road transportation accounts for 83% of greenhouse gases (GHGs) emissions from the transportation sector and 27% of all emissions in the U.S. in 2007 *(1)*. Life Cycle Assessment (LCA) for pavements is a procedure that calculates the environmental impacts, such as GHG emissions, energy consumption, water use, eutrophication potential, and others over the life of the pavement in much the same way that LCCA calculates costs. However, instead of minimizing the costs, the idea of LCA is to minimize the environmental impacts and make the pavement more sustainable.

While LCCA and LCA can be viewed as “accounting procedures” to determine which pavement has the lowest cost and environmental impact, the true benefit of both these processes is that they can guide design decisions by identifying the largest sources of cost or emissions of the different designs and thereby help prioritize ways to reduce the costs and environmental burden. However, the problem with LCCA – and presumably what will be a problem in LCA – is that there has not been a simple and reliable procedure to estimate performance of the different pavement alternatives. Instead, agencies have relied on historically based standard rehabilitation activities and schedules in their LCCA’s and LCA’s, which may or may not reflect the true performance of a particular pavement’s design.

With the development of the American Association of Highway and Transportation Officials (AASHTO) Pavement-ME Design Procedure and software (formerly known as DARWin-ME and MEPDG)*(2)*, it is now possible to predict performance for different pavement design alternatives. That is, whereas in the past, engineers could only use judgment to estimate the performance changes due to different design features, pavement engineers can now model several different pavement structures with Pavement-ME to estimate the performance over an extended analysis period (e.g. 50 years) and match the required rehabilitation activities for each design with the predicted distress development on that pavement. Then with this information, the designer can calculate the initial and rehabilitation costs and sustainability impacts (eg global warming potential, acidification potential, eutrophication potential, etc.) of the different pavement designs to determine which pavement design has the best combination of performance, low cost, and low environmental impacts.

PROCESS:

The process to optimize a concrete pavement design is essentially a 5 step iterative process:

1. Determine Basic Design Parameters (traffic, soil conditions, etc) and performance requirements / distress limits (cracking, faulting, roughness, etc.) that will be used to judge a pavement’s performance.
2. Develop a rigid pavement design for the roadway using the agency’s standard design procedure or another procedure such as the 1993 AASHTO Guide for the Design Pavement Structures.
3. Evaluate the pavement structure using the Pavement-ME Design. Based on the pavement’s predicted performance, develop appropriate rehabilitation activities and schedules.
4. Calculate cost and environmental impacts of the existing pavement design over the analysis period (e.g. 50 years) based on the initial design and anticipated rehabilitation costs.
5. Evaluate performance, costs and environmental impacts of design and if needed, revise the initial design to lower costs and environmental impacts. Continue iterating designs to develop a pavement section that has the best combination of low initial cost and environmental impacts, low life cycle cost and environmental impacts, and performance.

Note that while designing a pavement with the DOTs standard design procedure or a procedure such as an AASHTO 93 is not technically required; it gives a baseline from which all subsequent re-designs can be compared. It is also important to note that the re-design in step 5 is more than just decreasing slab thickness. For concrete pavements, other features of the pavement system, such as reinforcement, joint design, base design, etc., have a significant impact on performance, cost and environmental impact. The final optimized design is found by iterating thickness and design features, and balancing the costs, environmental burdens and performance.

TOOLS FOR OPTIMIZING PAVEMENT DESIGNS FOR COST AND ENVIRONMENTAL IMPACT

In order to optimize a pavement design to lower costs and environmental impacts, and to have results that are meaningful and reliable; the engineering, economic and sustainability analyses must reflect the most likely performance, rehabilitation activities, expenditures, and environmental burdens for each alternative over the analysis period. The Pavement-ME Design is the engineering tool that helps determine the initial pavement design, predicts the pavement performance over the analysis period, and allows the designers to match the rehabilitation activities to each individual design. While Pavement-ME is a major advancement in pavement engineering; it biggest benefit come when it is combined with LCCA and LCA to develop designs that meet the owner’s budget and have low environmental impact.

That is, it is easy to develop designs to meet a given performance criteria. But by combining it with a Life Cycle Cost Analysis and Life Cycle Assessment, the designer can optimize the pavement design to meet the functional requirements and performance needs without “over specifying” and driving up costs and environmental impact. The result is a pavement design where the Life Cycle Cost Analysis and Life Cycle Assessment results are balanced and as low as possible because the cost and environmental impacts are reflective of the each specific pavement’s design and anticipated performance.

