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UCPRC Life Cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance

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Partnered Pavement Research Center (PPRC) Contract Strategic Plan Element 4.26:
Studies to Support Global Climate Change Initiative

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Abstract: This report describes a pavement life cycle assessment (LCA) model developed to initially evaluate total energy use and greenhouse gas (GHG) emissions from pavement maintenance and rehabilitation (M&R) strategies. This LCA model allows analysis of the energy consumption and GHG emissions associated with material production, construction, and vehicle operation during pavement use, which includes the effects of pavement roughness and texture on vehicle operation; at this time the model does not include the effects of pavement deflection. Other types of treatments and the materials used for them, as well as other effects of the pavement on the environment in the pavement Use Phase will be considered in future studies. The model was used to evaluate four case studies of Caltrans pavement preservation treatments for both asphalt and concrete surfaces with different roughness and texture and traffic levels. The case studies were performed to provide a preliminary indication of the net effect of changing the roughness and texture on the analysis period performance of pavements, not to compare asphalt and concrete pavements. At this time, asphalt and concrete pavements cannot be directly compared because submodels are not yet included in the LCA model for factors in the Use Phase other than roughness and texture. For this reason, it was assumed that the pavement preservation treatments would not change the pavement structure type (asphalt or concrete). Energy and GHG-emissions savings from pavement preservation treatments with CAPM treatments as an example (CPR B involving diamond grinding with 3 percent slab replacements for concrete and pavement preservation overlays for asphalt, performed using nighttime closures) were then compared with an alternative strategy where no treatment occurs, except for routine maintenance of damaged pavement. A preliminary indication of the sensitivity of the case study results to the level of smoothness achieved during pavement preservation construction was evaluated. A preliminary indication of the sensitivity of the net effect on GHG emissions and energy use to the level of traffic in the Use Phase was also evaluated by inclusion of a high and a low traffic case study for both concrete and asphalt pavements. The potential benefits of the treatments are also compared with energy and emissions savings from projected improvements in vehicle fleet fuel economy and reductions of vehicle miles traveled, which are strategies adopted by the California Air Resources Board for reducing GHG emissions. For highways with high traffic volumes, results of the case studies show that the energy and GHG savings accrued during the Use Phase (due to reduced roughness and macrotexture change) can be significantly larger than the energy use and GHG emissions from material production and construction. The extent of the benefit was dependent on constructed smoothness with a much smaller benefit from change of texture. These savings can be larger than those from other strategies meant to reduce highway transportation energy use and emissions for a given route, such as projected improvements in fleet average vehicle fuel economy within the period analyzed for the project location, depending on the amount of traffic using the pavement. For low traffic volume highways, the smoothness obtained by the contractor and the materials used determine whether the net effect on GHG emissions and energy use is positive or negative, and may result in a net increase in energy use and GHG emissions if low traffic volumes and poor construction quality (rough pavement produced by construction) occur together. These initial case studies only represent example sections, and application of the LCA model to the network remains to be done. The materials datasets for the case studies used data from several sources outside California that were adjusted to California electrical energy supplies. Sensitivity analysis with the different data sets did not change the conclusions. All materials mix designs (taken from meetings with industry) and construction were representative examples. The method used to combine pavement characteristics (IRI and texture) and emissions models has not been validated, although the fuel economy models have been validated by Michigan State University. This report was reviewed by concrete and asphalt industry experts through their respective California industry organizations, and errors and omissions in the original draft have been addressed based on those comments, which are gratefully acknowledged.

Keywords: pavement, rehabilitation, maintenance, life cycle assessment, rolling resistance, energy, greenhouse gas, MIRIAM

Proposals for implementation:

Related document:

- Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines, by J. Harvey, A. Kendall, I.-S. Lee, N. Santero, T. Van Dam, and T. Wang. UCPRC-TM-2010-03. May 2010.

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PROJECT OBJECTIVES

The objectives of Partnered Pavement Research Center (PPRC) Strategic Plan Element 4.26 "Studies to Support Global Climate Change Initiative" are:

- Develop an initial LCA framework, including standard assumptions, system boundaries, and documentation requirements, and review, critique, and modify it with an expert group through a workshop to produce a final version.
- Develop data, methods, and models for use within the final LCA framework for simulation of greenhouse gas emissions and energy use on the state highway network as a function of the application of several typical treatments and the change in pavement surface characteristics (smoothness and macrotexture) due to that construction.
- Produce initial case studies looking at pavement preservation treatments and applying the framework and data, methods, and models in order to demonstrate their use. The following CAPM treatments were used as examples of preservation treatments: CPR B consisting of diamond grinding and 3 percent slab replacement for concrete and pavement preservation overlays for asphalt, both performed using nighttime closures. These initial case studies also provide a preliminary indication of the net effects on greenhouse gas emissions and energy use of changes in pavement smoothness and surface texture from pavement maintenance or rehabilitation, considering the entire life cycle of a preservation treatment as defined by the framework, including material production, construction, and vehicle use.

A technical memorandum completed the first objective. This report completes the second objective for two treatments commonly used by Caltrans, and the third objective.

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EXECUTIVE SUMMARY

Operation of the state highway pavement network makes it a major user of energy and producer of emissions, including greenhouse gases (GHGs), criteria air pollutants, and water pollutants. In 2006, the California State Legislature passed Assembly Bill 32 (AB 32), the Global Warming Solutions Act of 2006, which aims to reduce GHG emissions from all sources throughout the state. AB 32 requires that statewide GHG emissions be reduced to the level of the year 1990 by 2020, and to 20 percent of the 1990 level by 2050. Implementing these AB 32 objectives has led to studies that focus on the reduction of GHG emissions in each of the state's industrial sectors and to comparisons of the cost-effectiveness of different strategies within and between sectors.

In its 2006 AB 32 scoping documents, the California Air Resources Board (CARB) identified the contribution to statewide GHG emissions of different end use sectors of goods and services in the state's economy. It is shown in that document that the on-road vehicle use sector accounts for 36 percent of total statewide emissions.

Within the transportation sector, which is dominated by on-road vehicle use, the state has undertaken the implementation of three primary strategies for reducing GHGs through legislation and regulations: development of a low carbon fuel standard, development and production of advanced clean cars, and reduction of vehicle miles traveled through land use planning.

Pavement condition is another factor that affects the fuel efficiency and GHG emissions of on-road vehicles, and it does so by affecting vehicle emissions through three mechanisms—roughness, macrotexture, and deflection—that taken together can be called effective rolling resistance.

The relative impact of each of these three elements of rolling resistance on fuel economy and GHG emissions from on-road vehicles depends primarily on the level of pavement roughness and surface texture condition, the pavement structure (thickness, stiffness, and viscoelastic characteristics), the types of vehicles and traffic speeds on the pavement, and climate conditions (temperature and rainfall). For two pavements that are in the same condition and that are operated under the same conditions, the total impact of the pavements' characteristics on energy use and GHG emissions depends on the number of vehicles that use them.

A pavement in poor condition has greater effective rolling resistance, and therefore higher levels of fuel use and GHG emissions than a pavement that has received a maintenance or rehabilitation (M&R) treatment to reduce its rolling resistance. However, applying an M&R treatment to a pavement also results in energy use and GHG emissions due to the extraction and manufacture/refining of pavement materials (such as asphalt, cement, and aggregate), transportation of these materials, and the use of construction equipment.

Pavement management includes the measurement of pavement condition and the programming of M&R treatments to achieve goals for the pavement network, such as restoration of smoothness and elimination of cracking (which leads to roughness), at minimum cost to the agency and taxpayers. To date there has been no evaluation of the potential of pavement management strategies to help meet the objectives of AB 32 nor of their cost-effectiveness in achieving those objectives compared with current strategies.

The following are fundamental questions about the effects of pavement M&R on energy use and GHG emissions:

- Are the initial GHG emissions and energy consumption from the M&R treatment of a pavement recovered through the energy and emissions savings (as compared to a do-nothing strategy) of vehicles operating on that pavement if the M&R treatment results in reduced rolling resistance?
- How does that answer change for different cases?
- What is the cost-effectiveness of using pavement management strategies to help reduce energy consumption and GHG emissions?

With respect to the costs of timely application of M&R treatments, earlier UCPRC research for Caltrans on flexible pavements showed that applying a pavement maintenance treatment before a pavement reaches an advanced level of cracking (i.e., pavement preservation) can potentially reduce the life cycle cost compared with waiting until the pavement is damaged enough to require rehabilitation. Reduced pavement life cycle costs are also expected following the application of pavement maintenance treatments to concrete pavements (also referred to as "rigid pavements" or "PCC pavements") because faulting on plain jointed concrete pavement built before 1999 without dowels increases the impact of loading applied by heavy trucks, as do other causes of roughness on both flexible and rigid pavements. This phenomenon is due to the dynamic interaction of the pavement and the truck suspension, and it results in shortened pavement life and, therefore, increased life cycle cost. As noted earlier, pavement roughness is also a major cause of increased fuel use and GHG emissions for vehicles.

Because of its effect on vehicle fuel consumption and considerations regarding pavement surface in M&R strategy selection, rolling resistance of the pavement surface has been the focus of a number of studies. The first two mechanisms noted above that influence effective rolling resistance are characterized using the following terms:

- International Roughness Index (IRI) is used as a measure of "smoothness" (which is sometimes termed "roughness" from another perspective), and
- Mean profile depth (MPD) or mean texture depth (MTD) is used as a measure of pavement macrotexture, depending on whether pavement is rigid or flexible.

