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RESEARCH REPORT

Evaluation of Sustainable and Cost-Effective Concrete Pavement Life

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Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 2.12 (TO-017) (DRISI Task 4254): Support for Concrete Pavement Mechanistic-Empirical Design

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16. ABSTRACT

Caltrans jointed plain concrete pavements (JPCP) and continuously reinforced concrete pavements (CRCP) are currently designed for a 40-year life (based on 10% fatigue transverse cracking and 10 punchouts per mile criteria, respectively). While this is already a long-life design, there is the concern that it may not result in the minimum possible life cycle cost and environmental impacts. The current Caltrans *Highway Design Manual* (*HDM*), including the Rigid Pavement Design Catalog, and the Standard Specifications applicable to concrete pavements, are based on this 40-year design life. This study includes recommendations for the materials, design, and construction of concrete pavements aimed at extending the design life up to 100 years. These recommendations are based on existing knowledge and tools and indicate the changes necessary to Caltrans's existing specifications and practices. However, uncertainties remain in traffic load and climate predictions, as well as the limitations of current durability and structural design models, all of which complicate efforts to accurately predict pavement life beyond the current 40-year standard. As part of this study, the web version of the Rigid Pavement Design Catalog has been updated to allow any design life up to 100 years. This study includes the pavement structural design, life cycle cost analysis (LCCA), and the environmental life cycle assessment (LCA) of three case studies, each designed for 40-, 60-, and 100-year lives. The increase in design life from 40 to 60 years required an increase in JPCP thickness of 0.05 ft. for all three case studies, which carried an increase in the initial agency construction cost of around 5%. The LCCA and LCA results indicate that increasing the design life from 40 to 60 years is expected to result in 3% life cycle agency cost savings and 24% life cycle infrastructure global warming potential (GWP) savings. Some road user cost savings were seen from fewer construction work zone (CWZ) closures. Smaller life cycle costs and GWP reductions were found when the design life increased from 60 to 100 years, due in part to the relatively high discount rate used in this study (3.2% per year) and the fact that the reconstruction activity for the 60-year design life already lay beyond the end of the 100-year analysis period adopted in this study.

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7. PROPOSALS FOR IMPLEMENTATION It is recommended that design lives of up to 60 years be included in the Caltrans *HDM* for JPCP and CRCP. It is recommended that LCCA and LCA are conducted to select the optimum design life.	
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DISCLAIMER

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PROJECT OBJECTIVES

The objective of Partnered Pavement Research Center (PPRC) Project TO-17, “Support for Concrete Pavement Mechanistic-Empirical Design,” is to support Caltrans through the direct implementation of research results, primarily through software products related to past research projects that are now used as part of the regular Caltrans project delivery cycle. This project includes support to Caltrans in the following areas:

- Pavement management system, PaveM
- Flexible pavement design using *CalME*
- Rigid pavement design using *Pavement ME*
- Environmental life cycle assessment through *eLCAP*
- Life cycle cost assessment with *RealCost*
- Monitoring of pilot projects for new rigid pavement technologies

This report has been developed under the third area, rigid pavement design. The goal of the report is to provide guidance on project selection, materials, design, and construction of concrete pavements with extended long lives. The report also includes a life cycle cost analysis and environmental life cycle assessment, which provide an estimate of the initial cost increase, as well as the life cycle cost savings and environmental impact reductions associated with extending the concrete pavement design life from the current practice of 40 years to 60 years and 100 years.

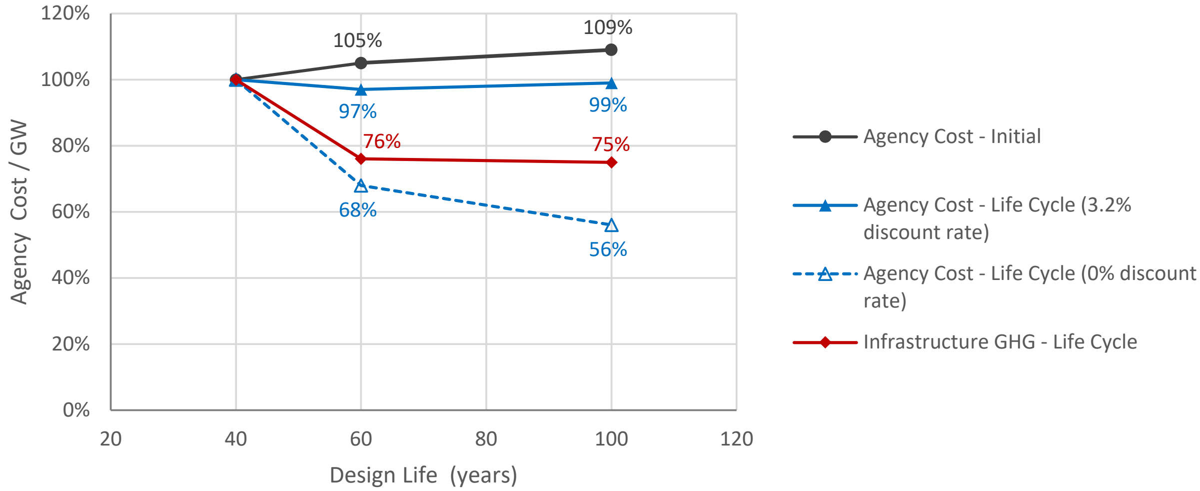
EXECUTIVE SUMMARY

Caltrans jointed plain concrete pavements (JPCP) and continuously reinforced concrete pavements (CRCP) are currently designed for a 40-year life. While this is already a long-life design, there is concern that it may not result in the lowest achievable life cycle cost and environmental impacts. From the thickness design point of view, extending the life from 40 years to 60 years would only require around 0.05 ft. (0.6 in.) additional concrete slab thickness, while extending the design life from 60 years to 100 years would only require around 0.05 ft. (0.6 in.) more. This raises a key question: With the small increase in concrete slab thickness needed to achieve an additional 20 years to 60 years of pavement life, would the life cycle costs and environmental and social impacts justify revising the current pavement design practice to a design life longer than 40 years?

Three case studies were formulated in this study to address this question. The three case studies included traffic and climate characteristics that correspond to three specific locations on the Caltrans highway network. The case with the lowest annual average daily traffic (AADT) (referred to as "medium traffic" in this paper) corresponds to a rural freeway with two lanes per direction, while the case with the highest AADT corresponds to one of the busiest locations in the Caltrans highway network. For each of the three case studies, three design lives have been adopted: 40 years (current Caltrans practice), 60 years, and 100 years.

The corresponding concrete slab thicknesses, assuming pavements are JPCP, were determined using the web version of the Caltrans Rigid Pavement Design Catalog, which is currently set at 40 years but can be used to design pavements up to 100 years. The life cycle cost analysis (LCCA) and environmental life cycle assessment (LCA) were conducted to determine the corresponding life cycle cost and greenhouse gas (GHG) emissions. The analysis period was set to 100 years; that is, the cost and environmental impacts of the initial construction and all expected maintenance, rehabilitation, and reconstruction activities for the 100-year analysis period were accounted for in the analysis. Included in the LCCA and LCA are the construction work zone (CWZ) impacts, which are the impacts on traffic that result from the initial construction, maintenance, rehabilitation, and reconstruction activities. The main potential impacts of CWZ are traffic delays and increased fuel consumption by cars and trucks.

The LCCA and LCA results, summarized in the following figure, show that 40 years may not be the optimal design life for concrete pavements. In fact, some life cycle cost savings and significant life cycle GHG emissions savings are expected if the design life increases to 60 years, while little additional benefit was found in increasing the design life from 60 years to 100 years.



Summary of LCCA and LCA for the averages of three case studies.

It is important to note that the LCCA and LCA predictions for an extended analysis period of 100 years carry a relatively high degree of uncertainty. The uncertainty is partly related to the limitations of current rigid pavement design procedures, exacerbated by the extremely long analysis period, and affected by the unclear future evolution of climate conditions and truck traffic characteristics. In fact, the current rate of climate change is significantly faster than any other period in recorded history. Furthermore, truck traffic characteristics, including total weight and axle loading, have changed and are expected to change more as the truck fleet shifts to alternative fuels like battery electric and hydrogen fuel cells, while the loading pattern (truck spacing and wandering) may change considerably as autonomous driving moves forward. The uncertainty in LCCA and LCA predictions is also related to the uncertainty about the materials that will be used for future pavement maintenance, rehabilitation, and reconstruction activities (e.g., what will be the embodied carbon of the rapid-strength concrete in 2060 compared with 2024?), the future of mobility (e.g., what percentage of cars will be zero emissions?), and other factors (e.g., what percentage of the California electricity grid will be renewable?). The existing uncertainty advises caution before extending the design life.

The increase in concrete slab thickness is not the only step required to extend the life of concrete pavements beyond 40 years. In fact, current materials, design specifications, and construction practices, conceived for a 40-year design life, must be revised. A comprehensive review of the Caltrans *Highway Design Manual* (*HDM*), concrete pavement design methods, and Caltrans Standard Specifications related to concrete pavements was conducted as part of this study. Based on that review, a collection of recommendations for concrete pavements with design lives of up to 100 years was formulated based on the authors' existing knowledge and tools that are already available. The recommendations address the following question: How should the materials, design, and construction of a concrete pavement with an extended long-life design differ from a conventional concrete pavement? The collection of recommendations—grouped into materials, design, and construction—can be regarded as a 2025 update of the 2008 recommendations in the *100-Year Sustainable Pavement Design and Construction* Caltrans report.

The following conclusions can be drawn from the LCCA and LCA results:

- The increase in concrete pavement design life from 40 years to 60 years and 40 years to 100 years required an increase in concrete thickness of 0.05 ft. and 0.1 ft., respectively. That thickness increase resulted in an increase in the initial agency cost of around 5% for the 60-year design and 9% for the 100-year design.
- Increasing the design life from 40 years to 60 years resulted in a reduction of about 3% in life cycle agency cost and 24% in life cycle GWP. Most of the GWP reduction was due to the elimination of the year 87 reconstruction activity that is required with the 40-year designs.
- On the other hand, the savings expected when the design life increased from 60 years to 100 years were not that high: an increase of about 2% in life cycle agency cost and a reduction of 1% in life cycle GWP (compared with the 60-year design). The reason for the small savings is that the reconstruction activities for the two design lives lie beyond the end of the 100-year analysis period adopted in this study.
- The 3.2% discount rate assumed for the LCCA had a tremendous impact on the results. Because of the discount rate, the costs incurred in the second half of the 100-year analysis period had almost no effect on the life cycle cost. If a discount rate of 0% is assumed, the increase in pavement design life from 40 years to 60 years and 100 years would carry a reduction in life cycle agency cost of around 32% and 44%, respectively. The fact that Caltrans does not borrow funding to pay for maintenance and rehabilitation (M&R) but instead uses pay-as-you-go tax funding supports the use of a 0% discount rate.
- The CWZ impacts in terms of cost (time and excess fuel consumption) were reduced when the design life increased from 40 years to 60 years. The expected reduction was much smaller when the design life increased from 60 years to 100 years.
- The conclusions listed above are applicable to the three case studies, despite their very different AADTs.

The following recommendations were formulated:

- Based on the LCA and LCCA studies of the three cases, there is evidence that extending the design life up to 60 years offers important life cycle savings, mainly in terms of life cycle environmental impacts and some cost savings. The results for design lives of 100 years show little or no improvement over the 60-year design life results. Given these results, the limitations of the current design procedure, the shortcomings of durability models, and the unknowns about materials, it is recommended that, at this time, the design life is not extended beyond 60 years.
- It is recommended that Caltrans develop non-standard special provisions (nSSPs) applicable to concrete pavements with a 60-year design life that implement the “What can be done today” recommendations included in this report.