AASHTOWare Pavement –ME (Mechanistic-Empirical Pavement Design)

The Pavement-ME Design was adopted by AASHTO in 2011 as its Pavement Design Procedure. It is a new mechanistic design procedure based on most advanced pavement performance models and calibrated to actual field data collected across the US and Canada. It uses mechanistic-empirical numerical models to analyze the specific traffic, climate, materials, and proposed structure (layer thicknesses and features) for a given project. Unlike most other pavement design procedures (1993 AASHTO, 1973 AASHTO, PCA Design procedure, etc.) which only provide a thickness, the Pavement-ME predicts performance for a given design using key design analysis parameters. This allows the designer to analyze a specific pavement’s performance over the analysis period and to match the required rehabilitation activities to that performance. This greatly improves the accuracy and reliability of the LCCA and LCA results.

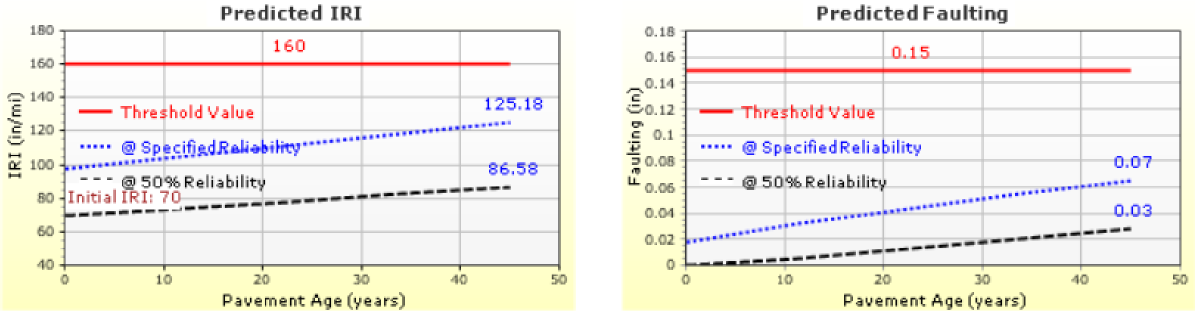

FIGURE 1 Typical MEPDG output and how it predicts pavement performance

FIGURE 1 shows typical prediction curves for International Roughness Index (IRI) and Faulting on a jointed pavement. For a given structure, Pavement-ME estimates the level of distresses (eg, ride, faulting, cracking, etc.) in the pavement for each month over the analysis period and plots it. The Predicted Performance Curve (bottom black dashed line) on both charts is the mean predicted distress at 50% reliability and shows the most likely pavement performance. The Predicted Performance Reliability Curve (middles blue dotted curve) on both charts is the level of distress for a given reliability such as 90%. Essentially, this line indicates the distress level at which 90% of all distress will be below (e.g. 90% of all pavement will have an IRI lower than 90). The Threshold value (top red line) is the agency defined design limit for that distress and is typically considered the point that defines the pavement life.

It is important to understand that Pavement-ME performance curves are calibrated estimates of performance based on modeling and similar pavements from around the US. That is, the Pavement-ME results are a distribution of what the actual performance for a given design (combination of layer thicknesses and design features such as joint spacing, dowel size, etc.) could be based on modeling and pavement performance in the Long Term Pavement Performance (LTPP) database and other test sections. Thus while not exact answers; the results give the engineer an understanding of how a particular design will perform compared to other designs with different features. From this, he or she can then remove the overdesign that has characterized concrete pavement designs in the past and use LCCA and LCA analysis to optimize the pavement design to meet the desired performance criteria.

Once a pavement performance curve hits the predefined distress level, the engineer or agency can determine when and what rehabilitation is required. It is important to note that hitting this distress level does not mean the pavement is no longer functioning. Rather, it is the level defined as to when major rehabilitation is needed (i.e. patching and diamond grinding or asphalt overlay). Note that depending on the road classification, the agency defined failure limit can be changed. For higher classes of roadway, an agency may set lower limits because the higher traffic volumes will have a larger impact. For lower volume applications, higher limits can be used. For further discussion on this, see the American Concrete Pavement Association Technical Bulletin "The Concrete Pavement Restoration Guide" TB020P which gives Trigger Values for when to do concrete pavement rehabilitation.*(*3*)*

For rehabilitation activities, it is recommended to use Concrete Pavement Preservation (CPP) activities as the first option. CPP activities are a series of engineered techniques, such as full depth repair, diamond grinding, joint and crack resealing, etc. used to repair isolated areas of deterioration in a concrete pavement and slow the rate of deterioration. CPP activities have historically provided 10 years or more of service at ¼ to ½ the cost of an asphalt overlay *(3)*. Furthermore, CPP activities can be done up to 3 times, after which time an asphalt or concrete overlay can be placed. The amount of CPP work to be done for the first rehabilitation is based on the amount of distress at the 50% reliability curve when the Predicted Performance Reliability Curve (eg, 90% reliability curve) hits the predefined distress level. Ideally the performance of each rehabilitation activity would be based on historical performance of similar pavements in the area or on the predicted rehabilitated pavement performance from Pavement-ME. However, for this paper it is assumed that each rehabilitation activity lasts 10 years.