A recent North American calibration of the World Bank's *HDM-4* model for vehicle operating costs, reported in NCHRP Report 720, found that

> *"…the effect of surface texture is statistically significant at [the] 95 percent confidence interval only for heavier trucks and at low speed."*

The NCHRP study found that between roughness and surface texture:

> *"For fuel consumption, the most important factor is surface roughness (measured using IRI). An increase in IRI of 1 m/km (63.4 in./mi) will increase the fuel consumption of passenger cars by about 2% irrespective of speed. For heavy trucks, this increase is about 1% at normal highway speed (96 km/h or 60 mph) and about 2% at low speed (56 km/h or 35 mph)."*

Coefficients for surface texture (measured by MPD) are included in the recommended model in NCHRP Report 720 and indicate that for heavy trucks "an increase in MPD of 1 mm will increase fuel consumption by about 1.5% at 88 km/h (55 mph) and about 2% at 56 km/h (35 mph)."

Pavement deflection, the third mechanism of effective rolling resistance affecting fuel consumption and therefore GHG emissions, has been associated with two phenomena:

- Deflection of the pavement surface creates a change in the geometry of the pavement, with a larger deflection causing curvature in the pavement surface that increases fuel consumption, and
- Dissipation of energy in the pavement structure due to the viscoelastic nature of asphaltic materials.

The first phenomenon, deflection of rigid and flexible pavements, is the subject of current research at the Massachusetts Institute of Technology. The second pavement deflection phenomenon, dissipation of energy in the pavement structure due to the viscoelastic nature of asphaltic materials, has been the subject of recent research at the University of Lyon, France. Recent experimental data from measurements of fuel consumption on different types of pavement in both winter and summer to calibrate the *HDM-4* model reported in NCHRP Report 720 indicated that "pavement type [does] not affect the fuel consumption of any vehicle class except for heavy trucks." More detailed analysis of the same data indicated that articulated (heavy) trucks and light trucks had statistically significant higher fuel consumption when operated on asphalt pavements at 35 mph in the summer, and that there was little if any difference at 45 or 55 mph (faster vehicle speeds increase asphalt stiffness and make it more elastic), or at any speed in the winter when the asphalt layers are stiffer and more elastic.

The influence of deflections on fuel economy and GHG emissions was not considered in this study because the research performed to date has not been implemented in a comprehensive framework that can account for the range of pavement structures (including rubberized mixes, composite pavements, semi-rigid pavements) commonly used across the state highway network. Implementation of a model to account for deflection effects is in the plan for future work.

As with all potential changes to a system to reduce environmental impacts, unintended negative consequences can occur that actually harm the environment more than help it. Because restoring pavement smoothness and texture introduces upstream environmental burdens from construction, material production, and transport, a system view and life cycle perspective is needed to examine the net impact of reducing pavement rolling resistance. The concepts of systems analysis and life cycle assessment (LCA) can help evaluate proposed changes as well as aid in the decision-making process.

LCA provides a comprehensive approach to evaluating the total environmental burdens of a product. It is an approach that examines a product from cradle-to-grave, evaluating all the inputs and outputs from raw material production to the final end-of-life. For pavements, the cycle includes the Material Production, Construction, Use, Maintenance and Rehabilitation (M&R), and End-of-Life (EOL) phases.

These are the objectives of Partnered Pavement Research Center (PPRC) Strategic Plan Element 4.26, "Studies to Support Global Climate Change Initiative":

- Develop an initial LCA framework, including standard assumptions, system boundaries, and documentation requirements, and review, critique, and modify it with an expert group through a workshop to produce a final version.
- Develop data, methods, and models for use within the final LCA framework for simulation of greenhouse gas emissions and energy use on the state highway network as a function of the application of several typical treatments and the change in pavement surface characteristics (smoothness and macrotexture) due to that construction.
- Produce initial case studies for two typical pavement preservation treatments (one for concrete pavement and one for asphalt pavement) applying the framework and data, methods, and models, in order to demonstrate their use and to provide a preliminary indication of the net effects (considering the entire life cycle of the preservation treatment as defined by the framework, including material production, construction, and vehicle use) on greenhouse gas emissions and energy use of changes in pavement smoothness and surface texture from pavement maintenance or rehabilitation.

The initial M&R practices selected as examples for evaluation are part of the Caltrans pavement preservation program, specifically two Capital Preventive Maintenance (CAPM) treatments: Concrete Pavement Restoration B (CPR B) for concrete and pavement preservation overlays for asphalt, both of which are performed using nighttime closures. CPR B consists of diamond grinding with two to five percent slab replacement. CAPM pavement preservation overlays are relatively thin overlays that often include milling of a portion of the existing asphalt surface prior to placement of the overlay. Both treatments are described in more detail in Chapters 3 and 4. These two practices (relatively inexpensive M&R treatments and smoothness specifications) were selected for this initial study for the following reasons:

- They were expected to have a relatively large potential impact.
- They can be implemented relatively quickly: smoothness specifications are already being implemented, and these M&R treatments only require identification of rough, high traffic volume sections in the pavement management system and additional funding, without the any requirement to upgrade non-pavement features of the road.
- They do not require models for pavement deflection effects, detailed modeling of pavement performance with recycled materials, creation of recycled material allocation rules, or models for fuel consumption from construction traffic delay, which require additional work before they are ready for implementation.

A technical memorandum completed the first objective. This report completes the second objective for two treatments commonly used by Caltrans and the third objective.

This study has been done in partnership with the MIRIAM (Models for rolling resistance In Road Infrastructure Asset Management systems) pooled-effort project, with funding from Caltrans and the University of California Office of the President. As part of MIRIAM, the methodology and results included in this report were reviewed by staff of the Swedish Road and Transport Research Institute (VTI), and the Slovenian National Building and Civil Engineering Institute (ZAG). The results presented in this report include comments, critique, and information provided by the Portland Cement Association (PCA), the Southwest Concrete Pavement Association, the California Asphalt Pavement Association, the Rubber Pavement Association, and some industry sources outside of these organizations. Their help and critical review are greatly appreciated.

This report first presents the methods, approach, tools, and models developed to calculate the net life cycle impact of the preservation treatment for the selected pavement M&R strategies—as initial examples—considering the Material Production, Construction, Use Phase, and End-of-Life phases. The report then presents four case studies to demonstrate the ability of the models to assess the change in the outcome (net energy and GHG emissions for the life cycle) for those example treatments. The results of the case studies also provide a preliminary indication of the relative effect on the outcome of the following variables:

- Automobile and truck traffic levels
- Constructed smoothness of the M&R treatment
- Material used for the M&R treatment (type of concrete or asphalt)

An effort was also made to compare pavement management strategies with two GHG-reduction strategies identified by CARB for the transportation sector: improved fuel efficiency for passenger vehicles and reductions in the growth of vehicle miles travelled (VMT), both of which are outside the decision-making scope of Caltrans, but which are of interest for other decision-makers in state and regional government who fund pavement improvements.

Chapter 2 presents the pavement LCA framework that the UCPRC used in preparing this report; this is the approach that will also be taken when applying the LCA models to the state pavement network in the future. The chapter also presents the factorial that will be used in a subsequent project and report where the state highway network will be divided into similar sections based on variables such as pavement type, level of traffic, level of congestion, and vertical gradients for use in sensitivity analyses and summarization of the results for the network as a whole.

The LCA framework was adopted from the *UCPRC Pavement LCA Guideline* and was reviewed as part of an international workshop on pavement LCA held in May 2010. The guideline recommends that a pavement LCA include any pavement structure characteristics that interact with the environment. However, at this stage only pavement roughness and texture are included.

Chapter 3 presents the goals and scope of use of the LCA models for this report. The scope includes the functional unit, system boundaries, and the processes and subprocesses that are within the system boundary, including the items that are considered in this stage and those that are not currently considered but are planned for future inclusion.

The goals of the LCA study documented here are to produce example results regarding the effects of the following items on GHG emissions and energy use:

1. The application of two types of pavement preservation treatment to rough pavement versus not performing the treatment—with one treatment applicable to concrete pavement and one applicable to asphalt pavement, and with two materials options for each treatment. The treatment for existing jointed plain concrete pavement is called "Concrete Pavement Restoration B (CPR B)" and it consists of (1) spall and joint seal repair and (2) "moderate" slab replacement (which ranges from 2 to 5 percent of slabs in a lane where third-stage cracking appears. The treatment for existing asphalt pavement is called "asphalt overlay."
2. Different levels of smoothness during construction for those two treatments, comparing good and poor initial smoothness.

3. Application of the treatments compared to doing nothing—as examples of using pavement management strategies to keep roads smooth—compared with the effects of expected changes in fleet fuel efficiency (one prediction of those changes) versus no change, and historical annual growth in vehicle miles traveled versus no growth.

The results are intended to provide both a calculation of the GHG emissions and energy use for each of these alternatives, and a comparison of the differences between them. The LCA is limited to the changes in the pavement itself caused by the M&R and the changes in emissions and energy use of the vehicles that use it; no changes beyond those are assumed.

Chapter 4 of the report presents the life cycle inventory (LCI) for the Material Production Phase of the preservation treatment life cycle. An LCI tracks all the quantified environmental flows in an LCA. Following the *UCPRC Pavement LCA Guideline*, in this report the system boundary of the Material Production Phase includes material acquisition; material production or processing prior to delivery to the mixing plant; mixing processes at the mixing plants; and material transport between the mixing plant and construction site by truck operation. While a typical LCA tracks many inputs to and outputs from a system, the analysis conducted here has been limited to energy inputs (as characterized by total primary energy) and GHG outputs.