- Instead of mandating a statewide design life of 60 years, Caltrans can allow designers to choose a design life of 40 years or 60 years and make the final decision based on LCCA and LCA on a case-by-case basis, considering that the case studies included in the scope of this study were not exhaustive. The LCCA and LCA should include the impacts on road users associated with the CWZ activities.
- The following are recommendations to improve the validity of the LCCA and LCA:
  - Additional case studies of highways slated for reconstruction can continue to build on the findings of this initial study and provide a stronger basis for making more definitive revisions to the current design practice.
  - Better assumptions regarding changes in the vehicle fleet fuel (from fossil fuels to electric and hydrogen fuel cells) should be developed for better CWZ analyses.
  - Better assumptions regarding future electric power generation should also be developed for materials production and CWZ analyses.
- The following actions are recommended before considering extending the design life to 100 years:
  - The performance of JPCPs older than 60 years following modern engineering and design in other states should be reviewed.
  - It is recommended that this study be updated every five years as the sustainability aspects advance, both in terms of modeling and practice, and as the effect of electrification on axle loads and GHG emissions becomes clearer.
  - It is also recommended that this study be reviewed by industry and trade associations for their input and perspective before changes are made to the current design practice.
  - This study identifies limitations of the current practice of concrete pavement materials, design, and construction that cannot be resolved with current knowledge and tools. For those limitations, recommended strategies are proposed in this report ("What should be done in the future"). It is recommended that Caltrans consider the current limitations and recommendations and put effort into addressing those strategies in future research requests and contracts. The benefit will be to more accurately predict the performance of pavements, especially for longer lives, and the ability to further optimize the pavements and enhance their sustainability.
  - LCCA guidelines should be updated to support longer design life in the following ways:
    - The same analysis period should be used when comparing design alternatives—for example, between asphalt, concrete, and cold recycling pavement alternatives.
    - The discount rate value is extremely critical in the LCCA results for extended analysis periods (e.g., 100 years). Caltrans needs to review the discount rate. Using the current 3.2%, any activities that occur in the second half of the 100-year analysis period result in negligible effects on LCCA results.

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LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AADTT	Annual average daily truck traffic
AB	Aggregate base
AC	Asphalt concrete
ASR	Alkali-silica reaction
CL	Clay with low plasticity
CRCP	Continuously reinforced concrete pavement
CWZ	Construction work zone
FRP	Fiber-reinforced polymer
GHG	Greenhouse gases
GWP	Global warming potential
HDM	Highway Design Manual
HMA	Hot mix asphalt
IRI	International Roughness Index
JPCP	Jointed plain concrete pavement
LCA	Life cycle assessment
LCB	Lean concrete base
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LLPRS	Long-Life Pavement Rehabilitation Strategy
M&R	Maintenance and rehabilitation
ME	Mechanistic-empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MiST	Moisture Induced Stress Tester
NMAS	Nominal maximum aggregate size
PCC	Portland cement concrete
PMED	Pavement mechanistic-empirical design
PMS	Pavement management system

RAP	Reclaimed asphalt pavement
SAM	Super air meter
SCM	Supplementary cementitious material
SJPCP-COA	Short jointed plain concrete pavement-concrete overlay on asphalt
SR	Slab replacement
USCS	Unified Soil Classification System
WIM	Weigh-in-motion

LIST OF STANDARDS AND SPECIFICATIONS

AASHTO

TP 118	Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method
TP 129	Standard Method of Test for Vibrating Kelly Ball (VKelly) Penetration in Fresh Portland Cement Concrete
TP 137	Standard Method of Test for Box Test in Slip Form Paving of Fresh Portland Cement Concrete
T 318	Standard Method of Test for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying

ASTM

C309	Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C1012	Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C1157	Standard Performance Specification for Hydraulic Cement
C1260	Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
C1567	Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)
D1293	Standard Test Methods for pH of Water
D7870	Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure

CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised April 2021)

1 INTRODUCTION

1.1 Background

The California Department of Transportation (Caltrans) implemented a standard of using a 40-year design life criterion for concrete pavements in its *Highway Design Manual* (*HDM*) Rigid Pavement Design Catalog in 2007. The catalog was developed by the University of California Pavement Research Center (UCPRC) using the *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*) (version 0.8) *(1)* in 2006. The 40-year design life is still in place, and it was followed in the development of the 2022 update of the *HDM* Rigid Pavement Design Catalog *(2,3)*.

The design life is defined as the time until 3% of slabs have third-stage cracking and therefore need replacement, which Caltrans/UCPRC research has shown corresponds to roughly 10% of slabs having transverse cracking *(4)*. The 2023 catalog was developed employing *AASHTOWare Pavement ME Design* (*PMED*) (version 2.5.5), which was calibrated using more than 40 years of Caltrans pavement management system (PMS) data for the entire concrete pavement network *(4)*.

While a design life of 40 years is now regarded as the standard practice for concrete pavements, it was a major change of practice in the early 2000s when new concrete pavements were designed for a 20-year life, a standard going back at least to the 1960s. The transition from a 20-year to a 40-year design life was the outcome of several initiatives, the most relevant of which is probably the development of the Caltrans Long-Life Pavement Rehabilitation Strategy (LLPRS), which changed the design life standard for pavement major rehabilitation from 10 years to 30 years and later to 40 years where there is high traffic. This initiative was commissioned by Caltrans in 1997 with the goal of implementing longer-life major rehabilitation strategies in California to minimize construction work zone (CWZ) closures and better balance agency and road user life cycle costs by considering the effects of frequent maintenance in overall economic terms.

As part of the LLPRS effort, and later in the mid-2000s as part of changing the standard major rehabilitation design life for all pavements from 10 years to 20 years, it was determined that extending the life of a concrete pavement from 20 years to 40 years, from the thickness design point of view, did not require much of an increase. Consider a reference case on the Caltrans road network (specific features are not described here since they are not relevant to the following discussion). The slab thickness required for a 20-year design life is 0.80 ft., while the thickness required for 40 years is 0.85 ft. In other words, 0.05 ft. (0.6 in.) of concrete can buy 20 years of extra life. A similar outcome would result for any location in the Caltrans road network.

In addition to the slab thickness increase, the successful adoption of the 40-year design life required updating other design features, including shortening transverse joint spacings to 14 ft. from the previous 15 ft., 18 ft., and 19 ft. spacings, and the use of dowels, as well as changes to the materials and construction specifications to improve the durability of the concrete and base layers. The proof that the initiatives worked is that Caltrans concrete pavements are overperforming nationally calibrated *PMED* predictions *(2,4)*. Overall, the Caltrans-calibrated *PMED* designs result in slabs that are 0.05 ft. (0.6 in.) thinner than the nationally calibrated *PMED* designs *(4)*.

While not comprehensively quantified yet, the adoption of a 40-year design life standard for concrete pavements has resulted in considerable life cycle cost savings for Caltrans and considerable mitigation of maintenance and rehabilitation (M&R) construction-related negative impacts on road users. The design life standard has also likely reduced life cycle greenhouse gas (GHG) emissions and other negative environmental impacts over the life cycle of the pavements.

Continuing with the reference case previously presented, extending the design life from 40 years to 60 years would only require an additional 0.05 ft. of concrete thickness, while extending the design life from 60 years to 100 years would only require an additional 0.05 ft. This raises a key question: With the small increase in concrete slab thickness needed to achieve an additional 20 years to 60 years of pavement life, would the life cycle costs and environmental and social impacts justify revising the current pavement design practice to a design life longer than 40 years?

While extending pavement life is generally considered a more sustainable practice, the question remains: How long is too long? Additionally, what updates to current specifications and design tools are necessary to reliably predict pavement performance beyond 40 years? Is the necessary information available to make reliable predictions today? Answering these questions requires a critical review and assessment of existing specifications and tools as well as comprehensive cost and environmental life cycle assessment (LCA) studies that account for all phases of a pavement's life, including the initial construction, maintenance, repair, and end of life—while also considering the impacts of the CWZ.

This study aims to evaluate whether extending the design life of concrete pavements from 40 years to 60 years or 100 years would improve the effectiveness of investments in road infrastructure by reducing life cycle costs and GHG.

1.2 Problem Statements

The following problem statements have been identified:

- The current Caltrans practice of adopting a 40-year design life for concrete pavements may not result in minimum life cycle costs and environmental impacts, particularly for high-volume freeways compared with longer design lives of 60 years or 100 years.
- Caltrans concrete pavement Standard Specifications are conceived for a 40-year design life. Some of these specifications, including those related to concrete durability, may need to be revised to achieve longer lives.
- The Caltrans Rigid Pavement Design Catalog, included in Chapter 620 of the *HDM*, includes jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) with only a 40-year design life.
- Caltrans uses the nationally calibrated *PMED*, which has significant limitations for durability considerations and relies on fixed values for critical design parameters. These limitations can hinder the ability to accurately predict the design life, especially when aiming for longer-life pavements.

1.3 Goal and Questions to Answer

The goal of this report is to provide guidance on the project selection, materials, design, and construction of concrete pavements with extremely long lives, greater than 40 years. The following are questions this report will address:

1. How should Caltrans concrete pavement specifications and design tools be adapted to achieve longer lives, particularly 60 years and 100 years?
2. When should a design life beyond 40 years be considered for concrete pavements?
3. What is the initial construction cost increase associated with extending concrete pavement design life from 40 years to 60 years and 100 years?
4. What are the life cycle costs and GHG emissions savings associated with extending the concrete pavement design life from the current practice of 40 years to 60 years and 100 years?

1.4 Research Approach

Question 1 was addressed by conducting a comprehensive review of the Caltrans concrete pavement design method in the *HDM* and Standard Specifications related to concrete pavements, including Section 23 to Section 30 (Subbases and Bases), Section 39 (Asphalt Concrete), Section 40 (Concrete Pavement), Section 41 (Existing Concrete Pavement), and Section 90 (Concrete). The 2008 document *100-Year Sustainable Pavement Design and Construction (5)* has been used as a starting point. The answer to Question 1—"How should Caltrans concrete pavement specifications and design tools be adapted to achieve longer lives, particularly 60 years and 100 years?"—is provided as a list of recommendations for project selection and a set of tables included in Chapter 2 of this report. The tables include materials, design, and construction recommendations for concrete pavements with up to 100 years of design life.

Questions 2 to 4 were addressed based on three case studies presented in Chapter 3 of this report. The case studies consider a five-lane-mile concrete pavement construction in three locations in the Caltrans road network. The three locations have one-way annual average daily traffic (AADT) of 5,500, 35,500, and 142,500, and the three case studies are referred to as "medium traffic volume," "high traffic volume," and "very high traffic volume," respectively. Three design lives have been considered for each of the three case studies: 40 years (current practice), 60 years, and 100 years. Each design life has its corresponding maintenance, rehabilitation, and reconstruction schedule. The analysis period (life cycle) is 100 years (i.e., the cost and environmental impacts of the initial construction and all expected maintenance, rehabilitation, and reconstruction activities for the 100-year analysis period have been accounted for in the analysis).

Life cycle cost analysis (LCCA) has been used to quantify the initial construction and the life cycle net present value. Environmental LCA has been used to quantify the life cycle environmental impacts, particularly GHG emissions. Included in the LCCA and LCA are the CWZ impacts, which are the impacts on traffic that result from the initial construction, maintenance, rehabilitation, and reconstruction activities. The main CWZ impacts are traffic delays and the increase in fuel or energy consumption. The former has an associated user cost while the latter has associated cost and environmental impacts (GHG and other pollutant emissions from additional energy production and consumption, whether from fossil fuels or alternatives).

The Caltrans Rigid Pavement Design Catalog includes only JPCP and CRCP with a 40-year design life. As part of this study, the web version of the catalog was updated to allow any design life up to 100 years.

1.5 Scope of the Report

This report considers JPCP and CRCP. While the three case studies presented in Chapter 3 are JPCP, the conclusions regarding how the design life affects initial and life cycle costs and GHG emissions can be extrapolated to CRCP. LCCA and LCA of CRCP require a CRCP mechanistic-empirical (ME) performance model that is not available yet. The development of such a model is the goal of the Partnered Pavement Research Center (PPRC) Project TO-19, "Modify CRCP Mechanistic-Empirical Models Used in PavementME and Update Rigid Pavement Design Catalog for CRCP."

The short jointed plain concrete pavement-concrete overlay on asphalt (SJPCP-COA), considered in Chapter 620 of the Caltrans *HDM*, is not the focus of this report. The SJPCP-COA is a pavement rehabilitation alternative that involves placing a 4 to 7 in. concrete overlay on an existing asphalt pavement. The SJPCP-COA is currently designed for a 20-year life and is typically used for low- and medium-volume roads.

In 2020, Governor Newsom signed Executive Order N-79-20, declaring a goal for California to reach that 100% of medium and heavy-duty vehicles be zero emissions by 2045 for all operations where feasible and by 2035 for drayage trucks and off-road vehicles *(6)*. This study does not consider the future changes in axle loadings that are expected as the truck fleet in California transitions to zero emissions, based on analysis in a recent report that indicates that axle weight increases from battery and fuel cell truck conversion will not be large by the time of widespread replacement in the truck fleet due to improvements in propulsion system efficiency *(7)*. Also included in Executive Order N-79-20 is a requirement that all new passenger car and light-duty truck sales be zero-emission (tailpipe emissions) vehicles beginning in 2035. The resulting effects of reduced tailpipe emissions and reductions in the carbon intensity of electric and later fuel cell energy production were estimated using gross simplifications for reduced emissions from CWZ, discussed in Section 3.7. The impacts of medium- and heavy-duty vehicle automation, including platooning, are not considered in this study. Changes in climate patterns and their effect on pavement performance were also not considered in this study.