Life Cycle Cost Analyses

Life-cycle cost analysis (LCCA) is an economic analysis tool that quantifies the differential costs of alternative investment options (pavement designs) for a given project over a given time period (analysis period). When done correctly, a LCCA identifies the strategy that yields the best and most cost effective solution by accounting for the expected performance and cost over the analysis period of each alternative. The actual mechanics of performing a life cycle cost analysis are not complicated. It is simply a mathematical calculation of the anticipated expenditures over time. To perform a LCCA, FHWA outlines the following eight basic steps *(4)*:

1) Design equivalent pavement sections
2) Estimate the initial construction costs.
3) Estimate the initial life of each alternate
4) Determine the maintenance and rehabilitation strategies (activities and timing) to be used on the pavement over the analysis period.
5) Estimate rehabilitation costs for each activity
6) Estimate user costs (optional)
7) Compute Net Present Value (NPV) of initial and rehabilitation costs.
8) Analyze results and reevaluate strategies as needed

It is important to note that in order to have LCCA that is meaningful and reliable, it is important that both Engineering and Economics need to be correct. This is main of the reason that Pavement-ME is such a powerful tool – it ensures that the engineering is correct. Likewise, it is important to use proper economics to ensure that the calculated costs are reflective of all expenditures, current economic conditions, and projected real material price changes of each alternative.

Life Cycle Assessment:

Life-cycle assessment (LCA) is a method to assess environmental impacts, energy consumption, material use, etc. throughout the life-time of a pavement. It does this by evaluating the material and energy flows for a product from cradle to grave, including raw material extraction, material processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling. The International Organization for Standardization (ISO) provides guidelines for the LCA framework under ISO-14040 and defines LCA with four major steps: goal and scope definition, inventory analysis, impact assessment, and interpretation *(5,6)*. The goal and scope definition entails determining the phases and processes that are included in the LCA study, and creating system boundaries. Then, material and energy flows for each process are collected through an inventory analysis of datasets and captured for the entire system. After processing the material and energy flow data, an impact assessment is performed that determines the effect of the product on the environment, people, ecosystem, etc. Note that there are many types of sustainability impacts that can be evaluated in a LCA. These include items such global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification potential (AP) and eutrophication potential (EP). The choice typically depends on the goal and scope of the study.

When calculating an LCA for a pavement, it is important that the "Use Phase" be included. The "use of the pavement" can account for up to 80% of a pavement's life time environmental impacts and is affected by items such pavement-vehicle interaction (PVI[1]), lighting differences, albedo effects, and other non-construction aspects based on the pavement selection. The inclusion of the "Use Phase" ensures that short term gains do not come at the expense of long-term deficits.

While LCCA and LCA are alike in many ways, they also differ in a few important aspects. Table 1, which is derived from Santero et al, shows that some requirements are shared between LCA and LCCA, while others are specific to a particular analysis approach *(7).*

EXAMPLE

The following project is an example of how a pavement design can be optimized to lower the economic and environmental impact, but still deliver the required performance. The pavement is in Ramona California (southern California) and falls within the *South Coast* climate region according to the California Department of Transportation (CALTRANS). The site is a moderate traffic volume road with an average annual daily traffic (AADT) of 23,400.

Step 1: Determine Basic Design and Performance Requirements

The initial pavement design and design life is based on the Caltrans Highway Design Manual *(8*) and the rehabilitation schedules are from Caltrans Life-Cycle Cost Analysis Manual *(9)*. For this analysis, the *functional unit* is defined as one mile of pavement from the top of the surface to the subgrade soil, extending from the outside shoulder to the outside edge of the opposite shoulder. The pavement design is 20 years but the analysis period is 50 years.

For the LCA portion, the elements included in the study are materials extraction and production; construction; transportation of materials; rehabilitation; and the use phase. In the use phase portion, only carbonation and differential Pavement Vehicle Interaction (PVI) fuel consumption due to roughness and deflection are evaluated. Albedo, lighting and annual maintenance are not included as they are assumed to be similar for two different concrete pavements. While several impact categories could have been chosen, for this example, only greenhouse gas (GHG) emissions, which relates the environmental footprint to equivalent CO_2 emissions, denoted by CO_2e will be used.

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[1] Pavement vehicle interaction (PVI) is affected by pavement roughness as it ages; structure stiffness and deflection as vehicles drive over the pavement; and surface texture which creates the "grip" between the tires and the road.