Materials and processes for which inventories were put together include crushed aggregate, natural aggregate, bitumen (asphalt binder), crumb rubber modifier, extender oil, recycled asphalt pavement, hot-mix asphalt (HMA) mixing plants, cement, concrete admixtures, dowel bars, and concrete mixing plants. Both conventional HMA and rubberized HMA (RHMA) were considered for asphalt pavement maintenance. Both Type III portland cement concrete and calcium sulfoaluminate concrete (CSA) were considered for use as Rapid Strength Concrete for concrete pavement slab replacement. These concrete materials are used extensively for repair of individual slabs under nighttime traffic closures, which was the assumed situation for the case studies in this report. Portland cement concrete using Type I/II cement is typically used for concrete lane replacement, which is a treatment planned for future investigation.

For some processes, researchers in different locations have produced LCI information that differs. All available alternative sources of LCI information were used to provide a sensitivity analysis with respect to data source. Electrical power sources were disaggregated for the different sources of information and converted to equivalent values using the California electrical power mix.

Chapter 5 of the report documents the Construction Phase LCI. In the Construction Phase, fuel use and emissions come from both construction equipment (including trucks) and construction-related traffic. For this study, construction work was scheduled to be performed at night, and given the rural location of the case studies, no work zone traffic delay was considered.

The analysis used a two-step method to assess the energy use and GHG emissions from construction equipment. The first step was to simulate the construction schedule and equipment activities, and the model included in the software program, *Construction Analysis for Pavement Rehabilitation Strategies* (*CA4PRS*). This study assumed that the construction work was performed using nine-hour nighttime partial lane closures. The result shows that the conventional hot-mix asphalt (HMA) and rubberized hot-mix asphalt (RHMA) overlays had productivities of about 0.6 and 0.9 lane-miles per night, respectively. The productivities for the concrete pavements were about 1 lane-mile of grinding and 27 slabs replaced per nine-hour nighttime closure. To estimate the equipment operating hours, major equipment included in the *CA4PRS* construction resource database were adopted based on Caltrans pavement preservation strategies and projects. Where required, some information on specific engine characteristics, such as horsepower and fuel consumption, were collected from industry references.

The second step in the analysis was conversion of the equipment operating hours to GHG emissions and energy consumption. The California Air Resources Board's (CARB) *EMFAC* model was adopted to calculate the direct emissions from hauling trucks, and CARB's *OFFROAD* model was adopted to calculate the direct emissions from construction equipment. Both models report emission factors for various engine sizes and include an inventory of activities for different types of equipment. Engine horsepower was used to match the emissions factor if the exact equipment could not be found in the *OFFROAD* database.

Chapter 6 presents the LCI for the Use Phase. This phase of the preservation treatment life cycle includes the additional fuel from vehicle operation due to the deterioration of the surface of the pavement. Deterioration of the pavement considers both roughness (International Roughness Index [IRI]) and macrotexture (Mean Profile Depth [MPD] for asphalt surfaces or Mean Texture Depth [MTD] for concrete surfaces) as indicators of the pavement surface condition. Roughness and macrotexture contribute to the rolling resistance of the pavement for vehicles that use it by increasing the engine load to move the vehicle, and thus the energy consumption and GHG emissions. As noted previously, deflection also contributes to effective rolling resistance, but was not considered in this initial study because of the lack of an implemented model. It was assumed to be the same for the *Do Nothing* and treatment cases for each type of pavement (concrete and asphalt).

The analysis for the Use Phase involved three steps. First, IRI progression models were developed for different pavement types and treatment strategies from the Caltrans Pavement Condition Survey (PCS) database, and MPD and MTD progression models were drawn from other sources. Second, rolling resistance based on IRI and MPD/MTD were calculated using the *HDM-4* model developed by the International Road Federation. The *HDM-4* model was recently calibrated to North American vehicles through the NCHRP 1-45 project. *HDM-4* can also consider the effects on rolling resistance caused by pavement deflection; however, because the calibration from NCHRP 1-45 indicated that pavement deflection was only significant when heavy trucks were moving at slow speeds (56 km/hr [35 mph] as opposed to 72 and 88 km/hr [45 and 55 mph]) on hot asphalt, for the current studies where vehicles are traveling at high speeds (greater than 72 km/hr [45 mph]) it was reasonable to assume that there would be no change in energy consumed by deflection for the *Do Nothing* case versus the maintenance alternatives.

In the third step, the calculated effective rolling resistance from *HDM-4* was used to update the corresponding parameters in a vehicle emissions model, *MOVES*, which was developed by the U.S. Environmental Protection Agency. While *HDM-4* assumes constant speed, *MOVES* can consider speed changes over short time increments, which is important when looking at congested traffic situations. *MOVES* uses *vehicle specific power* (VSP) as an indicator of engine running status, and this term can incorporate the effect from rolling resistance on fuel consumption and emissions. Although the *MOVES* model has terms for rolling resistance from a number of sources, they are all based on steel drum dynamometer testing; therefore rolling resistance due to pavement condition was assumed by the program to be constant—until an approach was developed in this project to use the *HDM-4* model to consider IRI and macrotexture. With traffic information for a specific section of highway, *MOVES* was used to calculate vehicle fuel use and GHG emissions for the baseline case of routine maintenance with little change and compare it with fuel use and GHG emissions after changing the pavement condition through maintenance or rehabilitation.

In the Use Phase, models for pavement surface characteristics are used to predict the construction quality of maintenance and rehabilitation, and how the pavement will perform after construction. Any applicable performance models can be used for IRI and macrotexture.

Traffic information for the California pavement network was acquired from the Caltrans traffic volume report and the truck traffic report. Because Caltrans, *HDM-4*, and *MOVES* use different vehicle classification methods, a transition matrix was developed and applied to map the vehicle classification from Caltrans data to the *HDM-4* model and then to the *MOVES* model. This matrix was based on data collected on 115 Caltrans Weigh-in-Motion (WIM) stations and previously analyzed by UCPRC, and on state average inventory data extracted from *EMFAC*.

Additional treatment of traffic data included assigning the traffic to different lanes and hours. The lane distribution factors were taken from another earlier UCPRC study. The hourly distribution factor for vehicles is an input for *MOVES* and it was developed from California Freeway Performance Measurement System (PeMS) data. For other *MOVES* inputs, including speed profile, meteorological data, and vehicle age distribution, this study used default data stored in the *MOVES* database or extracted from *EMFAC*.

Four case studies were performed based on four flat rural California road segments to show examples of the different effects of pavement roughness and traffic volume on the total life cycle GHG and energy use impact of pavement preservation treatments. The case study locations were selected to provide a preliminary indication of the effects of traffic level (high and low total traffic) within each pavement type (asphalt and concrete) on the net impact of treatment, while also considering different levels of constructed smoothness and two common material types within each pavement type. Other criteria used in selecting the particular road segments were the sections' poor condition and that nearby sections had been subjected to treatment and could provide reasonable performance information where models were not yet available (primarily asphalt IRI progression). Significantly different traffic levels, functional units, and other details of the asphalt and concrete sections were carefully selected so that direct comparison between the pavement types could not be made at this point in the research program. To provide a reasonable early indication of the effect of traffic on the results, the traffic on the sections is approximately near the upper and lower quartiles for each pavement type. The traffic levels are therefore higher for the concrete sections because of the distributions of traffic on the two pavement types across the network.

The results from the case studies and analysis of the results are shown in Chapter 7. The studies included an asphalt case with a high traffic volume segment (Interstate-5 in Kern County), an asphalt case with a low traffic volume segment (State Route 70 in Butte County), a concrete case with a high traffic volume segment (Interstate-5 in Los Angeles), and a concrete case with a low traffic volume segment (State Route 86 in Imperial County). Each case study considered a potential pavement preservation treatment carried out in 2012, and modeled the different materials used in construction, different levels of smoothness after construction, two traffic growth rates (zero percent and three percent), and different data sources for the LCI for material production. A *Do Nothing* scenario, in which only the minimum level of maintenance work was performed annually to keep the current pavement condition deteriorating at a very slow rate, was modeled as a baseline for each case.

Two types of pavement preservation work were analyzed, using CAPM treatments as examples: an asphalt overlay, where the old surface is milled prior to placing a new surface, and a concrete pavement restoration (CPR) that includes three percent slab replacement and full-lane diamond grinding (CPR B). For both pavement preservation strategies, the existing pavement was assumed to remain otherwise unaltered. The asphalt cases used a 5-year analysis period and the concrete cases used a 10-year analysis period, which reflects their respective design lives in the Caltrans *Life Cycle Cost Analysis Procedures Manual.*

Preservation treatments, such as the CAPM treatments used as examples in this study, are applied to pavements that do not have major structural failure requiring rehabilitation or reconstruction. They tend to be placed several times in succession until eventually rehabilitation or reconstruction is required and funds are available. For this reason, the analysis period was selected to be the design life, with the assumption that the treatment would be repeated. The analysis periods were specifically selected to be different for the asphalt and concrete treatments and the results were not annualized to avoid direct comparison between them, because that is not the objective of this first study in the research program. These case studies analyze a portion of an overall pavement's life cycle beginning with new construction or major rehabilitation, and only consider one of the subsequent repeated preservation treatments that would follow. Once life cycle inventories and other needed information is completed for other treatments in the life cycle, more complete life cycles will be analyzed. It should be remembered as well, that CAPM treatments are used extensively when M&R funding levels are insufficient for longer life treatments that may have lower life cycle costs and potentially lower life cycle environmental impacts.