Finally, while this study includes economic and environmental aspects of sustainability, the social impacts of extending the pavement design life beyond 40 years were not considered. Additionally, the quantitative calculation of the effects of climate change, economic development, geography, regulations, and other influences that may necessitate realigning or changing the functionality of the highway that requires its replacement or reconstruction before its intended service life falls outside the scope of this study. These uncertainties and their consideration in evaluating candidate pavement locations for 60-year and 100-year design lives are discussed in Section 2.1.

1.6 Definition of Design Life

The design life is the time when the pavement is expected to reach certain limits of structural deterioration that require prescribed rehabilitation treatments. Based on the Caltrans design practice for JPCP, the structural deterioration limit is 3% of shattered slabs (slabs with third-stage cracking) requiring slab replacement, which is minor rehabilitation (a state of distress in terms of wheelpath cracking requiring minor rehabilitation is also used for asphalt pavement design). This means the JPCP is expected to have 3% shattered slabs after 40 years in service, roughly equivalent to 10% of slabs with transverse cracking. It does not mean that the pavement will be reconstructed after 40 years. A slab replacement operation would suffice to bring the 40-year-old pavement back to acceptable conditions.

As the slabs continue failing, there will be a point when the most efficient action will not be slab replacement but reconstruction, which is defined as major rehabilitation and is quantified as when the pavement will have 10% shattered slabs requiring replacement. For a pavement designed for a 40-year life, reconstruction is not expected until approximately year 87 based on ME modeling using the *PMED* models calibrated in 2020 for California *(4)*. The sequence of expected actions and the corresponding timing constitute what is typically referred to as the "Maintenance and Rehabilitation Table." This topic is elaborated on in Section 3.5.1 of this report.

1.7 Global Warming Potential Definition

Several studies in the literature report global warming potential (GWP). However, GWPs are factors that have been calculated by the Intergovernmental Panel on Climate Change as an example for each emission type within the impact category. GWP is a relative measure of how much heat a GHG traps in the atmosphere over a period of time compared with CO_2; hence, every GHG has a different GWP. The *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts* (*TRACI*), from the US Environmental Protection Agency, uses the term "global warming air" as an example *(15)*. In this study, the term "global warming potential" (GWP), measured in kg CO_2 equivalent (CO2e), is used for reporting the results.

2 CONSIDERATIONS ABOUT PROJECT SELECTION, MATERIALS, DESIGN, AND CONSTRUCTION

2.1 Assumptions and Limitations of the Study

Traffic inputs to ME design are defined by observing past truck traffic characteristics; similarly, climate inputs typically consider the average climate during a few past decades. In particular, the development of the 2023 Caltrans Rigid Pavement Design Catalog is based on truck axle weight distributions that correspond to truck traffic characteristics existing on the Caltrans road network from 2004 to 2015 *(8)* and climate inputs that correspond to the average year from 1979 to 2003 for each climate region. Material properties assumed in ME design are also based on materials used in the past. For example, the concrete strength used for developing the Caltrans Rigid Pavement Design Catalog is the average value from the UCPRC's database, which includes almost 100 projects sampled and tested during the last two decades *(2)*.

Conventional pavement ME design assumes that pavements will perform in the future the same as in the past and that climate and truck traffic characteristics will remain unchanged during the life of the pavement. Such assumptions are simplifications. In fact, the current rate of climate change is significantly faster than at any other period in recorded history *(9)*. Further, truck traffic characteristics, including total weight and axle loading, have changed and are expected to change more as the truck fleet shifts to alternative fuels like battery electric and hydrogen fuel cells, while the loading pattern (truck spacing and wandering) may change considerably as autonomous driving moves forward, with either beneficial or detrimental effects depending on how the automation is programmed *(10)*.

While the simplifications mentioned above can be assumed to be acceptable for short design lives (up to 20 years), they become more and more questionable as the design life increases and can become highly uncertain for design lives above 40 years.

Furthermore, the mission of the highway can be in question when considering extremely long design lives, and the following questions should be considered:

- Will the route likely be changed or realigned, which can be driven by many factors, such as urban expansion, population changes (increases or decreases), changes in land use, changes in traffic and freight movement, economic development plans, changes in laws or regulations, public input, and other factors?
- Will there be demand for a route on this alignment in the next 50 to 80 years, or will the route be moved or abandoned?
- Are there climate resilience issues or natural or human-made disasters that will likely impact the project location within the next 50 to 80 years, such as sea level rise, flooding, or ground subsidence?

- What other elements might happen or be added to this alignment that might require removing or reconstructing the pavement, such as placement of rail down the middle, new interchanges that would tear up alignments, or changes in truck widths?

While the design life is not specified in Caltrans Standard Specifications for concrete pavements, they were developed and validated for a 40-year pavement design life. Some of these specifications may need to be narrowed or tightened, or additional specifications added, to ensure the concrete pavement reaches 100 years in service.

2.2 Recommendations for Materials, Design, and Construction

Due to scope limitations, this report does not intend to resolve all the limitations and uncertainties previously mentioned. The goal of this report is to highlight the limitations of current practice and, for each limitation, to recommend a strategy based on existing knowledge and tools that are already available. The recommendations provided are based on the authors' expertise and experience in concrete pavement materials, design, and construction, as well as years of close collaboration with industry and transportation agencies.

The recommendations have been grouped into materials (Table 2.1), design (Table 2.2), and construction (Table 2.3). The recommendations included in the “What can be done today” column of the tables respond to the following question: How should the materials, design, and construction of a concrete pavement with an extended long-life design differ from a conventional concrete pavement?

While the goal of this report does not include resolution of all the limitations previously mentioned, recommended strategies have been listed for the limitations that cannot be resolved based on current knowledge and tools. The strategies included in the “What should be done in the future” column of the tables respond to the following question: How should the materials selection, design, and construction of a concrete pavement with an extended long-life design be conducted in the future? The collection of strategies can be conceived of as a research roadmap whose vision is to improve life cycle cost, environmental impacts, and the social sustainability of concrete pavements by extending their performance life.

The recommendations included in Table 2.1, Table 2.2, and Table 2.3 can be regarded as a 2025 update to the 2008 recommendations in the *100-Year Sustainable Pavement Design and Construction* publication *(5)*. The topics not specifically discussed in these tables should be addressed in concrete pavements with a 60-year to 100-year design life in the same way as in conventional concrete pavements with a 40-year design life. Implementation of the recommendations listed in Table 2.1 to Table 2.3 would require revised Standard Specifications or non-standard special provisions (nSSPs). Two of the recommendations, regarding dowel diameter and slab width, would require minor changes to the Standard Plans.

Table 2.1: Recommendations for Concrete Pavements with 60- to 100-Year Design Life—Materials

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What Can Be Done Today	What Should Be Done in the Future
Subgrade			
Strength and stability	Section 25	Same as conventional design. Use intelligent compaction.	Same as what can be done today.
Soil stabilization	Section 24	Same as conventional design. Remove and replace frost-susceptible or swelling/collapsing soils or apply soil stabilization. Increase soil stabilization depth more than 2 ft. Use intelligent compaction.	Same as what can be done today.
Base/Subbase			
Type of base/subbase	Section 25, Section 26, Section 27, Section 28, Section 29, Section 30	Do not use AB or LCB without the right interlayer for new base construction. LCB with AC interlayer is allowable. Use dense-graded AC or rubberized gap-graded AC for building the base. Test moisture susceptibility of the AC using the Moisture Induced Stress Tester (MiST) device, following ASTM D7870; retained strength must be at least 75%. Use intelligent compaction.	Develop AC formulations customized for concrete pavement base.
Interlayer for Concrete Overlay on Concrete			
Type of interlayer	Asphalt binder, curing compound, or polyethylene film, following Section 36-2	Use 0.1 ft. AC interlayer for concrete overlay on existing concrete pavements.	Evaluate the use of Type II microsurfacing following Section 37-3.

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What Can Be Done Today	**What Should Be Done in the Future**
Concrete Components—Cementitious Materials			
Cement	Section 90-1.02B(2)	Same as conventional design.	Change the specifications to performance-based specifications, such as ASTM C1157. Remove prescriptive specifications. Add considerations for efficient use of cement (minimize paste content) and use of cement with lower embodied carbon.
SCMs: fly ash/natural pozzolans, slag, silica fume, other	Section 90-1.02B(3)	Remove specified amounts for the minimum cementitious materials. Change requirements to performance-based specifications: • Use reactivity test results: min 90 J/g SCM • 3.5 g of bound water/g SCM • Alkali-silica reaction (ASR) limits following ASTM C1567	Add considerations for the use of SCMs with lower embodied carbon.
Concrete Components—Coarse Aggregate			
Quality includes ASR	Section 40-1.01D(7) and Section 90-1.02C(2) Caltrans Authorization Criteria for Innocuous Aggregates for use in Concrete List (ASTM D1293, ASTM C1260)	Require ASTM C666 for freeze-thaw durability in high-mountain regions.	Develop specifications for the use of low-quality aggregate or recycled concrete aggregate in two-lift paving.
Gradation	Section 90-1.02B&C (Coarse aggregate grading), 90-1.02C (Combined aggregate grading)	Use haystack, shilstone, and tarantula curves to achieve maximum packing and workability by optimizing combined aggregate gradation.	Same as what can be done today.
Concrete Components—Fine Aggregate			
Quality includes ASR	Section 90-1.02C(3) and Caltrans Authorization Criteria for Innocuous Aggregates for use in Concrete List (ASTM D1293, ASTM C1260)	Same as conventional design.	Same as what can be done today.

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What Can Be Done Today	What Should Be Done in the Future
Gradation	Section 40-1.01D(7) and Section 90-1.02C(4)(c) (Fine aggregate grading), 90-1.02C(4)(d) (Combined aggregate grading)	Use haystack, shilstone, and tarantula curves to achieve maximum packing and workability by optimizing combined aggregate gradation.	
Concrete Components—Water			
Water quality	Section 90-1.02D (Water)	Same as conventional design.	Same as what can be done today.
Concrete Components—Chemical Admixtures			
Chemical admixtures	Section 90-1.02E (Admixtures)	Same as conventional design.	Continuously update specification to include new admixtures since SCMs other than slag and fly ash with diverse characteristics are being used in concrete: • Admixtures for rapid set mixtures • Workability retention • Air entrainment for high loss on ignition SCMs • Shrinkage reducing
Mix Design			
Method	Section 40-1.01D(5)	Design based on the paste-to-void volume ratio concept of 1.25, focusing on maximizing aggregate packing and minimizing paste content (24% to 25% excluding % air), depending on aggregate shape and NMAS. Remove specifications for minimum cement content.	Develop low-carbon and durable mix designs for rapid-setting mixtures.
Plastic (Fresh) Portland Cement Concrete			
General	Section 40 and Section 90 (PCC)	Revise specifications to include performance-based tests, such as the Box and VKelly tests, water content, setting time, maturity, and SAM number for areas with freeze-thaw cycling.	Develop performance-based tests to determine finishability, workability retention, and consolidation of mixture by vibration.

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What Can Be Done Today	**What Should Be Done in the Future**
Hardened Portland Cement			
Compressive and flexural strength	Section 40-1.01D(7)(b) and Section 90	Collect both compressive and flexural strength. Require maturity-strength formula.	Develop average values per aggregate and per paste content.
Coefficient of thermal expansion/contraction	Section 40-1-01C(9)	Should be under 5.5x10-6 strain/°F.	Develop regional average values for design.
Drying shrinkage	Section 90-1.01D(3)	Same as conventional design.	Develop a laboratory method that is more representative of drying shrinkage in the field condition. Develop input libraries for design for representative mixtures per region.
Durability	Section 40 and Section 90	Sulfate attack (ASTM C1012) requires a maximum expansion of 0.1%. Chloride permeability testing: minimum of 1000 for the total charge passed (coulombs). Require bulk or surface resistivity. Require a minimum of 8 KΩ-cm. For ASR, run ASTM C1567 used with SCMs and limit the expansion to a maximum of 0.1%.	Develop other durability testing and criteria: • Abrasion resistance • Chain wear resistance • Carbonation rate
Deformed Reinforcing Bars (Continuously Reinforced Concrete Pavement Reinforcement and Tie Bars)			
Material	Section 40-1.02C(4)	Same as conventional design. Use sufficiently corrosion-resistant steel and/or coating commensurate with corrosion risk associated with the climate region and the design life.	Look at other materials.
Load Transfer Dowel Bars (Jointed Plain Concrete Pavement)			
Material	Section 40-1.02C(3)	Same. Use sufficiently corrosion-resistant steel and/or coating commensurate with corrosion risk associated with the climate region and design life.	Look at other materials like FRP and other shapes.