Table 1 – Similarities and differences for LCA and LCCA's

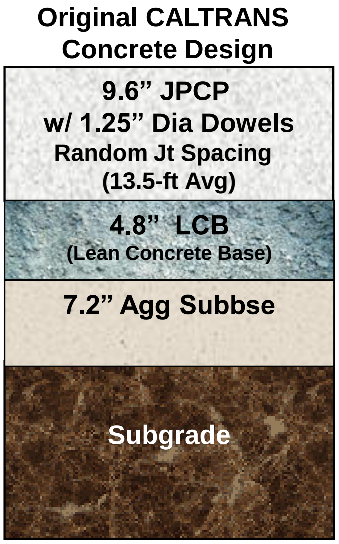
Analysis Type	Item	Description
Pavement LCAs and LCCAs	Goal	The purpose and audience of the study. The goal helps frame the problem being solved and defines the scope of the study (e.g., functional unit, system boundaries, necessary data sources, project- or policy-level scope).
	Functional Unit	The reference that all inputs and outputs are normalized against in order to evaluate the stated goal. The functional unit ensures that pavements are evaluated and compared against equivalent design and serviceability parameters.
	Analysis Period	The time period over which the functional unit is evaluated. Following LCCA precedent, a rule of thumb is to include at least one rehabilitation activity in the analysis period and should be long enough to ensure that the analysis period adequately captures differing features between the alternatives.
	Structural Designs	The relevant details regarding the pavement structural design for each design alternative. Layer thicknesses, traffic loading, material properties, location, and other parameters are necessary inputs to the LCCA and LCA, and can be determined using various pavement design methodologies.
	M&R Schedules	The activities and timing of maintenance and rehabilitation (M&R) activities over the analysis period. M&R schedules can be determined by using Department of Transportation (DOT) protocols and standard practices or – as advocated in this paper – using designs tools, such as Pavement-ME.
Pavement LCAs	LCA system boundaries	The phases and components considered in the LCA. Beginning with a comprehensive set of life-cycle phases—materials, construction, use, maintenance, and end of life—and adjusting based on the needs of the study will ensure that system boundaries are systematically, rather than arbitrarily, determined.
	LCI * environmental factors (EFs)	The factors linking processes and materials to environmental outputs. Each source of environmental output should be connected by an EF to an input defined in the functional unit, structural design, M&R schedule, etc. EFs are found in journals, reports, LCI databases, process-specific models, and other sources.
	LCIA ** methodology	The method used to transform LCI results into impact categories in terms of damage to the natural environment, human health, or natural resources. LCI results are converted to one or more midpoint categories (e.g., climate change) through characterization factors (e.g., global warming potential), which normalize similar pollutants to a single metric.
Pavement LCCAs	LCCA system boundaries	The types of costs considered in the LCCA, which can include agency and/or user costs within the system boundaries. Agency costs are the costs incurred by the DOT (or other owner) for the construction, M&R and end-of-life activities. User costs are the costs incurred by the public (e.g., drivers, residents) and are typically limited to costs related to traffic delay due to construction activities.
	Discount rate	The value (or range) used to model the time value of money. The discount rate is used in LCCAs to convert future costs to present costs. The FHWA recommends using the White House Office of Management and Budget (OMB) Circular 94 to estimate the discount rate, which currently recommends a 2.0% rate (*10*).
	Costs	The material, activity, and user unit costs. The LCCA should include the unit costs for each of the materials, activity, and/or user costs in the system boundary. Unit costs are available through a variety of sources, depending on the type of cost being evaluated.

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

Step 2: Develop Standard Designs

Figure 2 shows the standard CALTRANS design along with the basic information used to develop the designs. The pavement design and design life is based on the Caltrans Highway Design Manual and the rehabilitation schedule is from Caltrans Life-Cycle Cost Analysis Manual. The designs are based on initial traffic counts of approximately 23,400 vehicles per day, 5.8% trucks (AADTT= 1,357 trucks / day).



Moderate traffic: Route 67 - Ramona, CA
2 lanes in each direction
2 inner/2 outer shoulders (Lateral Support)
Daily traffic: 23,400
Daily truck traffic: 1,357