In the asphalt case studies (KER-5 and BUT-70), two types of materials were analyzed: dense-graded conventional hot-mix asphalt (HMA) and gap-graded rubberized hot-mix asphalt (RHMA). According to Caltrans pavement preservation guidelines (CAPM guidelines) and the *Highway Design Manual,* the conventional HMA overlay has a 0.15-ft (45-mm) milling depth and a 0.25-ft (75-mm) new HMA layer with reclaimed asphalt pavement (RAP), and the RHMA overlay has a 0.10-ft (30-mm) milling depth and a 0.20-ft (60-mm) new RHMA layer with no RAP. While the values used in the case studies were reasonable, the precise overlay thicknesses would depend on structural evaluation of the existing pavement. The mix designs for HMA and RHMA were based on typical mix designs from Caltrans.

To consider the effect of construction smoothness in the case studies, for asphalt pavement the IRI after overlay was assumed to range from 63 in. per mile (1.0 m/km) to 106 in. per mile (1.67 m/km), approximately spanning the range of a sample of initial IRI values on Caltrans pavement preservation overlays. The IRI progression after overlay was obtained directly from the Caltrans PCS database for the locations of the case studies.

In the cement concrete case studies (LA-5 and IMP-86), two types of material, high early strength portland cement concrete (Type III PCC) and calcium sulfoaluminate (CSA) cement concrete, were considered for the slab replacement in CPR B. Both types of cement concrete are used in California to acquire high early strength because the road segments need to be open to traffic within four to five hours of removal of the shattered slabs during nighttime construction. The mix designs of the two types of concrete were based on the sample designs provided by the cement industry. In addition, 1.6-in. (40-mm) diameter dowel bars and tie bars were assumed to be installed between slabs because the pavement thickness is greater than 0.7 ft (215 mm). The IRI and MTD changes and progressions were assumed to be the same for both types of concrete.

For concrete pavement, the change in IRI from diamond grinding (the major activity in CPR B) and IRI progression were estimated from the model in a report on Caltrans grinding projects (Stubstad *et al.*, 2005) and the Caltrans PCS database. Three levels of construction smoothness were considered in the concrete pavement case studies: the mean smoothness after construction minus two standard deviations from the model of initial IRI; the mean smoothness after construction; and, the mean smoothness after construction plus two standard deviations from the model.

Because the Caltrans PCS has historically not collected macrotexture information, the progression of MPD for asphalt pavements was taken from models developed for a previous UCPRC project that provided an estimate of MPD progression based on mix type, air voids, age, thickness, temperature, and truck traffic experienced by a pavement. For concrete pavements, the progression of macrotexture after diamond grinding was taken from a study by Rao *et al*. (1999), represented as a function of MTD and number of years. In this study, the IRI progression of conventional HMA and RHMA for each case study was assumed to be the same, with one progression for the low traffic case study and another for the high traffic case study taken from Caltrans Pavement Condition survey data. A regression equation for IRI as a function of ESALs and other variables was used for the concrete case studies, and the two types of concrete mix used for slab repairs were assumed to have the same IRI progression. Material-specific MPD models were used for the two types of asphalt mix, which indicate that HMA starts with a lower MPD but deteriorates faster, while RHMA starts with a higher MPD but has a lower deterioration rate. For concrete, the same MTD progression model was used for both types of concrete used for all case studies.

Typical transport distances between the plant and the construction site and typical vehicles were assumed for all projects. It was assumed that the mixing plants were at the quarry.

Figures and tables in Chapter 7 show the fuel cycle energy consumption by vehicles in the Use Phase over the respective analysis periods under a number of scenarios, including zero percent or three percent traffic growth; static or improving vehicle fuel economy; and the *Do Nothing*, *less smooth construction,* and *smooth construction* interventions (and for concrete, mean smoothness). The zero or three percent annual traffic growth was used to estimate the relative importance of reducing vehicle mileage traveled (VMT) compared to other parameters tested in the scenario analyses. The improvements in vehicle fleet-average fuel economy are based on the default assumptions for fuel economy improvements in *MOVES*, and demonstrated the relative importance of changing vehicles and vehicle technology to achieve reductions in fuel use and GHG emissions compared to changes in rolling resistance and VMT. These comparisons are outside the decision-making scope of Caltrans, but are of interest for other decision-makers in state and regional government who fund pavement improvements.

The results show that the most significant reduction in fuel use in the Use Phase will come from less vehicle use, generally followed by pavement maintenance, and then by changes in vehicle fuel economy. For example, placing a smooth construction on an asphalt pavement can bring down the annual energy consumption by about 2.5 percent, which is equivalent to about 125,000 to 150,000 gallons of gasoline used by vehicles annually on a 10-mile (16.1-km) long one-direction section. Because GHG emissions in this phase are completely generated from vehicles burning gasoline or diesel, GHG emissions have a trend that closely resembles that of fuel consumption in the Use Phase.

Figures and tables in Chapter 7 also show the net fuel use and GHG emissions over the entire analysis period for pavement preservation treatment versus the *Do Nothing* (minimal maintenance) cases, versus change in traffic growth rate, and versus change in vehicle fuel economy for each case study. For a pavement section with high traffic volume, the energy savings in the Use Phase can outweigh the energy consumed in the Material Production and Construction phases with either material used. Considering an average value from the different data sources for material production and zero percent traffic growth, the energy saving during the Use Phase is 7 and 11 times the energy consumption in the upstream phase (Material Production and Construction, respectively) for the asphalt cases. The concrete pavement case studies showed a similar trend. However for pavement segments with low traffic volume, whether a positive saving can be achieved will depend heavily on other factors, including materials and construction quality, represented by initial smoothness right after construction, and the amount of traffic.

Reporting of feedstock energy for asphalt is shown in all results but not discussed in the analyses, based on the assumption that recycled asphalt pavement will likely not be used as an energy resource in California.

To assess the difference between all the different scenarios, especially the low traffic volume cases, the payback time in each case was calculated and compared. *Payback time* is the time necessary for fuel and GHG emissions savings in the Use Phase to equal the energy and GHG emissions from Material Production and Construction phases. The range of payback times indicates that the result is highly dependent on the traffic volume and the traffic growth rate. For a segment with high traffic (for example, LA-5), the energy consumption due to initial construction is offset within one year of the construction event, regardless of the material used and smoothness after construction.

The second most influential factor affecting payback time is construction quality, which is represented by the smoothness after construction: a smoother pavement leads to a shorter payback time for concrete and asphalt pavement. Two reasons account for this result: (1) smoother pavement can directly contribute to reduced vehicle fuel consumption during pavement use; and (2) a smooth pavement has slower rate of deterioration compared to a rough pavement, which is reflected in the IRI progression model. For example, in the IMP-86 case, a concrete segment with low traffic volume, the construction quality significantly affected energy savings in the Use Phase, consequently changing the payback time in each smoothness scenario. When this construction was poorly performed (i.e., the less smooth result), the energy consumption was barely recovered over its 10-year design life. However, for a smooth construction, the payback period was about two to three years.

The relative impact of the changes in IRI and macrotexture for the asphalt and concrete treatments for the high traffic cases are shown in Figures B.9 and B.10 of the report, respectively. The results show that the changes in texture have a small effect on payback time compared with the changes in IRI.

The following conclusions are drawn from the results of the case studies:

- Pavement maintenance can result in an important net reduction in GHG emissions and energy use over the analysis period for high-volume routes. The net result is most dependent on the number of vehicles that use the segment. For segments with low traffic volumes, the potential benefits take much longer to accrue, and payback may not occur before the end of the life of the treatment.
- Construction pavement smoothness has an important effect on GHG emissions and energy use in the Use Phase and therefore on the net result. If construction does not result in a smooth pavement, then the benefit of the treatment is greatly reduced.

- Pavement maintenance for a given route with rough surface characteristics can produce energy savings and net GHG emission reductions of similar size to expected changes in the fleet average fuel economy included in the *MOVES* model. Reductions in the growth rate of vehicle miles traveled on a route have a much larger impact than pavement maintenance or changes in fleet fuel economy.
- The differences in net energy consumption and GHG emissions and payback time between materials for a given treatment (RHMA and HMA for asphalt overlays, CSA cement and Type III portland cement for slab replacement) were smaller compared with the effects of construction smoothness considered in this study. It should be also noted that the analyses in this study assumed that alternative materials have the same performance, which may vary depending on the actual materials and construction quality for a given project. The very low amount of slab replacement used in CPR B (3 percent) made the impact from cement and concrete production insignificant.

Important limitations of this study include the following:

- These initial case studies only represent example sections, and application of this analysis to the network is work that remains.
- The materials datasets for the case studies used data from several sources outside California that were adjusted to California electrical energy supplies. Sensitivity analysis with the different data sets did not change the conclusions.
- All materials mix designs (taken from a series of meetings with the concrete and asphalt industry organizations noted in the acknowledgments) and construction were representative examples. There is a range of mix designs that could have been used for this analysis, these mix designs were provided by industry with the intention that they be typical.
- The method used to combine pavement characteristics (IRI and texture) and emissions models has not been validated, although the fuel economy models have been validated by Michigan State University.

This report was reviewed by concrete and asphalt industry experts through their respective California industry organizations, and written comments were provided. Errors and omissions in the original draft have been addressed based on those comments, which are gratefully acknowledged. Responses to each comment were returned in writing to industry along with the revised report for review and additional comment.

The case studies presented in this report indicate that the potential impacts of pavement management decisions warrant further evaluation for an entire factorial of cases representing the full network. These are the current plans for the development and implementation of improvements to the models used in this study:

- Implement the variable speed aspects of the vehicle operation model for the Use Phase.
- Develop and implement a work zone traffic delay element for the Construction Phase.
- Develop and implement Material Production and Construction phase LCI models and pavement performance (IRI and macrotexture) models for concrete lane reconstruction (long-life rehabilitation) using Type I/II cement for concrete pavement, and thicker asphalt overlays (rehabilitation) for asphalt pavement.
- Improve Material Production and Construction phase inventories where possible with data more applicable to California material production and construction.