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What Can Be Done Today	What Should Be Done in the Future
Curing			
Curing compound	Section 90-7.01B (six types accepted)	Same as conventional design.	Same as what can be done today.
Other materials	Section 40 and Section 90	Consider other additives such as polymer and cellulose fibers and internal curing agents.	Same as what can be done today.

Notes: AB: aggregate base; LCB: lean concrete base; AC: asphalt concrete; SCM: supplementary cementitious materials; ASR: alkali-silica reaction; NMAS: nominal maximum aggregate size; PCC: portland cement concrete; SAM: super air meter; FPR: fiber-reinforced polymer.

Table 2.2: Recommendations for Concrete Pavements with 60- to 100-Year Design Life—Design

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What can be done today	What should be done in the future
Traffic Loadings			
AADTT initial year	Caltrans procedure in Highway Design Manual (HDM)	Same as conventional design.	Same as what can be done today.
Growth of AADTT	Caltrans Rigid Pavement Design Catalog assumes 3% linear growth annually	Linear growth of 2% to 4% annually based on the best estimate of long-term evolution. Assume truck percentage remains constant. Cap AADT evolution based on highway capacity.	Estimate truck percentage, lane distribution factors, and AADT evolution based on future of freight transport and mobility rather than past traffic.
Axle load distribution	Select Caltrans WIM spectra (1 to 5) that corresponds to the project location	Adopt UCPRC-developed WIM spectra that accounts for potential increase in trucks weight because of transition to zero-emission trucks.	Develop new WIM spectra with improved reliability that accounts for future trucks.
General	Caltrans procedure in HDM	Same as conventional design.	Consider impacts of vehicle automation, including truck platooning and reduced or increased wandering depending on automation programming.
Climate			
Climate	Select Caltrans climate region that corresponds to the project location	Same as conventional design.	Develop climate projections under different scenarios of climate change.
Design Process			
Reliability	95%, following Caltrans HDM	Same as conventional design.	Same as what can be done today.

Procedures and Features	Conventional Design	60- to 100-Year Design Life	
		What can be done today	**What should be done in the future**
Failure criteria	Maximum IRI: 170 in./mi. Maximum transverse cracking (JPCP): 10% Maximum faulting (JPCP): 0.15 in. Maximum number of punchouts (CRCP): 10 per mile	Same as conventional design.	Add longitudinal and third-stage cracking predictions to the JPCP design procedure; conduct JPCP design based on third-stage cracking rather than transverse cracking; develop CRCP mechanistic-empirical performance model.
Slab thickness	Caltrans procedure in HDM	For conceptual design, use web version of Caltrans Rigid Pavement Design Catalog. For final design, use PMED.	Update Caltrans Rigid Pavement Design Catalog with low embodied carbon concrete materials and sustainable practices (e.g. low-lift paving, concrete overlays).
Design Features			
Transverse joint spacing	14 ft.	Same as conventional design.	Same as what can be done today.
Dowel bar diameter	1 to 1.5 in. as specified in Caltrans Standard Plans	Adopt 2 in. dowel bar diameter if PMED faulting or IRI predictions do not meet design criteria.[a]	Same as what can be done today.
Shoulder	Widened slab (14 ft.), tied concrete, or untied shoulder following Caltrans HDM	Adopt 13 ft. widened slab with tied concrete shoulder.[a]	Same as what can be done today.
Tie bar diameter	#6 as specified in Caltrans Standard Plans	Same as conventional design.	Same as what can be done today.
CRCP longitudinal reinforcement—percentage	0.7% as specified in Caltrans HDM and Standard Plans	Same as conventional design.	Same as what can be done today.
CRCP longitudinal reinforcement—vertical placement	Minimum 4 to 5.5 in. concrete cover as specified in Caltrans Standard Plans	Same as conventional design.	Same as what can be done today.

[a] Implementation would require minor changes to Caltrans Standard Plans.

Notes: AADTT: annual average daily truck travel; HDM: *Highway Design Manual*; AADT: average annual daily traffic; WIM: weigh-in-motion; JPCP: jointed plain concrete pavement; CRCP: continuously reinforced concrete pavement; PMED: Pavement ME Design.

Table 2.3: Recommendations for Concrete Pavements with 60- to 100-Year Design Life—Construction

Procedures and Features	Conventional Design	60-Year to 100-Year Design Life	
		What can be done today	What should be done in the future
Contractor Selection, Inspection, and Field Engineering			
Selection	Low bid	Prequalified low bid.	Same as what can be done today.
Inspector and oversight team prequalification	Not required	Prequalification and just-in-time training required.	Same as what can be done today.
Concrete Placement			
Timing	N/A	Avoid paving or adopt specific practices during adverse weather conditions either in cold or warm seasons.	Develop guidelines for concrete paving in adverse weather conditions.
Slab Thickness			
Tolerance	0.05 ft. max deficiency allowed (with penalties at or above 0.01 ft. deficiency)	Same as conventional design.	Same as what can be done today.
Field Tests of Plastic Concrete			
Air content and void system	Air content monitoring only	Same as conventional design.	In high desert and all mountain climate regions, consider testing the quality of the air-voids system using the sequential pressure method (AASHTO TP 118) or similar.
Water-cementitious materials ratio	N/A	Set maximum limit for water-cementitious materials ratio based on mix design. Measure water content following AASHTO T 318.	Same as what can be done today.
Workability	N/A	Consider workability test such as the Box test (AASHTO TP 137), VKelly test (AASHTO TP 129), or similar test.	Same as what can be done today.
Concrete Finishing			
Texture	Burlap or turf drag or broom, followed by longitudinal tining Initial friction >0.30 (California Test 342)	Recommend using grind and groove texturing (also referred to as Next Generation Concrete Surface).	Same as what can be done today.

Procedures and Features	Conventional Design	60-Year to 100-Year Design Life	
		What can be done today	What should be done in the future
Curing			
Concrete temperature	Maintain the concrete pavement surface temperature at not less than 40°F for the initial 72 hours.	In addition, maintain within range for required strength development without premature or delayed set.	Same as what can be done today.
Control loss of moisture	N/A	Same as conventional design.	Consider implementing tool for estimating moisture loss and set moisture loss limit.
Curing compound	Resin-based, white pigmented, curing compound (Type 2B, ASTM C309) applied at a nominal rate of 150 sq ft./gal.	Double application rate (75 sq. ft./gal.).	Same as what can be done today.
Protecting Concrete Pavement			
Protecting concrete pavement	Do not allow traffic or use equipment on concrete pavement before the concrete has attained a modulus of rupture of 550 psi, or equivalent compressive strength if using maturity.	Recommended to use maturity to determine time for opening to traffic.	Determine opening to traffic strength requirements based on project-specific conditions (expected traffic, pavement structure, climate, etc.).
Joint Sawing			
Time	Saw contraction joints before cracking occurs and after the concrete is hard enough to saw without spalling, raveling, or tearing.	In addition to contractor expertise, it is recommended that maturity is used to determine the saw cutting window.	Same as what can be done today.
Joint sealing	Required for new and reconstructed JPCP in all desert and mountain climate regions.	Same as conventional design.	Same as what can be done today.
Field Acceptance			
Deficient concrete	Based on flexural strength on companion beams cured in a sand pit.	Coring and testing of cores are required for petrographic analysis and compressive strength. Flexural strength equivalent should be higher than 85% of the design strength, and no core should be less than 75% of the design strength.	Same as what can be done today.

Procedures and Features	Conventional Design	60-Year to 100-Year Design Life	
		What can be done today	**What should be done in the future**
Smoothness			
Requirements	IRI limits associated with pavement type (JPCP or CRCP) and project type (new alignment, widening, or lane replacement), together with pay adjustment factors.	Select the most demanding IRI limits (Target 60 Smoothness table) regardless of pavement type and project type. If grind and groove texturing is required, consider IRI limits stricter than Target 60 Smoothness table.	Consider implementation of techniques for real time smoothness evaluation during construction.

Notes: JPCP: jointed plain concrete pavement; CRCP: continuously reinforced concrete pavement; IRI: International Roughness Index.

3 QUANTIFICATION OF LIFE CYCLE COST AND ENVIRONMENTAL SAVINGS

3.1 Case Studies

Three case studies were formulated in this study. The three case studies are referred to as "medium traffic volume" (Case Study 1), "high traffic volume" (Case Study 2), and "very high traffic volume" (Case Study 3) in this report. The climate *(11)*, highway configuration, and traffic characteristics of each case have been chosen based on a specific location in the Caltrans highway network (Table 3.1). The medium traffic volume case study corresponds to a rural freeway with two lanes per direction, while the very high traffic volume case study corresponds to one of the busiest locations in the Caltrans road network.

Table 3.1: Case Study Definitions

	Case Study 1 Medium Traffic Volume	Case Study 2 High Traffic Volume	Case Study 3 Very High Traffic Volume
Location	District 3, Yolo County, Route I-505, northbound direction, PM 20.000	District 11, San Diego County, Route I-5, northbound direction, PM R0.500	District 7, Los Angeles County, Route I-5, northbound direction, PM 20.500
Climate	Inland Valley	South Coast	South Coast
Highway Type	Rural freeway	Urban freeway	Urban freeway
Highway Configuration	Two lanes per direction	Four lanes per direction	Four lanes per direction
Traffic Characteristics	Initial AADT (one way): 5,500 with 12.7% trucks	Initial AADT (one way): 35,500 with 3.8% trucks	Initial AADT (one way): 142,500 with 5.0% trucks

3.2 Analysis Period

The analysis period (life cycle) is 100 years for both the LCCA and LCA. Project construction is assumed to occur in 2025.

3.3 Functional Unit

The functional unit of the LCCA and LCA is one lane-mile of JPCP pavement designed for a 40-year, 60-year, or 100-year design life and evaluated for a 100-year analysis period.

3.4 Traffic Growth Hypothesis

The assumptions for the traffic growth hypothesis are as follows:

- The AADT is assumed to grow linearly at a 3% annual rate until reaching highway capacity. The 3% linear growth means that the AADT in year X is the initial AADT (year 0) multiplied by 1 + 0.03*X; in year 100, the AADT is the initial AADT multiplied by 4.

- The maximum AADT (highway capacity) is assumed to be 36,000 vehicles/lane/day in the three case studies. This is roughly the initial AADT for Case Study 3.
- For Case Study 1 and Case Study 2, assuming 3% linear annual growth, the highway does not reach capacity by the end of the 100-year analysis period.
- As stated previously, Case Study 3 corresponds to one of the busiest locations in the Caltrans road network. Since the highway has already reached capacity, further traffic increases would require lane additions. Consequently, traffic growth for Case Study 3 is assumed to be 0%.
- The truck percentage is assumed to remain constant throughout the 100-year analysis period.

3.5 Pavement Design

As part of this study, the web version of the Caltrans Rigid Pavement Design Catalog was updated to allow any design life up to 100 years. The former version of the web tool allowed designs up to 60 years. The web tool uses a database of concrete damage and differential deflection energy generated by using *PMED* (version 2.5.5). The database encompasses the different climates, truck traffic, and design features that can be expected in the Caltrans highway network. Based on *PMED*-generated damage and deflection energy, the web tool calculates predicted transverse cracking, faulting, and IRI by using the *PMED* models' empirical transfer functions.

To update the tool, it was assumed that the rates of concrete damage and differential deflection energy did not continue to decrease after 60 years in service. This hypothesis is illustrated in Figure 3.1, which shows the yearly concrete damage (how much concrete damage increases each year). As shown in the figure, the rate of *PMED*-predicted yearly concrete damage decreases as the pavement ages due to the increase in concrete strength. For updating the web tool, it was assumed that the rate of damage remains unchanged after year 60, a conservative hypothesis that is likely closer to reality than *PMED* predictions.