JPCP new construction:
Design life =20 yrs,
Maintenance Level = 1,2,3

Caltrans Rehabilitation Schedule

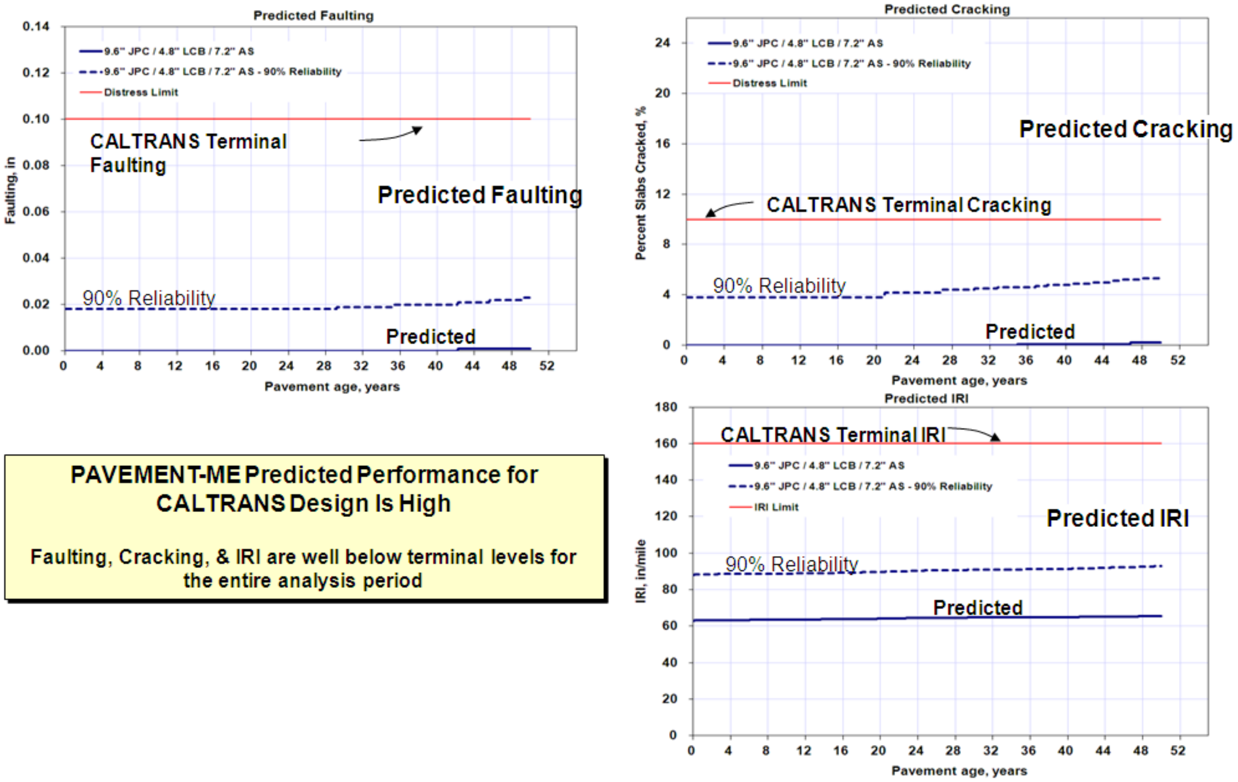
- **2% Patch & DG at year 25,**
- **4% Patch & DG at year 30**
- **6% Patch & DG at year 40**
- **3" Asphalt overlay in year 45 (10 year life)**

FIGURE 2   Pavement Design and rehabilitation schedule per CALTRANS High Design Manual and Life Cycle Cost Analysis Manual.

Step 2: Evaluate the Standard Pavement Design using the Pavement-ME

Using the concrete design in Figure 2 and Pavement-ME, the performance curves shown in Figure 3 were developed for the pavement structures. Note that Pavement-ME results have been re-plotted so that alternate re-designs can be plotted on the same graphs in order to make comparison easier. On these graphs, the red line is still the pre-defined Threshold Value; the solid lines are the actual or most likely level of distresses predicted for the given pavement; and the dotted line is the predicted distresses at the 90% reliability level.

As can be seen the predicted performance curves (faulting, cracking and IRI) remain well below the CALTRANS predefined threshold values. These curves show that this pavement is over-designed because it will not require any structural rehabilitation for the entire 50 year analysis period. While this means the pavement will perform well, it also means that “money is left on the table” because there are things that can be done to reduce the total cost and environmental impacts of the pavement, yet still deliver the 20 year required performance.



PAVEMENT-ME Predicted Performance for CALTRANS Design Is High

Faulting, Cracking, & IRI are well below terminal levels for the entire analysis period

FIGURE 3 MEPDG results for faulting, cracking, and IRI for CALTRANS Standard Design.

Step 3: Calculate the Standard Pavement Design Costs and Environmental Impacts

Table 2 shows the initial and life cycle cost and global warming potential (GWP) for the standard CALTRANS concrete pavement. The Costs and GWP are shown for both the rehabilitation cycles from the CALTRANS LCCA manual, as well as the rehabilitation cycle based on the Pavement-ME results (which is no rehabilitation required). The cost analysis accounts for both the initial costs of the pavement and life cycle costs. Initial costs include all the pavement material and labor costs as well as the base and subgrade preparation costs. Non-pavement incidental costs such as engineering and inspection, traffic control, mobilization, signage, utilities, guardrails, etc. are not included as their costs will be similar regardless of which pavement design is selected. Rehabilitation costs include all the pavement material and labor costs needed to carry out the rehabilitation activity. However, the non-pavement incidental costs for rehabilitation activities are included as they occur in different years and therefore have an impact on the LCCA results due to the time value of money.