Additional case studies will be performed to assess the net life cycle energy and GHG emissions from application of the preservation treatment for the factorial shown in Table 2.1 of the report (prior to implementation of the energy dissipation model), which is intended to encompass all types of pavement facilities within the state highway network. Within each of the cells in the factorial the following variables will be considered:

- Automobile and truck traffic levels
- Constructed smoothness of the M&R treatment
- Material used for the M&R treatment (type of concrete or asphalt)
- Management strategy/design life (pavement preservation versus rehabilitation versus routine maintenance)

These case studies will be applied to the state highway network to develop preliminary example comparisons of the treatment life cycle impact on energy use and GHG emissions for the pavement management strategies (overlays, CPR, and lane reconstruction). These comparisons will be done for different levels of M&R funding and different strategies for selecting projects for application of the funding. Different levels of construction smoothness will also be evaluated. Recent improvements in the Caltrans PMS database will provide network traffic, IRI, and texture (asphalt only) information, and improved models for IRI performance.

As was done for the four case studies presented in this report, the effects of pavement management strategy will also be compared with one prediction of expected change in fleet fuel efficiency versus no change, and with continuation of the historical annual growth in vehicle miles traveled versus no growth, which are two of the strategies being implemented by the California Air Resources Board as part of implementation of AB 32 (as discussed in Chapter 1 of the report).

Work will also be performed on methods of integrating the results of LCA and life cycle cost analysis (LCCA). The work on combining LCA and LCCA in decision making is primarily funded by the University of California Office of the President for use by both state and local government.

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ACRONYMS

AADT	Annual average daily traffic
AADTT	Annual average daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
AB	Aggregate base
AB 32	Assembly Bill 32: Global Warming Solutions Act
AC	Asphalt concrete
ASTM	American Society for Testing and Materials
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
CAPM	Capital Preventive Maintenance
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CRCP	Continuously reinforced concrete pavement
CSA	Calcium sulfoaluminate
CTB	Cement-treated base
CTE	Coefficient of thermal expansion
DOT	Department of Transportation
EOF	End-of-life
EIO-LCA	Economic input-output life cycle assessment
EPA	Environmental Protection Agency
ESAL	Equivalent Single Axle Loads
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GWP	Global warming potential
HHV	Higher heating value
HMA	Hot-mix asphalt
HTP	Human toxicity potential
IPCC	Intergovernmental Panel on Climate Change
IRI	International roughness index
ISO	International Organization for Standardization
JPCP	Jointed plain concrete pavement
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value
M&R	Maintenance and rehabilitation

MEPDG	Mechanistic Empirical Pavement Design Guide
MIRIAM	Models for rolling resistance In Road Infrastructure Asset Management systems
MPD	Mean profile depth
MTD	Mean texture depth
MSOD	Mobile Source Observation Database
MSWI	Municipal solid waste incineration
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
PaLATE	Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects
Pb	Lead
PeMS	Performance Measurement System
PCA	Portland Cement Association
PCC	Portland cement concrete
PIARC	World Road Association (Permanent International Association of Road Congresses)
PM_{10}	Particulate matter with diameters of 10 microns or smaller
$PM_{2.5}$	Particulate matter with diameters of 2.5 microns or smaller
PMS	Pavement management system
RAP	Recycled asphalt pavement
RCP	Recycled concrete pavement
RHMA	Rubberized hot-mixed asphalt
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulfur dioxide
SO_X	Sulfur oxides
TRLHP	Track load horsepower
UCPRC	University of California Pavement Research Center
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOC	Volatile organic compound
VSP	Vehicle specific power
WMA	Warm-mix asphalt

1. INTRODUCTION

1.1 Background

The national pavement network is a key component of the transportation infrastructure that the U.S. economy depends on for mobility and movement of goods. Construction of new lane-miles and the maintenance and rehabilitation (M&R) of existing pavement infrastructure in this network consumes large amounts of resources. It is estimated that about $160 billion and 320 million metric tons of raw materials are used in annual construction, rehabilitation, and maintenance for the U.S. highway system (*1, 2*). In addition, operation and use of the pavement network makes it a major consumer of energy and producer of environmental emissions, including greenhouse gases (GHGs), criteria air pollutants, and water pollutants.

In 2006, the California State Legislature passed Assembly Bill 32 (AB 32), the Global Warming Solutions Act of 2006, which aims to reduce GHG emissions from all sources throughout the state. AB 32 requires that statewide GHG emissions be reduced to the level of the year 1990 by 2020, and to 20 percent of the 1990 level by 2050 (*3*). Implementing these AB 32 objectives has led to studies that focus on the reduction of GHG emissions in each of the state's industrial sectors and to comparisons of the cost-effectiveness of different strategies within and between sectors, as in a study by Lutsey (*4*).

Figure 1.1 shows the sources of GHG emissions from 2002 to 2004 for different sectors of the California economy according to the California Air Resources Board (CARB), the lead agency for implementation of AB 32 (*3*). The figure shows that total GHG emissions can be attributed to seven areas within the industrial sector, including transportation, electricity, industry, etc. Pavement condition itself and M&R activities to improve pavement condition affect two of the major industrial sectors. The first sector is "transportation," in which the fuel economy and GHG emissions of vehicles are affected by the interaction of the vehicle and the pavement. The second sector is "industry," in which pavement materials are produced from oil extraction and refining, cement manufacture, aggregate mining, the production and transport of other materials used in pavements, as well as construction equipment. Within the transportation sector, which is the largest, the state has started to implement three primary strategies for reducing GHGs from light-duty vehicles (the major GHG contributors for the transportation sector) through legislation and regulation (*3*):

- Developing a low carbon fuel standard,
- Facilitating development and production of advanced clean cars, and
- Reducing vehicle miles traveled (VMT) through land use planning.

Strategies to help heavy-duty vehicles meet AB 32 objectives have been grouped by CARB into a category of efficiency goals called "overall freight movement" (also referred to as "goods movement") (*3*).

Figure 1.2 (*3*) shows the "end user's view" of GHG emissions from 2002 to 2004, and it reveals that on-road vehicles account for 36 percent of total statewide emissions, the largest of the categories considered. Pavements can influence the fuel efficiency of vehicles, and therefore the GHG emissions as well, through three mechanisms which together can be called the *effective rolling resistance*, although that is not a precise definition of rolling resistance:

- Consumption of energy through the working of shock absorbers as the wheels pass over deviations from a flat surface in the wheelpath—converting mechanical energy into heat which is then dissipated into the air—and greater work required by the engine,
- Consumption of energy through viscoelastic working of the tire rubber as it passes over the positive surface macrotexture (texture caused by stones or other texture protruding above the average plane of the pavement surface) of the pavement and converts it into heat that is dissipated into the tire and the air (pavements for high speed vehicles must have a minimum amount of macrosurface texture in order to remove water films from the pavement surface to provide frictional resistance for braking), and
- Consumption of energy through deflection of pavement materials under passing vehicles, primarily heavy trucks.

Pavements that are in poor condition have higher effective rolling resistance than those in good condition because they become rougher in the wheelpaths, with roughness defined as deviations from the planar surface with wavelengths between 0.5 and 50 m (0.5 and 164 ft), which influences the first mechanism listed above. Pavements in poor condition also often have rougher surface macrotextures, with roughness defined as deviations from the planar surface with wavelengths between 0.5 and 50 mm (0.02 and 2 in.), which consume more energy through viscoelastic energy dissipation through the working of tire treads. Pavements in poor condition therefore increase fuel use and GHG emissions by both mechanisms. Pavement maintenance and rehabilitation treatments can reduce pavement roughness and positive surface texture, and therefore lower fuel use and GHG emissions. However, performing these treatments also requires energy and produces emissions. Specifically, M&R of pavement contributes to three other GHG-emissions source categories, as shown in Figure 1.2 (*5*):

- Extraction and refining of oil: a portion of this sector's emissions come from the production of paving asphalt;
- Cement plants: a portion of this sector's emissions includes the manufacture of cement used for pavements; and
- Industrial manufacturing, construction and mining: a portion of this sector's emissions includes some of the processes used for pavement M&R, including mining and transportation of aggregate, manufacture and transportation of lime, and construction equipment operation.

The third element of rolling resistance noted above, deformation of the pavement structure, can be influenced by the design of the pavement structure, with less energy dissipated by more elastic (as opposed to viscoelastic) materials such as concrete or stiff conventional asphalt, and thicker structures. For asphalt pavements, more energy is consumed under conditions with hot temperatures and slow-moving heavy trucks.

The relative impact of each of these three elements of rolling resistance (roughness, macrotexture, deflection) on fuel economy and GHG emissions from vehicles operating on pavement depends primarily on the level of roughness, the surface texture condition, the pavement structure (thickness, stiffness, and viscoelastic characteristics), the types of vehicles, climate conditions (temperature and rainfall), and traffic speeds. For two pavements that are in the same condition and that are operated under the same conditions, the total impact of the pavement's characteristics on energy use and GHG emissions depends on the number of vehicles using it.