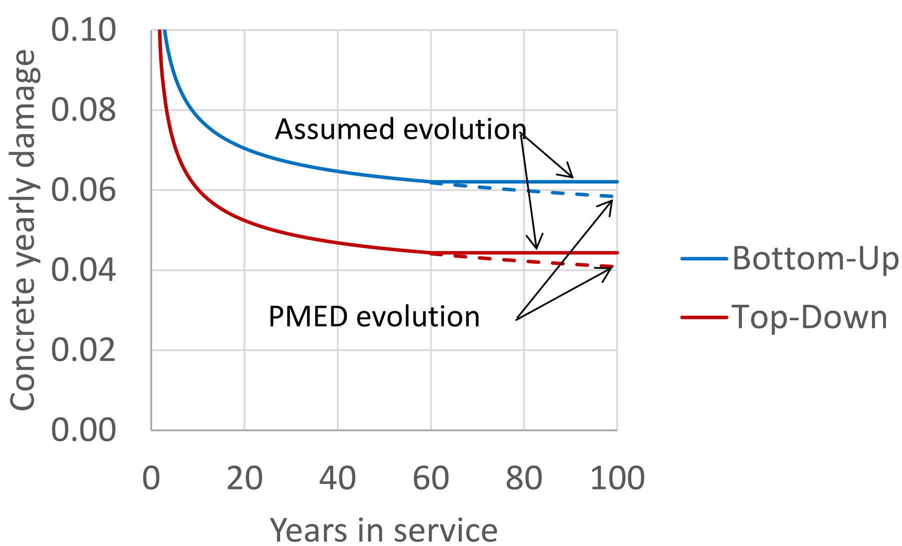

Figure 3.1: Concrete damage evolution.

Once the web tool was updated, it was used to design the pavements in this study. The web tool design hypotheses match the hypotheses behind the development of the Caltrans Rigid Pavement Design Catalog, included in Chapter 620 of the *HDM*. The hypotheses are detailed in a previous UCPRC technical memorandum *(2)*.

Following Caltrans practice, the between-project design reliability was 95%, and the failure criterion was 10% of slabs with transverse cracking, which is roughly equivalent to 3% of slabs with third-stage cracking. The third-stage cracking consists of two or more longitudinal and/or transverse cracks in a slab, frequently two cracks that intersect each other and break the slab into three or more pieces. The initial IRI was assumed to be 67.5 in./mi.

The same underlying structure was assumed in the three case studies:

- Hot mix asphalt (HMA) base: 0.25 ft. The HMA was assumed to be a Superpave mix with 15% reclaimed asphalt pavement (RAP) and 4.0% virgin plain asphalt binder (percent by total weight of mix).
- Crushed aggregate subbase: 0.50 ft.
- Subgrade: clay with low plasticity (CL), according to the Unified Soil Classification System (USCS).

Other design features common to the three case studies include 14 ft. spaced transverse joints with dowels and longitudinal joints with tie bars, following Caltrans practice, and a tied concrete shoulder.

Three design lives were considered for each case study: 40 years (current practice), 60 years, and 100 years. The required slab thicknesses are shown in Table 3.2.

Table 3.2: JPCP Slab Thicknesses

Case Study	40-Year Design Life (ft.)	60-Year Design Life (ft.)	100-Year Design Life (ft.)
Case Study 1 (medium traffic volume)	0.70	0.75	0.80
Case Study 2 (high traffic volume)	0.70	0.75	0.80
Case Study 3 (very high traffic volume)	0.80	0.85	0.90

Currently, the Caltrans thickness design for rigid pavements does not consider the type of concrete. Consequently, the slab thicknesses in Table 3.2 remain unchanged regardless of the type of concrete used for construction. Nonetheless, the type of concrete has a strong impact on the cost and GHG emissions of the initial construction and reconstruction of the concrete pavements. Therefore, for this study, a type of concrete was assumed for each case study's initial construction and reconstruction. The type of concrete was determined as a function of the type of construction expected in each case (e.g., nighttime paving, continuous paving working eight hours a day), which was selected based on the existing traffic. For Case Study 1, initial construction was assumed to be conducted with normal-strength concrete. For Case Study 2 and Case Study 3, initial construction was assumed to be conducted with rapid-strength concrete. For the sake of simplicity, the reconstruction—when applicable—was assumed to be conducted with the same type of concrete used in the initial construction in all three cases. The justification for the type of construction and the corresponding type of concrete is elaborated in Section 3.5.2. In the three case studies, the replacement of individual slabs was assumed to be done with rapid-strength concrete.

It was assumed that the normal-strength concrete was fabricated with portland limestone cement and that the concrete was designed to be opened to traffic (550 psi flexural strength) in 10 days. For the sake of simplicity, no distinction was made between the rapid-strength concrete used in Case Study 2 and Case Study 3. In both cases, it was assumed that the rapid-strength concrete was designed to be opened to traffic in four hours (reaching a 400 psi flexural strength). The same assumption was made for the rapid-strength concrete used for the replacement of individual slabs.

3.5.1 Maintenance, Rehabilitation, and Reconstruction Tables

The maintenance, rehabilitation, and reconstruction schedule is presented for each design life in Table 3.3. It should be noted that the schedule is the same for all three case studies (i.e., the schedule depends only on the design life).

Table 3.3: Schedule of Maintenance, Rehabilitation, and Reconstruction Activities

Action	Year the Action Takes Place (Construction Year is Year 0)		
	40-Year Design Life	60-Year Design Life	100-Year Design Life
1% SR + Grinding	—	—	32
2% SR + Grinding	—	44	76
3% SR + Grinding	41	61	101
4% SR	53	77	—
6% SR + Grinding	68	98	—
8% SR	79	113	—
Reconstruction	87	—	—
3% SR + Grinding	128	—	—

Notes: SR: slab replacement. X% SR means that X% of the slabs are replaced. The grinding is assumed to be blanket grinding.

The maintenance, rehabilitation, and reconstruction schedule included in Table 3.3 for a 40-year design life was developed as part of PPRC Project 3.59, "Updates and Improvements to RealCost-CA." The schedules for the 60-year and 100-year design lives have been developed following the same procedure as in PPRC Project 3.59:

- Set distress thresholds that trigger maintenance, rehabilitation, or reconstruction activities. The thresholds are defined in the Caltrans PMS decision trees. In particular, the following thresholds and actions are applicable to JPCP:

    - 3% third-stage cracking triggers slab replacement, which is minor rehabilitation.
    - 10% third-stage cracking triggers reconstruction, which is major rehabilitation.
    - 170 in./mi. IRI triggers grinding, which is maintenance.
- Predict transverse cracking evolution (transverse cracking versus time). Transverse cracking evolution has been predicted with *PMED* (version 2.5.5).
- Predict third-stage cracking evolution (third-stage cracking versus time). The third-stage cracking was predicted based on *PMED*-predicted transverse cracking using a statistical model that was developed as part of the *PMED* JPCP cracking model calibration for the Caltrans road network *(4)*. The statistical model translates transverse cracking into third-stage cracking.
- Calculate years to each slab replacement operation. This calculation is straightforward once the thresholds are set and the third-stage cracking evolution has been predicted. It is assumed that the replaced slabs will last for 10 years.
- Estimate the IRI at each slab replacement operation. The IRI is predicted by using the appropriate roughness performance statistical model from the Caltrans PMS.
- Define the need to conduct grinding at each slab replacement operation. The goal of the grinding schedule is to ensure that the IRI always remains below 170 in./mi. The grinding is assumed to result in an IRI drop of 40%, with a minimum of 60 in./mi.

As shown in Table 3.3, 1% and 2% slab replacement thresholds have been added to the 100-year designs, compared with the 40-year designs. The reason for adding the two thresholds is that it does not seem realistic to assume that no intervention will be done in 100 years. If the design period is 100 years, the elapsed time between 1% and 3% cracking is 70 years. Most likely, Caltrans would complete a slab replacement project to fix the cracked slabs and a grinding operation to restore the lost smoothness. The 60-year design assumptions fall between the assumptions for the 40-year and 100-year designs.

3.5.2 Traffic Closures

Traffic closures impact the LCCA and LCA because of the costs and environmental impacts associated with the CWZ. As explained in the introduction, the main CWZ impacts, which are the impacts considered in this study, are traffic delays and an increase in fuel consumption. The former has an associated cost, while the latter has both an associated cost and environmental impact.

It was assumed that the traffic closures for the initial construction and the reconstruction of the pavement were conducted as follows:

- Case Study 1 (medium traffic volume, two lanes per direction): Full-day lane closure, working 8 hours a day; need to shut down two lanes to provide access to the contractor (traffic counterflow on the other roadbed). This construction operation is compatible with the use of normal-strength concrete.

- Case Study 2 (high traffic volume, four lanes per direction): Full-day lane closure, working 24 hours a day to minimize closure duration; need to shut down two lanes to give access to the contractor while two lanes remain open. This construction operation is compatible with the use of rapid-strength concrete.
- Case Study 3 (very high traffic volume, four lanes per direction): Nighttime closure, 10 hours; need to shut down two lanes to give access to the contractor while two lanes remain open. The overnight construction was selected because of the very high traffic, which would make extended closures and detours extremely difficult. This construction operation requires rapid-strength concrete.

The traffic closures for slab replacement and grinding are assumed to be conducted as follows:

- All case studies: Nighttime closure, 10 hours. This construction operation requires the use of rapid-strength concrete for the slab replacement.

The construction duration is the number of days it takes to complete an activity for one lane-mile under the given traffic closure condition. It was calculated using the productivity rate (lane-mile/closure) for each activity, as shown in the LCCA Procedure Manual (*12*). The durations for each activity for the three cases are shown in Table 3.4**Error! Reference source not found.**.

Table 3.4: Duration of Initial Construction, Maintenance, Rehabilitation, and Reconstruction Activities

Action	Number of Work Days of CWZ Per Lane-Mile		
	40-Year Design Life	60-Year Design Life	100-Year Design Life
	Case 1 (Medium Traffic Volume)		
Initial Construction	20	20	20
1% SR + Grinding	—	—	2
2% SR + Grinding	—	2	2
3% SR + Grinding	2	2	—
4% SR	2	2	—
6% SR + Grinding	2	2	—
8% SR	2	—	—
Reconstruction	20	—	—
	Case 2 (High Traffic Volume)		
Initial Construction	2	2	2
1% SR + Grinding	—	—	2
2% SR + Grinding	—	2	2
3% SR + Grinding	2	2	—
4% SR	2	2	—
6% SR + Grinding	2	2	—
8% SR	2	—	—
Reconstruction	2	—	—

Action	Number of Work Days of CWZ Per Lane-Mile		
	40-Year Design Life	60-Year Design Life	100-Year Design Life
	Case 3 (Very High Traffic Volume)		
Initial Construction	20	20	20
1% SR + Grinding	—	—	2
2% SR + Grinding	—	2	2
3% SR + Grinding	2	2	—
4% SR	1	2	—
6% SR + Grinding	2	2	—
8% SR	2	—	—
Reconstruction	20	—	—

For Case Study 1, with medium traffic volume, the initial construction activity requires 20-day continuous traffic closures, including 10 days of construction and 10 days of curing duration, to complete one lane-mile of concrete. The productivity rate of the initial construction was assumed to be 0.10 lane-miles every 8-hour closure.

For Case Study 2, with high traffic volume, the initial construction activity requires 2-day continuous traffic closures to complete rapid-strength concrete for one lane-mile, assuming that a contractor uses maximum resources and access and completes 0.5 lane-miles in 24 hours.

For Case Study 3, with very high traffic volume, the initial construction activity requires 20 instances of 10-hour night closures. The productivity rate was as low as 0.05 lane-mile/10-hour night closure, as a contractor needs time for mobilizing/demobilizing equipment and traffic control devices each night and for allowing rapid-strength concrete curing time. The same productivity rates were used for the 40-year, 60-year, and 100-year design lives, as the differences in concrete thickness are only 0.05 between each design life.

As rapid-strength concrete is used for Case Study 2 and Case Study 3, extra traffic closure days for curing time are unnecessary. While a contractor demobilizes construction equipment and traffic control devices, the rapid-strength concrete reaches the strength level that can handle traffic loads.

The CWZ study also assumed that 5% of the traffic was detoured and that 5% would not show due to the presence and/or anticipation of the traffic closure.

3.6 Life Cycle Cost Analysis

3.6.1 Scope

The schedule of maintenance, rehabilitation, and reconstruction activities throughout the 100-year analysis period is shown for each of the three design lives in Table 3.3. The LCCA conducted in this study is a comparative analysis where the use and end-of-life stages are not included. “Salvage” costs have been deducted for the last treatment before the 100-year analysis period. The cost deduction assumes a linear depreciation over the treatment's life, where the treatment's life is the time to the next treatment (the first one after 100 years).

3.6.2 Assumptions, Data, and Sources

The Caltrans LCCA Procedure Manual (*12*) and Caltrans Contract Cost Database (*13*) were used to determine the agency and road user costs for each activity shown in Table 3.3. Additional travel time due to the CWZ causing traffic delays—including idling, waiting in queues, or traffic slowdowns—is considered as a road user cost in this LCCA. A cost of $16.20/hour and $35.90/hour was used for passenger car and commercial truck times, respectively. The excess fuel consumption was also converted to a user cost. A cost of $4.50/gallon was used for both gasoline and diesel. For simplicity, it was assumed that the costs of electric vehicle charging and hydrogen fuel cell replenishment would be the same as those for gas and diesel.