The environmental analysis includes the life-cycle GHG emissions for the aggregated “production” processes (materials extraction and production, construction, and rehabilitation activities) and the different Use phases. The effects of carbonation; PVI impacts caused by pavement structure (pavement and base layers); and PVI impacts caused by roughness are presented separately in Table 2 to show the magnitude of each. For this report, the LCA software GaBi (version 4) by PE International *(11)* along with the Ecoinvent Database (*12* were used as the analysis platform and as documented in the report "Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle" *(7)*. PVI impacts due to deflection are calculated as outlined in the Report "Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements" *(13)*

As can be seen the initial cost and GWP are $3,147,585 and 3,954 tons of CO_2e respectively. Table 2 also shows the initial construction component costs and GWP emissions for the pavement layers (pavement, lean concrete base, and aggregate subbase) so that the designer can see what is driving cost and GWP. In this case, the pavement and lean concrete base have the majority of cost and GWP.

For the rehabilitation activities, cost and GWP are split based on whether the CALTRANS assumed rehabilitation schedule or the Pavement-ME schedule is used. As discussed, the predicted performance curves in Figure 3 show that this pavement is over-designed because it will not require any rehabilitation for the entire 50 year analysis period. In reviewing these results, it is important to note that the rehabilitation cost and GWP are a small portion of the overall LCCA and LCA results (22% and 7% respectively) and therefore trying to decrease the pavement's sustainability and life cycle costs by having longer life pavements will have limited impact. The most impactful way to lower the pavements life cycle cost and CO_2e is to optimize the initial designs – specifically the pavement and LCB – so that the predicted performance matches the required design life (eg 20 to 30 years).

With respect to the use phase, note that the PVI impacts for roughness are much higher than pavement deflection. There are 2 two reasons for this. First, the roughness PVI calculations are based on the 90% Pavement-ME IRI prediction curve, which start at a high 88 in/mile. If the roughness calculations were based on the "most likely" IRI prediction, which started at 63 in/mile, the roughness PVI calculations would be lower. However, as long as a consistent IRI basis is used, results can be compared.

	LCA (tons CO2e/mile)		**LCCA (NPV $/mile)**	
	CALTRANS	**CALTRANS - no rehab (per Pavement-ME)**	**CALTRANS**	**CALTRANS - no rehab (per Pavement-ME)**
Initial Const.	3,954		$3,147,585	
Pavement	*2,860*		*$2,229,803*	
LCB	*781*		*$644,902*	
Agg Subbase	*313*		*$272,880*	
Rehab	479	-	$911,663	--
Carbonation	(123)	(72)		
Deflection	604	643		
Roughness	1,912	2,080		
Total	6,826	6,605	$4,059,248	$3,147,585

Table 2 Cost and GWP for the CALTRANS Standard Design (for both the CALTRANS Assumed Rehab schedule and the Pavement-ME schedule)

The second reason that deflection PVI is lower is because both pavements are concrete and have low deflections. Therefore their deflection PVI is low. If an asphalt pavement, which generally has lower stiffness and higher deflections, were being evaluated, the deflection PVI would higher. It is also important to note that the reason that the deflection-PVI for the CALTRANS with rehabilitation scenario is lower than the CALTRANS no-rehabilitation scenario is because the last rehabilitation in the CALTRANS with rehabilitation scenario is a 3-inch asphalt overlay. This increases the pavement thickness, which decreases pavement deflection. Similarly, the GWP due to roughness PVI are higher for the Pavement-ME rehabilitation schedule versus the CALTRANS rehabilitation schedule because the additional rehabilitation keeps the pavement smooth and lowers the impacts due to roughness. However, even with these benefits, the assumed rehabilitation scenario has a higher GWP because the improved stiffness and smoothness does not compensate for the extra rehabilitation activities. This highlights that in optimizing designs, it is important to iterate pavement rehabilitation timing to find out what are the impacts of changing rehabilitation schedules.

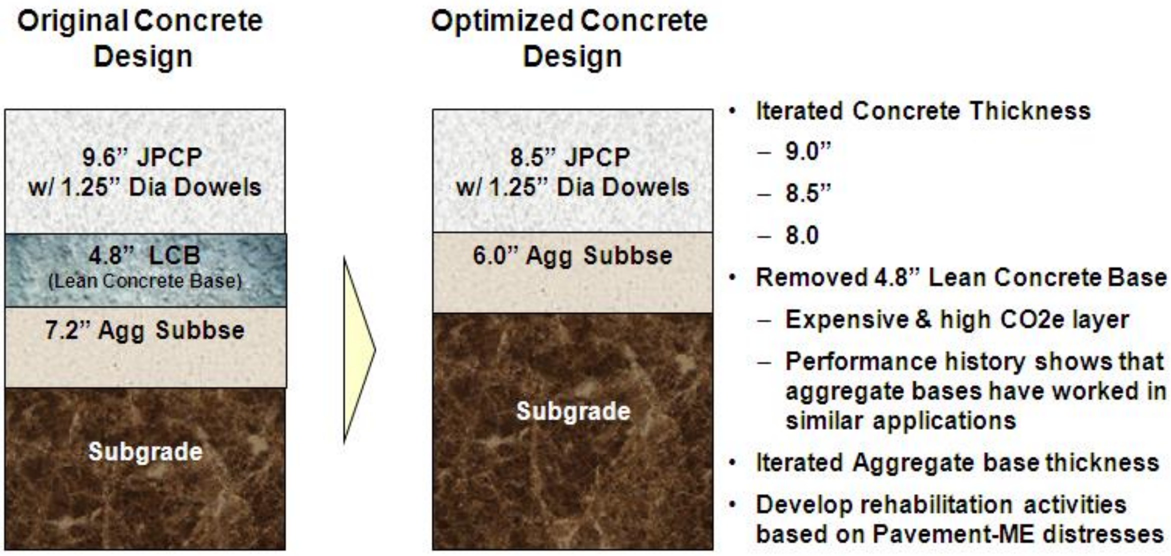
Step 4 and 5: Revise Concrete Pavement Designs and Re-evaluate Performance, Costs and GWP.