Pavement management includes the measurement of pavement condition and the programming of M&R treatments to achieve goals for the pavement network, such as smoothness and elimination of cracking (which leads to roughness), at minimum cost to the agency and to taxpayers. To date, there has been no evaluation of the potential of pavement management strategies to help meet the objectives of AB 32 nor of their cost-effectiveness in achieving those objectives compared with current strategies. The following are fundamental questions about the effects of pavement M&R on energy use and GHG emissions:

- Are the initial GHG emissions and energy consumption from the M&R treatment of a pavement recovered through the energy and emissions savings (as compared to a do-nothing strategy) of vehicles operating on that pavement if the M&R treatment results in reduced rolling resistance?
- How does that answer change for different cases?
- What is the cost-effectiveness of using pavement management strategies to help reduce energy consumption and GHG emissions?

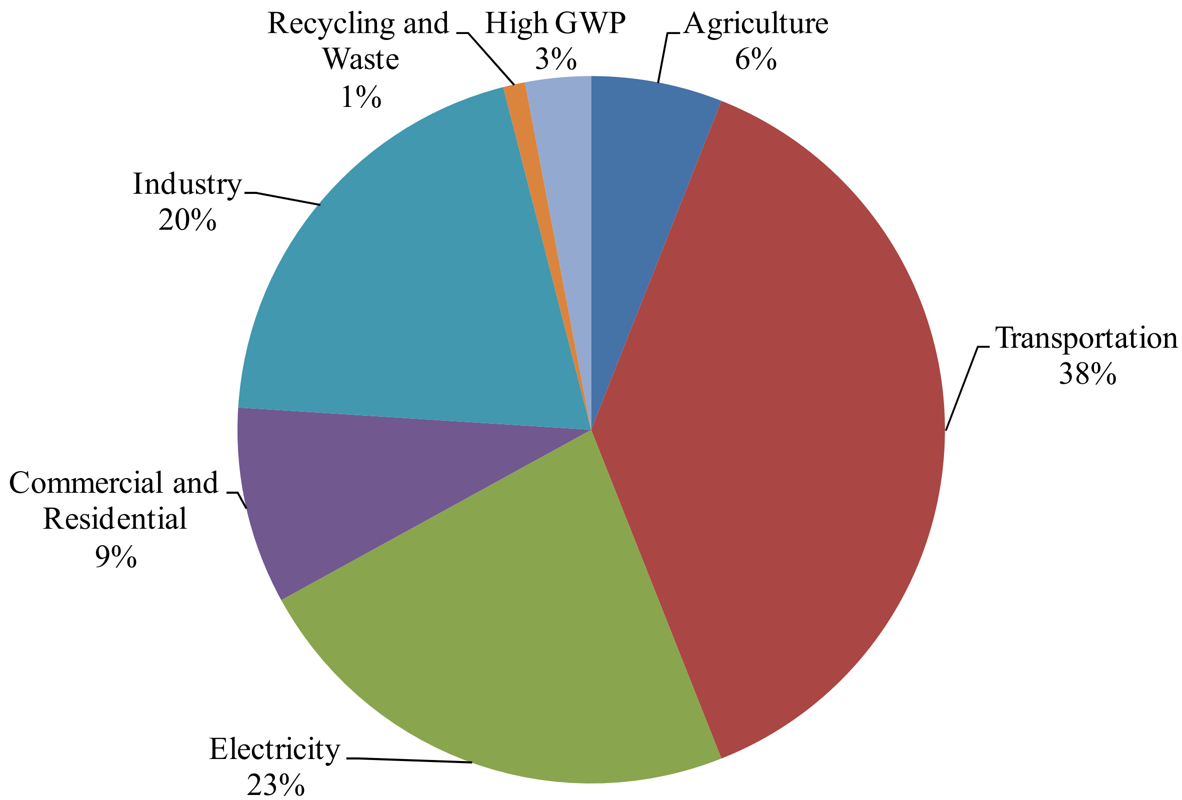

Figure 1.1: California's Greenhouse Gas Emissions (2002–2004 Average), Direct Emissions by Industrial Sector (*3*).

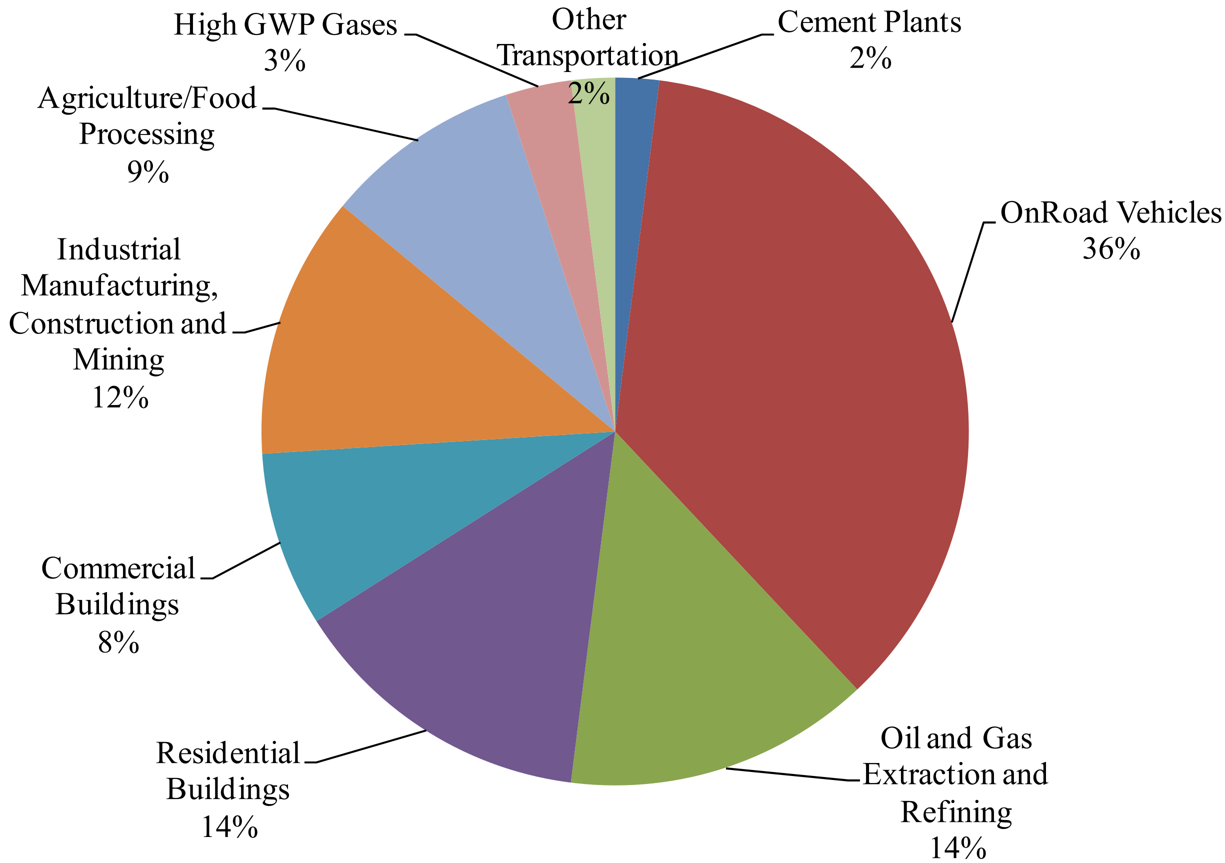

Figure 1.2: California's greenhouse gas emissions (2002–2004 Average), Direct Emissions Based on End Use (*3*).

Lutsey developed a framework that considers the current research on GHG emissions reduction alternatives from all sectors of the U.S. economy, and puts these alternatives on an equal footing (*4*). In his framework, the alternatives are prioritized by how cost-effectively they reduce GHG emissions. The study's findings show that there are many GHG-mitigation strategies in which the cost reductions from energy savings outweigh the initial cost. These strategies can be considered "no regrets" strategies because they are low cost and save energy in the meantime.

Figure 1.3 illustrates this analytical framework, where a "supply curve" concept is used to combine the environmental impacts and the cost-effectiveness of measurements of a number of GHG-mitigation alternatives. Each GHG-mitigation option yields an incremental GHG reduction (e.g., metric tons of GHG reduced with expected market penetration) that appears on the x-axis Each option's cost-effectiveness (e.g., net cost per ton of GHG reduced) appears on the y-axis. These options are then ranked and displayed by their relative cost-effectiveness.

Two types of cost are considered in this analysis: the initial implementation cost and the life cycle cost. The latter includes both the initial cost of implementation and the future costs of ongoing operations after implementation over a time horizon. When there are future energy savings, the initial cost may be offset by the operating cost savings. When the future operating cost savings is higher than the initial cost, the net cost (initial cost minus the direct benefits) can be negative. Those alternatives that show a negative net cost per ton of CO_2-e reduction are the "no regrets" measures (Alternatives 1, 2, and 3), meaning that in the analysis period they can bring down GHG emissions and save money at the same time. These options are recommended as the highest priority for implementation.

Although Lutsey's analysis includes a variety of GHG-mitigation measures, it does not consider any pavement-related strategies.