The CWZ length is one mile, and the assumed posted speed limit at the CWZ is 55 mph, which is 10 mph lower than the posted speed limit when there is no CWZ and upstream and downstream of the CWZ. The assumed base traffic capacity values were 2,300 and 1,600 passenger cars per hour per lane for multi-lane and single-lane configurations, respectively. The actual traffic capacities were adjusted from the base traffic capacity by the proportion of heavy vehicles and the passenger car equivalent factor of 2.0, which counts one heavy vehicle as equivalent to two passenger cars in the capacity calculation.

The material unit costs were collected from the Caltrans Contract Cost Database (*13*) for the past five years based on the activity size. The unit costs of the materials took into account the activity size; specifically, as the quantity of material increases, its unit cost decreases.

The unit prices assumed for rapid-strength concrete, normal-strength concrete, HMA, and aggregate subbase in the initial construction and reconstruction were $420/yd^3, $280/yd^3, $150/ton, and $120/yd^3, respectively. The same unit prices were used for all three cases. However, the different unit prices for slab replacement were selected based on the quantity of slab replacement, shown in Table 3.5. The unit cost of grinding activity was assumed to be $71,217/lane-mile, collected from the Caltrans 2020 State of the Pavement Report (*14*).

Table 3.5. Unit Cost of Slab Replacement by Quantity Group

Quantity of Slab Replacement (yd^3)	Unit Cost of Slab Replacement ($/yd^3)
0~400	$1,600
401-600	$1,150
600-800	$1,050
>801	$500

The cost of each activity was calculated from the pavement material cost multiplied by an indirect cost multiplier of 1.75. The indirect cost multiplier reflects the costs of engineering, traffic handling, headquarters support, project management, and contingency. The agency and road user costs of future maintenance, rehabilitation, and reconstruction activities were converted to the present value by applying an annual discount rate of 3.2%.

3.6.3 Life Cycle Cost Results

The agency cost due to the initial construction, maintenance, rehabilitation, and reconstruction of the pavement is shown in Table 3.6 for each case study and design life. The cost has been split into two components: (1) Agency–Initial (which includes the cost of the initial construction) and (2) Agency–M&R (which includes the costs of the maintenance, rehabilitation, and—if applicable—reconstruction, including the salvage value discount at 100 years). The figures in Table 3.6 do not include the CWZ road user cost. The agency cost data are also shown in Figure 3.2 and Figure 3.3. In Figure 3.3, the cost numbers have been normalized by the Agency Cost–Initial of the 40-year design life pavement of each case study.

Table 3.6: Life Cycle Agency Cost Per Lane-Mile

	40-Year Design Life ($/lane-mile)	60-Year Design Life ($/lane-mile)	100-Year Design Life ($/lane-mile)
	Case 1 (Medium Traffic Volume)		
Agency Cost–Initial	$1,353,000 (100%)[a]	$1,410,000 (104%)	$1,468,000 (108%)
Agency Cost–M&R	$219,000 (16%)	$103,000 (8%)	$61,000 (5%)
	Case 2 (High Traffic Volume)		
Agency Cost–Initial	$1,755,000 (100%)	$1,841,000 (105%)	$1,928,000 (110%)
Agency Cost–M&R	$239,000 (14%)	$103,000 (6%)	$61,000 (3%)
	Case 3 (Very High Traffic Volume)		
Agency Cost–Initial	$1,928,000 (100%)	$2,014,000 (104%)	$2,100,000 (109%)
Agency Cost–M&R	$265,000 (14%)	$110,000 (6%)	$65,000 (3%)
	Average—Three Cases		
Agency Cost–Initial	$1,679,000 (100%)	$1,755,000 (105%)	$1,832,000 (109%)
Agency Cost–M&R	$241,000 (14%)	$105,000 (6%)	$62,000 (4%)
	Average—Three Cases		
Agency Cost–Life Cycle (Initial + M&R)	$1,920,000 (100%)	$1,860,000 (97%)	$1,894,000 (99%)

[a] The figures in parentheses are % cost normalized to Agency Cost–Initial of the 40-year design life. For example, the 8% Agency Cost–M&R in Case 1 (60-year design life) corresponds to $103,000/$1,353,000.

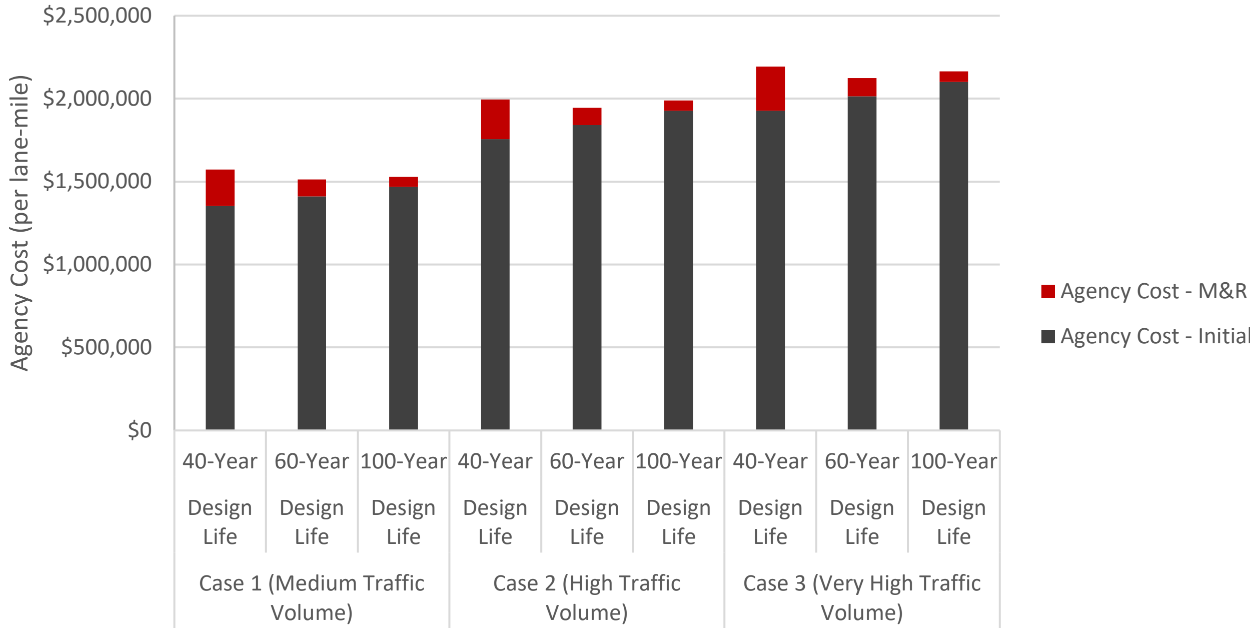

Figure 3.2. Life cycle agency cost.

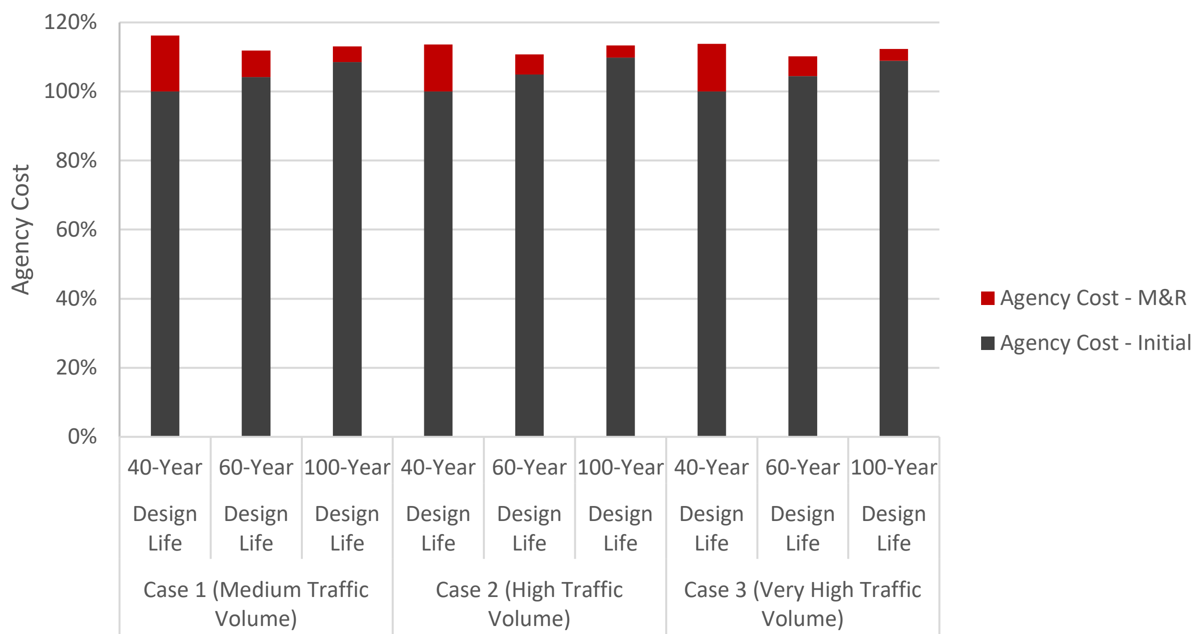

Figure 3.3. Life cycle agency cost, % (normalized to Agency Cost–Initial of the 40-year design life).

The main conclusions from Table 3.6, Figure 3.2, and Figure 3.3 are the following:

- The initial agency costs for 40-year, 60-year, and 100-years design lives are, respectively, $1.68 million, $1.76 million, and $1.83 million per lane-mile. These numbers are averages across the three case studies.
- The increase in pavement design life from 40 years to 60 years and 100 years carries an increase in initial agency cost of around 5% and 9%, respectively.

- The life cycle agency costs (Initial + M&R) for the 40-year, 60-year, and 100-year design lives are, respectively, $1.92 million, $1.86 million, and $1.89 million per lane-mile. These numbers are averages across the three case studies.
- The increase in pavement design life from 40 years to 60 years and 100 years carries a reduction in life cycle agency cost (Initial + M&R) of around 3% and 1%, respectively.
- The costs normalized versus the initial agency cost (shown in Figure 3.3 and also in parentheses in Table 3.6) varied little from one case study to another. For example, the increase in pavement design life from 40 years to 100 years carries an increase of the initial agency cost of 4% for Case Study 1 and Case Study 3 and 5% for Case Study 2. Consequently, the conclusions regarding the percent change in cost due to the changes in design life are roughly the same for the three case studies.

The CWZ road user costs are shown in Table 3.7. The Table 3.7 numbers include the cost of the increase in travel time and the cost of the excess fuel or energy consumption that result when the road users are affected by the initial construction, maintenance, rehabilitation, and reconstruction activities. While case-study-dependent, the increase in design life from 40 years to 60 years and 100 years carries a considerable reduction in road user cost throughout the 100-year design period considered in this LCCA. Road user cost was also subject to salvage value calculations where the life of the activity that caused the road user cost extended past the end of the 100-year analysis period.

Table 3.7: CWZ Road User Cost Per Lane-Mile

40-Year Design Life ($/lane-mile)	60-Year Design Life ($/lane-mile)	100-Year Design Life ($/lane-mile)
Case Study 1 (Medium Traffic Volume)		
$176,000	$11,000	$11,000
Case Study 2 (High Traffic Volume)		
$190,000	$7,000	$5,000
Case Study 3 (Very High Traffic Volume)		
$585,000	$529,000	$526,000

3.7 Life Cycle Assessment

3.7.1 Scope

The schedule of maintenance, rehabilitation, and reconstruction activities throughout the 100-year analysis period is shown in Table 3.3 for each of the three design lives. The LCA conducted in this study is a comparative cradle-to-grave analysis (A1 to C4, in terms of ISO 21930 terminology) where the use and end-of-life stages are not included, except for the CWZ part of the use stage, which is included. "Salvage" GWP values have been deducted for the last treatment before the end of the 100-year analysis period. The GWP deduction assumes a linear depreciation over the life of the treatment, where the life of the treatment is the time to the next treatment (the first one after 100 years).