Given the performance shown in Figure 3, and cost and GWP analysis, the concrete pavement design was revised. Though thickness reduction always plays a role in optimizing concrete pavements, as mentioned previously, re-design is more than just decreasing slab thickness. Other features can have a significant impact on performance, cost and GWP. In this case, we evaluated different concrete thicknesses and removed the 4 inch lean concrete as it accounts for 20% of the initial construction pavements costs and GWP. Past experience has also shown that granular bases have performed well for non-interstate applications. Figure 4 shows the initial pavement design and the items iterated used to determine the final pavement design and Figure 5 shows the Pavement-ME performance curves for several of the iterations. Note that only the 90% reliability curves are shown for clarity's sake. .

Discussion of Results:

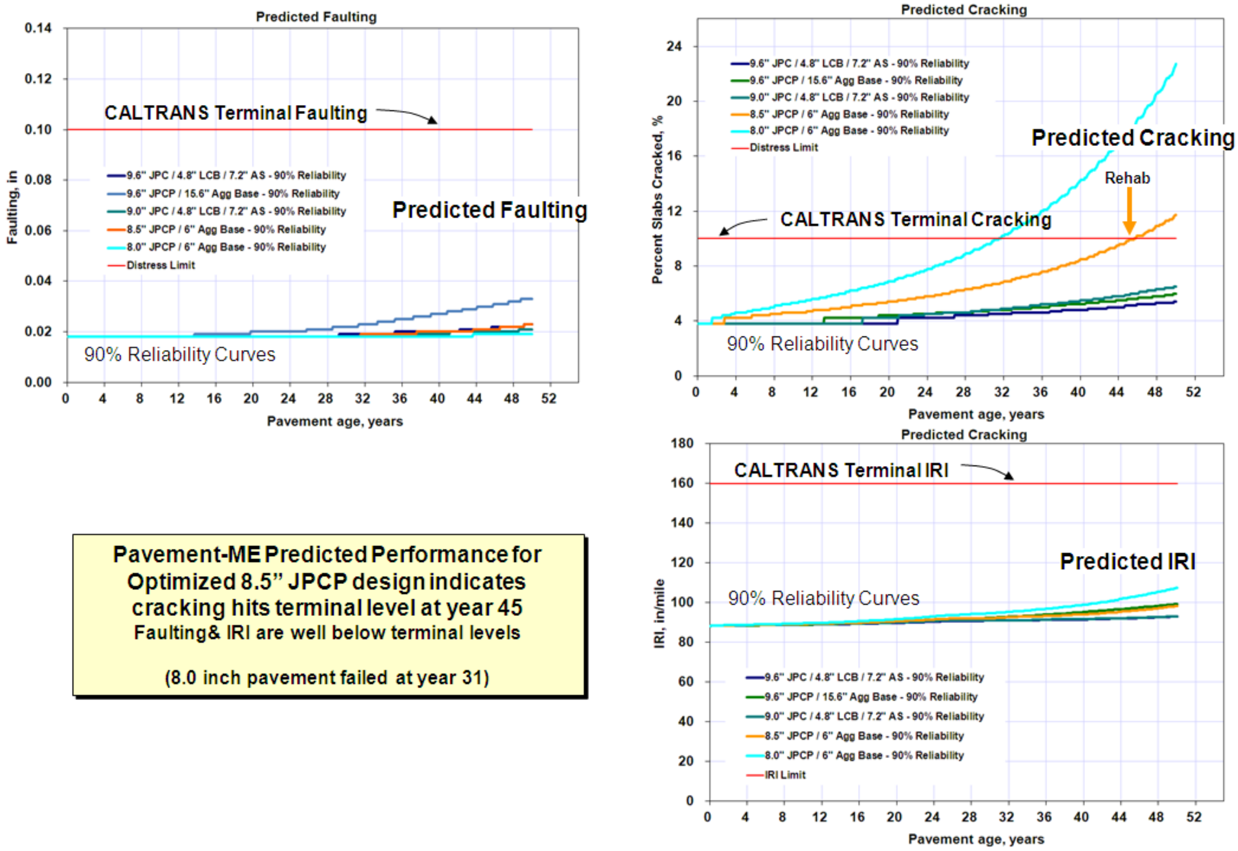
The final pavement design selected was an 8.5 inch pavement on a 6 inch granular base. As shown in Figure 5, all the pavement options evaluated exhibited good performance and exceeded the required 20 year performance criteria. Cracking does not become an issue until the pavement is at 8.5" or less. Likewise, faulting and IRI are well below unacceptable levels for the entire analysis period. While theoretically the 8.0 inch pavement met the 20 year design life, its sharp rising cracking curve indicated that it could have performance issues later on in the 50 year analysis period and could be hard to repair. As such, it was determined that the 8.5 inch pavement with one rehabilitation activity at year 45 was a good balance between providing long term performance (and a hedge against increased traffic) and low cost and low GWP.