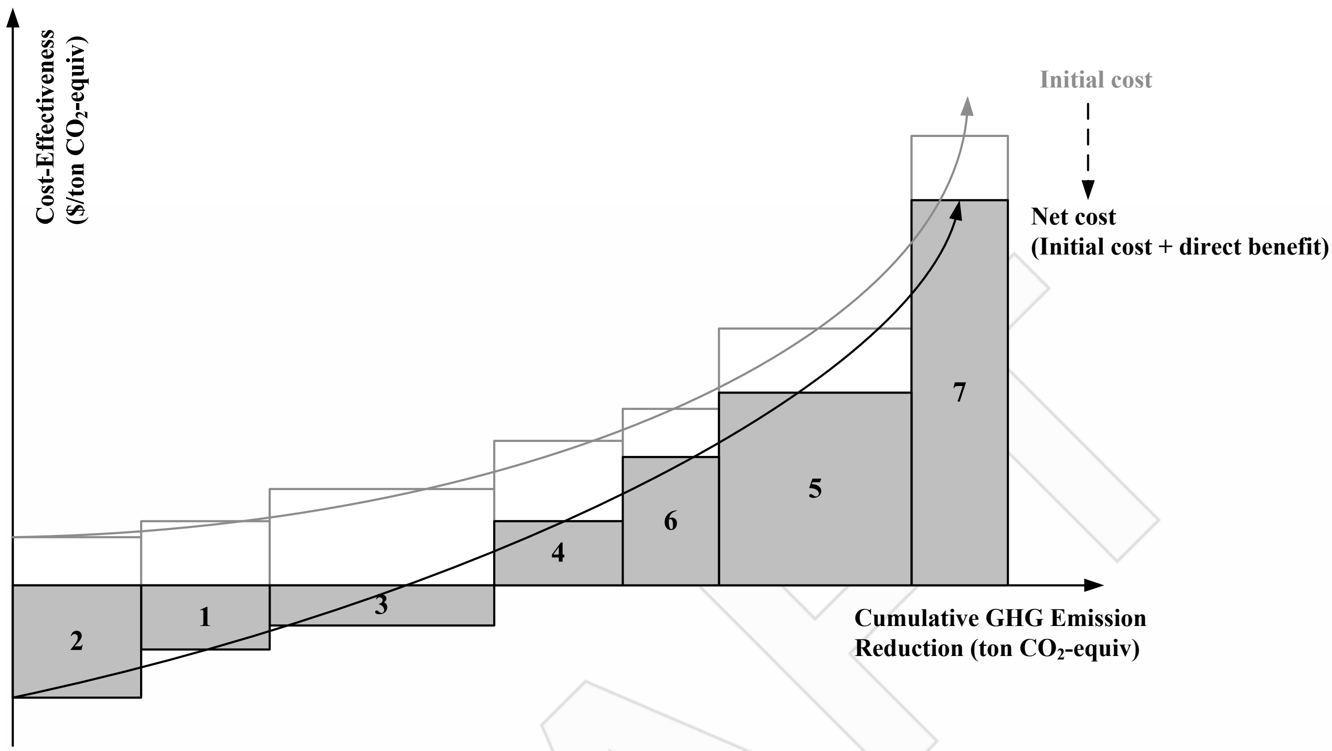

Figure 1.3: Illustration of cumulative CO_2 reduction cost-effectiveness curve: Illustration of cumulative CO_2 reduction cost-effectiveness curve (*4*).

With respect to the costs of timely application of M&R treatments, earlier UCPRC research for Caltrans on asphalt pavements (also referred to as "flexible pavements") showed that applying a pavement maintenance treatment before a pavement reaches an advanced level of cracking (i.e., pavement preservation) can potentially reduce the life cycle cost compared with waiting until the pavement is damaged enough to require rehabilitation (*6*). Reduced pavement life cycle costs are also expected to result from pavement preservation treatments to concrete pavements (also referred to as "rigid pavements" or "PCC pavements") because faulting of joints increases the effects of loading applied by heavy trucks, as do other causes of roughness on both flexible and rigid pavements. This phenomenon is due to the dynamic interaction of the pavement and the truck suspension, and it results in shortened pavement life and, therefore, increased life cycle cost. Faulting has been a common distress on jointed plain concrete pavements in California, most of which were built before 1999 without dowels and prior to the early 1980s often with 18 and 19 ft (5.5 and 5.8 m) joint spacings; the state has since changed design practices. As noted earlier, pavement roughness is also a major cause of increased fuel use and GHG emissions for vehicles.

1.2 Pavement Life Cycle Assessment

1.2.1 Pavement Characteristics and Fuel Consumption in the Use Phase

Although there are multiple aspects of the interaction between pavement and the environment, the rolling resistance of the pavement surface has been the focus of a number of studies because of its effect on vehicle fuel consumption. The first two mechanisms noted above that influence effective rolling resistance are characterized using the following terms:

- International Roughness Index (IRI) is used as a measure of “smoothness” (which is sometimes termed “roughness” from another perspective), and
- Mean profile depth (MPD) or mean texture depth (MTD) is used as a measure of pavement macrotexture (*7*), depending on whether pavement is rigid or flexible.

There are four components of pavement texture defined based on the maximum dimension (wavelength) of their deviation from a true planar surface: roughness (unevenness), megatexture, macrotexture, and microtexture. The relative scale between each component is shown in Figure 1.4 (*8*). As part of a pavement management system (PMS), IRI and macrotexture can be measured on an entire state pavement network each year by using high-speed vehicles, as Caltrans is currently doing. Studies have shown generally that for passenger vehicles a 10 percent reduction in rolling resistance can lead to a 1 to 2 percent improvement in fuel economy *(9-11).*

A recent North American calibration of the World Bank’s *HDM-4* model for vehicle operating costs, reported in NCHRP Report 720 (*12*), found that:

> *“…the effect of surface texture is statistically significant at [the] 95 percent confidence interval only for heavier trucks and at low speed. An explanation of this observation is that at higher speeds, air drag becomes the largely predominant factor in fuel consumption. The increase in rolling resistance (i.e., fuel consumption) due to texture is masked by the increase in air drag due to speed.”*

The NCHRP study also found that between roughness and surface texture:

> *“For fuel consumption, the most important factor is surface roughness (measured using IRI). An increase in IRI of 1 m/km (63.4 in./mi) will increase the fuel consumption of passenger cars by about 2% irrespective of speed. For heavy trucks, this increase is about 1% at normal highway speed (96 km/h or 60 mph) and about 2% at low speed (56 km/h or 35 mph).”*

Coefficients for surface texture (measured by MPD) are included in the recommended model in NCHRP Report 720 and indicate that for heavy trucks “an increase in MPD of 1 mm will increase fuel consumption by about 1.5% at 88 km/h (55 mph) and about 2% at 56 km/h (35 mph).”

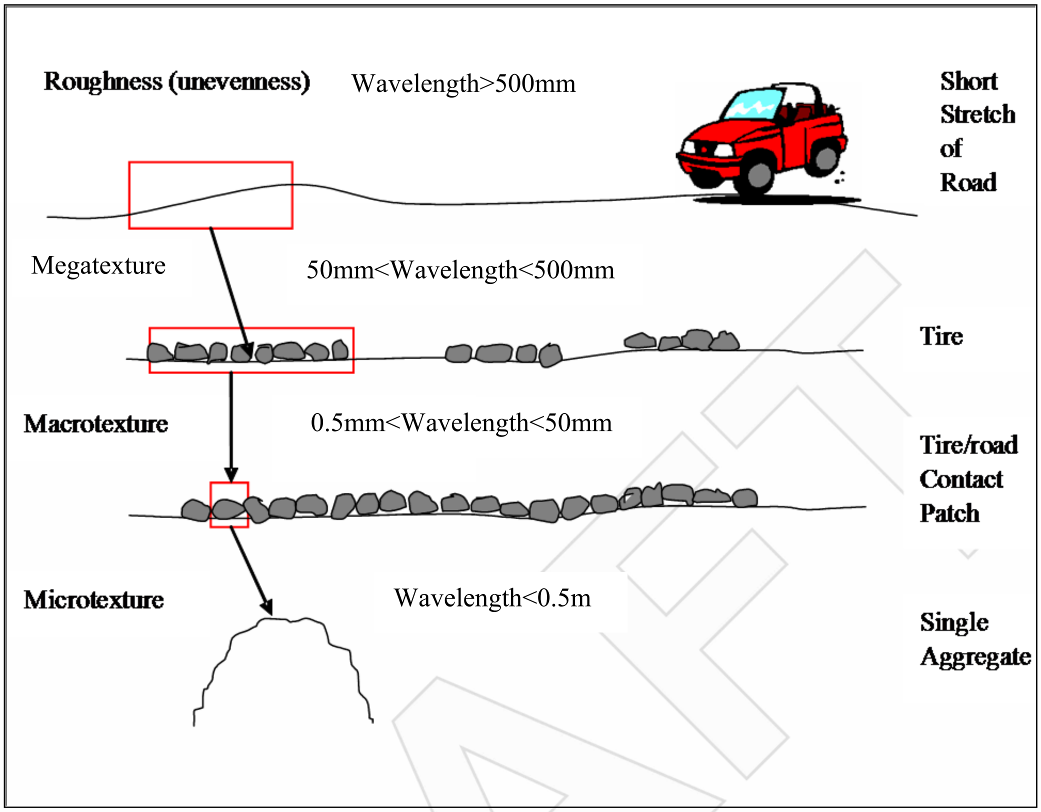

Figure 1.4: Pavement texture and wavelength (Sandberg, 1997, pp 3).

Pavement deflection, the third mechanism of effective rolling resistance affecting fuel consumption and therefore GHG emissions, has been associated with two phenomena:

- Deflection of the pavement surface creates a change in the geometry of the pavement, with a larger deflection causing curvature in the pavement surface that increases fuel consumption, and
- Dissipation of energy in the pavement structure due to the viscoelastic nature of asphaltic materials.