Excess fuel consumption due to the CWZ causing traffic delays—including idling, waiting in queues, or traffic slowdowns—is considered in this LCA. The excess fuel consumption is the additional fuel consumption affecting vehicle GHG emissions beyond normal operations. GHG emissions from excess fuel consumption were simplistically reduced beyond 2025 to roughly reflect reductions in GHG as cars and trucks in the fleet are replaced with electric and hydrogen fuel cell alternatives. The simplification consisted of applying a reduction factor to the GHG emissions obtained under the assumption that all cars and trucks are gasoline or diesel-fueled vehicles. The reduction factor was assumed to be 1 (no reduction) in 2025 and to decrease linearly over time until zeroing in 2060. After 2060, it was assumed that the GHG emissions from car and truck operations are zero. The GWP was quantified, using *TRACI (15)*, in terms of CO_2 equivalent (CO2e) mass.

3.7.2 Assumptions, Data, and Sources

The Caltrans *environmental Life Cycle Assessment for Pavement* (*eLCAP*) tool (version 1.0) *(16)* was used to determine the GWP for each of the life cycle activities shown in Table 3.3. The life cycle inventory (LCI) data used for this study was acquired from the Caltrans LCI report *(17)*. The CWZ impacts were calculated following a previously developed methodology *(18)*. The fuel types and quantities used at the corresponding plant for producing the HMA and concrete are shown in Table 3.8.

Table 3.8: Fuel Type and Quantities to Produce 1 kg of Material

Fuel Type	Units	HMA (asphalt plant)	Concrete (concrete plant)
Electricity	kWh	3.66 E-03	1.72 E-03
Diesel	m^3	0	2.54 E-07
Natural gas	m^3	8.75 E-03	1.22 E-04

The electricity mix was modeled in *eLCAP* using the 2023 California grid mix data acquired from the US Energy Information Administration (Table 3.9). Grid losses of 5% were assumed. For simplicity, the grid mix was not updated over the analysis period due to the study's scope limitations. This results in an overestimation of the GHG emissions for materials production. However, electricity is neither the largest nor the second-largest contributor to GHG emissions in pavement materials production.

Table 3.9: Electricity Grid Mix for California in 2023

Source	Quantity of Total Electricity Grid Mix (%)
Biogas	0.57
Biomass	2.00
Geothermal	4.49
Hard Coal	0.09
Heavy Fuel Oil	0.03
Hydropower	12.76
Natural Gas	38.58
Nuclear	7.25
Photovoltaics and Solar Thermal	28.16
Wind	6.10
Total	**100**

Source: US Energy Information Administration (n.d.) *(19)*.

Other assumptions of the LCA conducted in this study are the following:

- The type of HMA assumed for the base is described in Section 3.5.
- The type of concrete assumed for initial construction, slab replacement, and reconstruction in each of the three case studies is described in Section 3.5.
- It was assumed that concrete produced from slab removal, which is usually recycled concrete aggregate, and the dust/debris generated from diamond grinding were transported to the nearest concrete plant or landfill site located 10 miles from the construction site.
- The RAP was assumed to be stockpiled at the asphalt plant. Consequently, no transportation impacts are associated with the use of this material. However, electricity energy and diesel consumption are required for handling and processing the RAP at the plant.
- All materials that include aggregate (subbase, HMA, and concrete) were assumed to be transported from plants or facilities located 25 miles away from the construction site.
- Caltrans rapid-strength concrete for overnight paving and slab replacement is typically made with one of two cement types: Type III portland cement and belitic calcium sulfoaluminate cement. These two cements have different embodied carbon and different environmental impacts. However, for simplification and to reduce the number of cases in the LCA calculations, it was assumed that the GHG emissions associated with the manufacturing of the rapid-strength concrete are the average of the numbers estimated for each of the two cements.

It should be clarified that the impacts quantified in this study refer to indirect emissions. These include emissions from the production and combustion of fuels used in the unit processes throughout the life cycle of material production. The direct emissions that arise in a concrete plant or from grinding pavement surfaces are not included in this analysis. Natural carbonation of concrete pavement over the design life or at the end of life was not considered in the study.

3.7.3 Life Cycle GWP Results

The GWP resulting from the initial construction, maintenance, rehabilitation, and reconstruction of the pavement is shown in Table 3.10 for each case study and design life. The GWP has been split into two components: (1) Infrastructure–Initial (which includes the embodied carbon from the initial construction) and (2) Infrastructure–M&R (which includes the embodied carbon from maintenance, rehabilitation, and, if applicable, reconstruction). The figures in Table 3.10 do not include the GWP from road users.

The GWP data are also shown in Figure 3.4 and Figure 3.5. In Figure 3.5, the GHG emissions have been normalized by the Infrastructure–Initial of the 40-year design life pavement of each case study.

Table 3.10: Infrastructure (Embodied Carbon) Global Warming Potential

	40-Year Design Life (kg CO2e/lane-mile)	60-Year Design Life (kg CO2e/lane-mile)	100-Year Design Life (kg CO2e/lane-mile)
	Case Study 1 (Medium Traffic Volume)		
Infrastructure–Initial	421,000 (100%)[a]	442,000 (105%)	464,000 (110%)
Infrastructure–M&R	248,000 (59%)	58,000 (14%)	20,000 (5%)
	Case Study 2 (High Traffic Volume)		
Infrastructure–Initial	616,000 (100%)	654,000 (106%)	691,000 (112%)
Infrastructure–M&R	310,000 (50%)	58,000 (9%)	20,000 (3%)
	Case Study 3 (Very High Traffic Volume)		
Infrastructure–Initial	691,000 (100%)	729,000 (105%)	767,000 (111%)
Infrastructure–M&R	350,000 (51%)	66,000 (10%)	22,000 (3%)
	Average of Three Case Studies		
Infrastructure–Initial	576,000 (100%)	608,000 (106%)	641,000 (111%)
Infrastructure–M&R	303,000 (53%)	61,000 (11%)	21,000 (4%)
	Average of Three Case Studies		
Infrastructure–Life Cycle (Initial + M&R)	879,000 (100%)	669,000 (76%)	662,000 (75%)

[a] In parenthesis, GWP normalized to Infrastructure–Initial of the 40-year design life; for example, the 14% Agency Cost–M&R in Case Study 1 (60-year design) corresponds to 58,000/421,000.

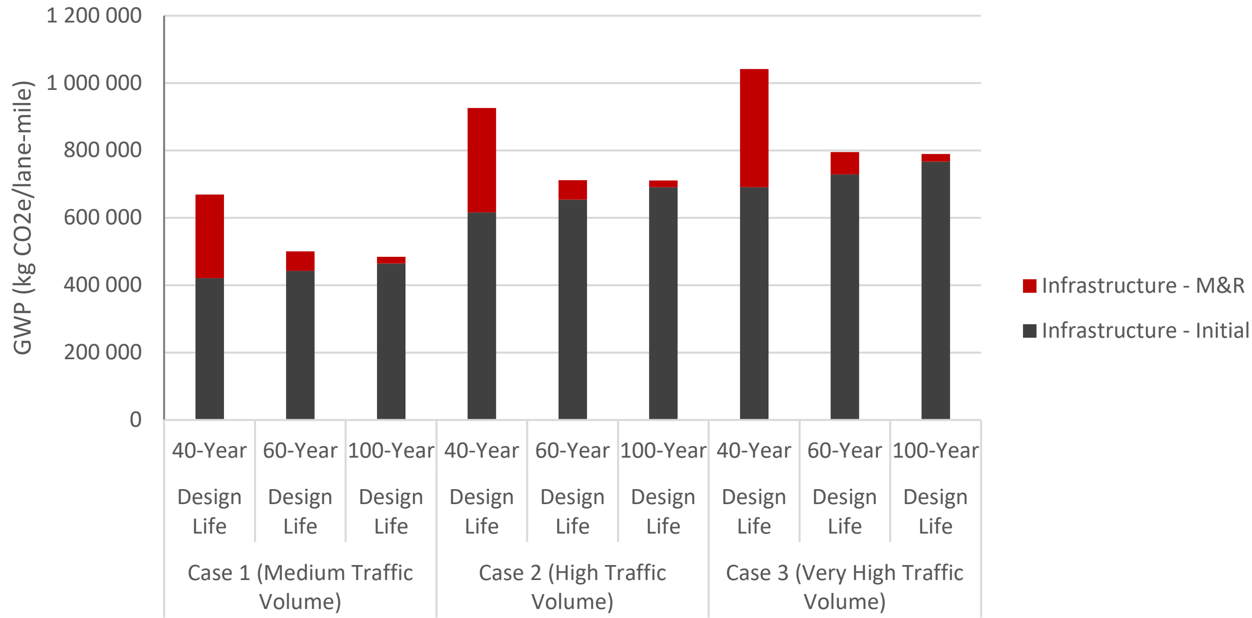

Figure 3.4: Infrastructure (embodied carbon) GWP (kg CO2e/lane-mile).

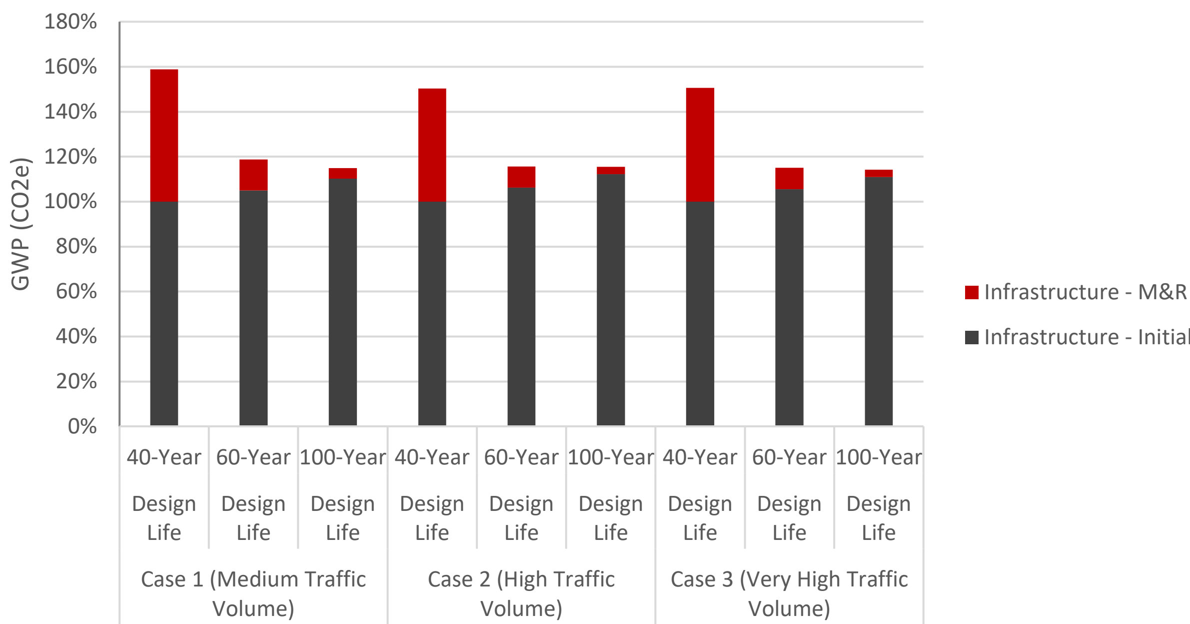

Figure 3.5. Infrastructure (embodied carbon) GWP, %
(normalized to Infrastructure–Initial of the 40-year design life).

The main conclusions from Table 3.10, Figure 3.4, and Figure 3.5 are the following:

- The initial infrastructure GWP for the 40-year, 60-year, and 100-year design lives is, respectively, 576, 608, and 641 metric tons (MT) of CO2e per lane-mile. These figures are averages across the three case studies.
- The increase in pavement design life from 40 years to 60 years and 100 years carries an increase in the initial infrastructure GWP of around 6% and 11%, respectively.
- The life cycle infrastructure GWP for the 40-year, 60-year, and 100-year design lives is, respectively, 879, 669, and 662 MT of CO2e per lane-mile. These numbers are averages across the three case studies.
- The increase in pavement design life from 40 years to 60 years and 100 years carries a reduction in life cycle infrastructure GWP (Initial + M&R) of around 24% and 25%, respectively.
- The normalized GWP results (shown in Figure 3.5 and also in parentheses in Table 3.10) varied little from one case study to another. For example, the increase in pavement design life from 40 years to 100 years carries an increase in initial infrastructure GWP of 10% for Case Study 1, 12% for Case Study 2, and 11% for Case Study 3. Consequently, the conclusions regarding the percent change in GWP due to the changes in design life are roughly the same for the three case studies.