Table 3 shows the costs and GWP for the recommended 8.5" pavement design comparing it to the original design.



- Iterated Concrete Thickness
  - 9.0"
  - 8.5"
  - 8.0
- Removed 4.8" Lean Concrete Base
  - Expensive & high CO2e layer
  - Performance history shows that aggregate bases have worked in similar applications
- Iterated Aggregate base thickness
- Develop rehabilitation activities based on Pavement-ME distresses

FIGURE 4 Alternate pavement designs compared for project example.



Pavement-ME Predicted Performance for Optimized 8.5" JPCP design indicates cracking hits terminal level at year 45
Faulting& IRI are well below terminal levels

(8.0 inch pavement failed at year 31)

FIGURE 5 Pavement-ME results for faulting, cracking and IRI of alternate optimized pavement designs evaluated

	LCA (tons CO2e/mile)		
	CALTRANS	CALTRANS - no rehab (per MEPDG)	Optimized Design (rehabs per MEPDG
Initial Const.	3,954		3,063
Pavement	*2,860*		*2,803*
LCB	*781*		*--*
Agg Subbase	*313*		*260*
Rehab	479	-	54
Carbonation	(123)	(72)	(87)
Deflection	604	643	704
Roughness	1,912	2,080	2,110
Total	6,826	6,605	5,844
	LCCA NPV ($/mile)		
Initial Const.	$3,147,585		$2,256,638
Pavement	*$2,229,803*		*$2,021,307*
LCB	*$644,902*		*$-*
Agg Subbase	*$272,880*		*$235,331*
Rehab	$911,663	-	$315,798
Total	$4,059,248	$3,147,585	$2,572,437

Table 3 Cost and GWP for the CALTRANS Standard Design and Optimized Designs

Overall, the optimization process reduced the initial construction GWP by 900 tons of CO_2e /mile and the life cycle GWP by between 800 and 1,000 tons of CO_2e / mile depending on whether one is comparing the results to the CALTRANS assumed rehabilitation schedule or the Pavement-ME schedule. In either case, there was a significant reduction with a 29.0% decrease in initial construction GWP and between a 13.0% to 16.8% reduction in life cycle GWP.

With respect to costs, the redesign lowered the initial cost of the concrete pavement from $3.14 M to $2.25M (a 39.5% reduction) and lowered life cycle cost between 57.8% and 22.3% depending on whether the results are compared to the CALTRANS assumed rehabilitation schedule or the Pavement-ME schedule for the original pavement design.

Of the possible comparisons, the most realistic is between the optimized design and the original CALTRANS design with rehabilitation schedule based on Pavement-ME. In reviewing the results, one can see that even though the optimized pavement requires rehabilitation at year 45, its initial cost and GWP savings more than compensate for the additional rehabilitation as compared to the original CALTRANS design.

CONCLUSION

With the development of the Pavement-ME Mechanistic Empirical Pavement Design, it is now possible to develop optimized concrete pavement designs that are much lower in initial cost and environmental impact than traditional concrete pavements, but still demonstrate good long term performance. Because of this, optimized concrete pavements have lower cost of ownership and lower environmental costs than alternate designs.

Optimized designs are developed using an engineering analysis (Pavement-ME), cost analysis (LCCA), and environmental analyses (LCA) that considers both the initial and the long term costs and environmental impacts.

In this process, it is important to note that optimizing concrete pavements is more than just reducing thickness. Other features such as proper joint design (spacing and dowel size), edge support, etc. play an important role and each pavement design must look for the best combination of features for its given need. The final design is found by iterating designs and balancing the initial costs and environmental impacts, rehabilitation costs and environmental impacts, and long term performance.

While this is just an example, the idea is to provide a snapshot of the role that LCA and LCCA can play in producing more sustainable solutions, and how the methodology offers a foundation for future research to build upon. While not discussed here, an improvement to the process would be to conduct a probabilistic LCCA and LCA using the average and standard deviations of the costs, rehabilitation timing, and different activity scenarios to get a better understanding of the impact these variations and changes can have on the robustness of the results.

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