The CWZ GWP is presented in Table 3.11. The figures in Table 3.11 represent the GHG emissions resulting from excess fuel consumption by road users affected by the initial construction, maintenance, rehabilitation, and reconstruction activities. The CWZ GWP from the initial construction was calculated by assuming that all cars are gas-powered vehicles. However, the CWZ GWP from maintenance, rehabilitation, and reconstruction activities—all of which take place after 2025—was calculated by considering the transition of cars and trucks to zero-emission technologies, following the simplified approach described in Section 3.7.1. Since most of the maintenance, rehabilitation, and reconstruction activities take place when the transition to zero-emission technologies is very advanced or fully accomplished, the CWZ GHG figures in Table 3.11 come mainly from the initial construction CWZ. Consequently, because the CWZ impacts of the initial construction are the same for the three design lives, the figures in Table 3.11 are roughly the same for all three design lives. In other words, the design life (ranging from 40 years to 100 years) did not affect the CWZ GWP.

The CWZ GWP is negative for Case Study 1 and Case Study 2 (Table 3.11). This means that the CWZ impact is beneficial in terms of GWP. This outcome is due to the combination of two facts: (1) the capacity of the CWZ is higher than the traffic demand, and consequently, the only CWZ impact is that vehicles travel at 55 mph (CWZ reduced speed limit) instead of 65 mph (speed limit outside the CWZ), and (2) fuel and energy consumption for cars and trucks is lower at 55 mph than at 65 mph.

Table 3.11: Construction Work Zone Excess Fuel Consumption Global Warming Potential

40-Year Design Life (kg CO2e/lane-mile)	60-Year Design Life (kg CO2e/lane-mile)	100-Year Design Life (kg CO2e/lane-mile)
Case Study 1 (Medium Traffic Volume)		
-300	-300	-300
Case Study 2 (High Traffic Volume)		
-500	-500	-500
Case Study 3 (Very High Traffic Volume)		
69,200	69,200	69,800

3.8 Discussion of Life Cycle Cost Analysis and Life Cycle Assessment Results

The LCCA and LCA presented in the previous section indicate that increasing the concrete pavement design life from 40 years (current practice) to 60 years or 100 years would carry savings in terms of agency costs and infrastructure GWP throughout the 100-year analysis period. The average results (the average of the three case studies) are summarized in Figure 3.6.

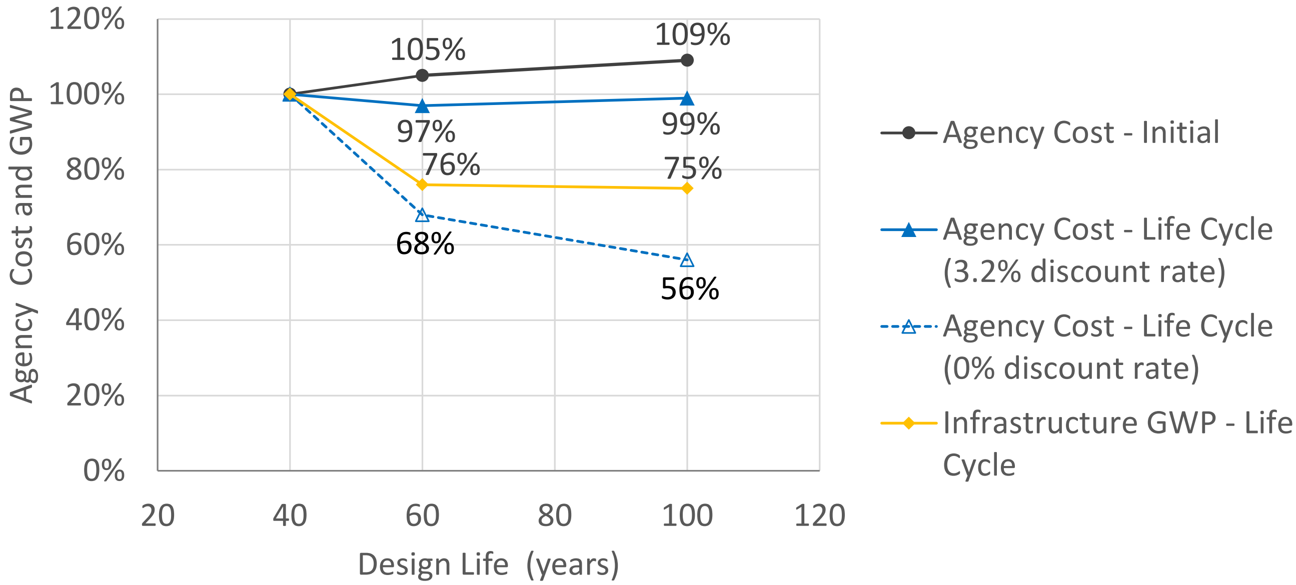

Figure 3.6. Agency cost and Infrastructure GWP versus design life.

The life cycle infrastructure GWP savings (without considering CWZ) are significant at 24% when the design life increases from 40 years to 60 years (Figure 3.6). Most of the savings are due to the elimination of the year 87 reconstruction activity that is required with the 40-year design. However, only an additional 1% savings are expected when the design life increases from 60 years to 100 years. The reason for the small savings is that the reconstruction activities occur after the 100-year analysis period adopted in this study.

The life cycle agency cost decreases by only 1% to 2% when the design life increases from 40 years to 60 years or 100 years (Figure 3.6). This reduction is strongly dependent on the discount rate, which was assumed to be 3.2%. For example, the cost of the reconstruction required for the 40-year design in year 87 is reduced by a factor of 15.5 (15.5 = 1.032^87) to determine the net present value (i.e., net present value = future cost divided by 15.5). Consequently, the cost of the reconstruction in year 87 has very little impact on the life cycle agency cost. The same applies to all costs that take place in the second half of the 100-year analysis period. The discount rate effect is the reason why the life cycle agency cost savings that result from increasing the design life are only 2% to 3%. On the contrary, if a discount rate of 0% is assumed, supported by the fact that Caltrans does not borrow funding to pay for M&R but instead uses pay-as-you-go tax funding, the increase in pavement design life from 40 years to 60 years and 100 years would carry a reduction in life cycle agency cost of around 32% and 44%, respectively (Figure 3.6).

Based on the life cycle agency cost and infrastructure GWP (without considering CWZ), the design life of 40 years for concrete pavements may not be optimal. In fact, considerable savings are expected if the design life increases from 40 years to 60 years: 3% life cycle agency cost and 24% life cycle GWP savings. Nonetheless, the savings expected from increasing the design life from 60 years to 100 years do not appear to be significant. CWZ road user cost savings are also expected when the design life increases from 40 years to 60 years (Table 3.7). Again, cost savings are very small when the design life increases from 60 years to 100 years. Increasing the concrete pavement design life from 40 years to 60 years is expected to result in an increase in the initial agency cost of 5%. It should be mentioned that the 5% refers only to the cost of the pavement. Since the cost of the pavement is a fraction of the typical construction project, the expected impact on the project cost is lower than 5%.

The design life impact on the life cycle agency costs and infrastructure GWP did not vary much, in relative terms, across the three case studies, despite the case studies having very different AADTs. Consequently, it is believed that the previous discussion is broadly applicable across different traffic conditions.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

A comprehensive review of the Caltrans *HDM*, concrete pavement design method, and Standard Specifications related to concrete pavements has been conducted in this study. Based on that review, a collection of recommendations for concrete pavements with design lives of up to 100 years has been formulated. The recommendations are based on the authors' existing knowledge and tools that are already available. These recommendations have been grouped into materials (Table 2.1), design (Table 2.2), and construction (Table 2.3), and they are included in the "What can be done today" column of the tables to address the following question: How should the materials, design, and construction of a concrete pavement with an extended long-life design differ from a conventional concrete pavement? The limitations and what needs to be done in the future are also provided in the tables.

This study includes the LCCA and LCA of three case studies with characteristics corresponding to three specific locations on the Caltrans highway network. The case with the lowest AADT corresponds to a rural freeway with two lanes per direction, while the case with the highest AADT corresponds to one of the busiest locations in the Caltrans road network. For each of the three case studies, three design lives have been adopted: 40 years (current Caltrans practice), 60 years, and 100 years. The corresponding thicknesses, assuming pavements are JPCP, were determined using the web version of the Caltrans Rigid Pavement Design Catalog. The LCCA and LCA were then conducted to determine the corresponding life cycle costs and GWPs. The analysis period was set to 100 years.

The results show that the design life of 40 years may not be the optimum for concrete pavements. In fact, some cost and significant life cycle GWP savings are expected if the design life increases to 60 years, while little additional benefit was found in increasing the design life from 60 years to 100 years. The following conclusions are based on the research results:

- The increase in concrete pavement design life from 40 years to 60 years and 100 years required an increase in concrete thickness of 0.05 ft. and 0.1 ft., respectively. That thickness increase resulted in an increase in the initial agency cost of around 5% for the 60-year design and 9% for the 100-year design.
- Increasing the design life from 40 years to 60 years resulted in a reduction of about 3% in life cycle agency cost savings and 24% in life cycle GWP. Most of the GWP reduction was due to the elimination of the year 87 reconstruction activity that is required with the 40-year designs.
- On the other hand, the savings expected when the design life increased from 60 years to 100 years were not that high: an increase of about 2% in life cycle agency cost and a reduction of 1% in life cycle GWP (compared with the 60-year design). The reason for the small savings is that the reconstruction activities for the two design lives lie beyond the end of the 100-year analysis period adopted in this study.

- The 3.2% discount rate assumed for the LCCA had a tremendous impact on the results. Because of the discount rate, the costs incurred in the second half of the 100-year analysis period had almost no effect on the life cycle cost. If a discount rate of 0% is assumed, the increase in pavement design life from 40 years to 60 years and 100 years would carry a reduction in life cycle agency cost of around 32% and 44%, respectively. The fact that Caltrans does not borrow funding to pay for M&R but instead uses pay-as-you-go tax funding supports the use of the 0% discount rate.
- The CWZ impacts in terms of cost (time and excess fuel consumption) were reduced when the design life increased from 40 years to 60 years. The expected reduction was much smaller when the design life increased from 60 years to 100 years.
- The conclusions listed above are applicable to the three case studies, despite their very different AADTs.

4.2 Recommendations

The following are suggested recommendations:

- Based on the LCA and LCCA studies of the three cases, there is evidence that extending the design life up to 60 years offers important life cycle savings, mainly in terms of life cycle environmental impacts and some cost savings. The results for design lives of 100 years show little or no improvement over the 60-year design life results. Given these results, the limitations of the current design procedure, the shortcomings of durability models, and the unknowns about materials, it is recommended that, at this time, the design life is not extended beyond 60 years.
- It is recommended that Caltrans develop non-standard special provisions (nSSPs) applicable to concrete pavements with a 60-year design life that implement the recommendations formulated in Table 2.1, Table 2.2, and Table 2.3 in the "What can be done today" column.
- Instead of mandating a statewide design life of 60 years, Caltrans can allow designers to choose a design life of 40 years or 60 years and make the final decision based on LCCA and LCA on a case-by-case basis, considering that the case studies included in the scope of this study were not exhaustive. The LCCA and LCA should include the impacts on road users associated with the CWZ activities. The following are recommendations to improve the validity of the LCCA and LCA:
  - Additional case studies of highways slated for reconstruction can continue to build on the findings of this initial study and provide a stronger basis for making more definitive revisions to the current design practice.
  - Better assumptions regarding changes in the vehicle fleet fuel (from fossil fuels to electric and hydrogen fuel cells) should be developed for better CWZ analyses.

    - Better assumptions regarding future electric power generation should also be developed for materials production and CWZ analyses.

- The following actions are recommended before considering extending the design life to 100 years:
    - The performance of JPCPs older than 60 years following modern engineering and design in other states should be reviewed.
    - It is recommended that this study be updated every five years as the sustainability aspects advance, both in terms of modeling and practice, and as the effect of electrification on axle loads and GHG emissions becomes clearer.
    - It is also recommended that this study be reviewed by industry and trade associations for their input and perspective before changes are made to the current design practice.
    - This study identifies limitations of the current practice of concrete pavement materials, design, and construction that cannot be resolved with current knowledge and tools. For those limitations, recommended strategies are proposed in this report (the "What should be done in the future" column of Table 2.1, Table 2.2, and Table 2.3). It is recommended that Caltrans consider the current limitations and recommendations and put effort into addressing those strategies in future research requests and contracts. The outcome will be to more accurately predict the performance of pavements, especially for longer lives, and the ability to further optimize the pavements and enhance their sustainability.
    - LCCA guidelines should be updated to support longer design life in the following ways:
        - The same analysis period should be used when comparing design alternatives—for example, between asphalt, concrete, and cold recycling pavement alternatives.
        - The discount rate value is extremely critical in the LCCA results. Caltrans needs to review the discount rate. Using the current 3.2%, any activities that occur in the second half of the 100-year analysis period result in negligible effects on LCCA results.

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