The first phenomenon is the subject of current research at the Massachusetts Institute of Technology (*13*). The current goal of that work is to provide "a first-order understanding of the impact of deflection within pavement-vehicle interaction and the effect of structural and material properties on fuel consumption." A purely mechanistic model has been developed, and the deflections it produces have been calibrated and validated with deflections measured by means of Falling Weight Deflectometers (FWD) for a set of Long-Term Pavement Performance (LTPP) test sections. In the MIT model "the pavement system is modeled as a beam on a viscoelastic subgrade and the impact of the base layer on pavement performance is not included." The model assumes a two-layer pavement structure with a linear elastic surface layer on a linear elastic fluid subgrade (referred to as a Winkler foundation) with viscous damping added, creating a viscoelastic subgrade. The model includes consideration of delayed deflection that is based on the viscoelastic behavior of the subgrade, while it considers asphalt and concrete as linear elastic materials, although asphalt is a highly viscoelastic material with stiffness and damping dependent on time of loading and temperature.

The fuel consumption model in the current MIT work treats it as a function of the uphill grade caused by the deflection under the axle load to estimate the increased fuel consumption on pavements with higher deflections based on the positive grade caused by the deflection. The model allows comparison of the grade caused by pavement deflection for pavement structures with different stiffnesses, different thicknesses and subgrade damping ratios, and commensurate fuel consumption. The model otherwise assumes a completely flat profile. Using the distributions of backcalculated surface layer stiffnesses and thicknesses for the surface layers (asphalt or concrete) and the backcalculated stiffnesses of subgrades collected across a large national LTPP data set, the MIT researchers have estimated deflections and additional fuel consumption compared to a flat profile for asphalt and concrete pavements. They have found that on average concrete pavement deflections increase fuel use for passenger cars by 0.2 percent and asphalt pavement deflections increase fuel use for passenger cars by 1.2 percent. For trucks, the MIT researchers found that on average concrete pavement deflections increase fuel use by 1.3 percent and that asphalt pavement deflections increase fuel use by 7.7 percent compared to a flat profile.

The MIT researchers note that the two types of pavement were compared using two different sets of pavements, and the distribution of surface layer thicknesses (asphalt) for the flexible pavement LTPP sections were generally thinner, most likely reflecting pavements designed for low traffic, while the surface layer thicknesses (concrete) for the concrete LTPP sections were thicker, most likely reflecting pavements designed for heavier traffic. In the LTPP data set used, the average asphalt thickness was 0.49 ft (150 mm, 5.9 in.)] and the average concrete thickness was 0.79 ft (240 mm, 9.4 in.). The MIT model cannot currently consider composite (asphalt surface on concrete pavement) or semi-rigid (asphalt surface on cement-bound base) pavement structures, which are common in California, particularly on routes with heavy traffic. It can potentially consider aggregate base and subbase layers if they are combined with the subgrade to produce a single unbound layer. The first-order comparison with a flat profile for both pavement surface types does not consider interactions of deflection on fuel use with roughness. The MIT model also does not consider vehicle energy lost through hysteresis in the viscoelastic layers, and in particular does not consider viscoelastic energy dissipation losses in asphalt-bound surface or base materials that are a function of the stiffness and damping in those layers. The stiffness and damping of the asphalt-bound layers are controlled by the temperature of the asphalt-bound materials and the speed of the vehicles on the pavement, and are therefore highly specific to different materials, climates and traffic patterns.

The second pavement deflection phenomenon, dissipation of energy in the pavement structure due to the viscoelastic nature of asphaltic materials, has been the subject of recent research at the University of Lyon, France (*14*). This model assumes linear viscoelastic behavior for asphalt-bound layers and a linear elastic underlying soil layer, and uses a viscoelastic model developed at Lyon that considers both the stiffness and the damping of the asphalt-bound materials to be functions of temperature and time of loading (vehicle speed). The model is implemented in a three-dimensional finite element code. Demonstration results for an example asphalt pavement with a polymer-modified surface layer (0.2 ft, 60 mm thick) and two conventional asphalt concrete layers (each 0.26 ft, 80 mm thick) beneath it indicate that "for summer conditions at 63°C [145°F pavement temperature], the dissipated energy may represent up to 5.5% of the total energy consumed to make the truck move at a speed of 100 km/h [63 mph]. However, at 15°C (59°F, reference mean temperature for pavement design in France) and for the same vehicle speed of 100 km/h, the increase in fuel consumption is limited to 0.25%. More generally, at very low temperatures (< 15°C) and at very high [speeds], where bituminous material can be considered as purely elastic in a first approximation, fuel consumption excess is negligible (< 0.25%)." This model can potentially be simplified and implemented in the future to consider different types of pavement structures in California, including various thicknesses, different types of asphalt materials (including rubberized and polymer-modified asphalt which have different stiffness and damping than conventional asphalt), base layers including unbound and cement stabilized bases, composite pavement, aging (which makes asphalt stiffer and more elastic), different axle weights, different pavement temperatures, and interaction of pavement temperatures across the day and year with the times when traffic is using the pavement.

The combined effects of both pavement deflection phenomena have been included in rolling resistance models such as the *HDM-4* model (*15*), where there is a deflection rolling resistance factor for asphalt pavements and vehicles weighing more than 2,500 kg (5,500 lb), and no deflection effect shown for concrete pavements or lighter vehicles. The coefficient requires estimation of the deflection of the pavement using a Benkelman Beam device (which uses a 9,000 lb wheel load [40 kN]), which requires simulation of pavement stiffness. Recent experimental data from measurements of fuel consumption on different types of pavement in both winter and summer to calibrate the *HDM-4* model reported in NCHRP Report 720 (*12*) indicated that "pavement type [does] not affect the fuel consumption of any vehicle class except for heavy trucks." More detailed analysis of the same data (*16*) indicated that articulated (heavy) trucks and light trucks had statistically significant higher fuel consumption when operated on asphalt pavements at 35 mph (56 km/hr) in the summer, and that there was little if any difference at 45 or 55 mph (72 or 88 km/hr, faster vehicle speeds increase asphalt stiffness and make it more elastic), or at any speed in the winter when the asphalt layers are stiffer and more elastic.

The effects of the three mechanisms (roughness, macrotexture, deflection) by which pavements influence fuel consumption and GHG emissions becomes significant because the change affects all of the vehicles using the pavement, although it is a relatively small change for an individual vehicle. Furthermore, improvements to pavement surface characteristics can be implemented rapidly using currently available technology and an established industrial capability to achieve reductions in fossil fuel consumption and GHG emissions. In contrast, some other approaches to improving fuel economy, such as changes in land use policy or to tires, vehicles, or fuel technology, can take many years to achieve full market penetration. This is particularly true in times of economic uncertainty, when consumers are less able to make an initial investment in new housing, tires, or vehicles. Renovation of a pavement network that has been neglected with respect to maintenance and rehabilitation over a number of years can also take time to implement; however, it can be accomplished in a relatively short period of time compared to changing the vehicle fleet or land use, if sufficient funding and industry capacity is available. Changing pavement characteristics is also different from other approaches that can have a significant and relatively rapid impact, such as maintaining proper tire inflation and changes in tire technology, because it does not require attention, action, or direct out-of-pocket spending decisions by the vehicle operator.

1.2.2 Use of Life Cycle Assessment to Consider Net Effects of Changing Pavement Characteristics

As with all potential changes to a system to reduce environmental impacts, unintended negative consequences can occur that actually harm the environment more than help it. Because restoring pavement smoothness and texture introduces upstream environmental burdens from construction, material production, and transport, a system view and life cycle perspective is needed to examine the net impact of reducing pavement rolling resistance. The concepts of systems analysis and life cycle assessment (LCA) can help evaluate proposed changes as well as aid in the decision-making process.

LCA provides a comprehensive approach to evaluating the total environmental burdens of a product. It is an approach that examines a product from cradle-to-grave, evaluating all the inputs and outputs from raw material production to the final end-of-life. For pavements, the cycle includes the Material Production, Construction, Use, Maintenance and Rehabilitation, and End-of-Life (EOL) phases.

The International Organization for Standardization (ISO) has set up a series of guidelines for conducting LCAs (*17*); however, an LCA on a pavement is much more complex than one for a general consumer product, the initial application of many LCAs (*18, 19*). The literature on pavement LCA offers conflicting answers to questions regarding the environmental impacts of pavement decisions, often because of a lack of consistent practice for LCA and the use of different data sources. Other problems with current pavement LCA research include the following:

- unrepresentative functional units (the quantified performance of a product system for use as a reference unit) and analysis periods;
- a lack of transparency in life cycle inventory development, such as allocation practices for bitumen and other industrial co-products;
- incomplete scope, such as missing life cycle phases, most typically the Use Phase; a lack of state-of-the-art models for many subprocesses in the pavement life cycle; and
- exclusion or incomplete analysis of the EOL Phase.

In addition, many studies have relied on a single data source, while in reality there may be a range of data sources for a given process reflecting differences between materials sources, manufacturing processes, transport distances, construction practices, pavement structure and materials design practices, vehicle fleets, and a host of other variables that vary among projects, regions, and over time (*20, 21*).

1.3 Long-Term Goal of Research Program and Initial Practices Considered in this Study

The long-term goal of the overall Caltrans- and UC-sponsored UCPRC pavement life cycle assessment research program is to develop and adapt existing LCA models. The purpose behind this is to develop the models so they can be used to evaluate state and local government practices for management, design, and construction of pavement M&R in terms of their potential contribution to meeting AB 32 objectives, as well as other energy use and environment-related goals, such improved water quality or criteria air pollutant requirements. Once the LCA models are fully developed and can model both the entire range of conditions existing in the state highway network and all the treatment types commonly used by the state, the goal is to apply them to the full Caltrans network through evaluations of factorials that cover the conditions across the entire network. After accomplishing this, the state can then evaluate the cost-effectiveness of pavement management practices and policies to help meet AB 32 objectives by considering life cycle costs relative to any potential environmental and energy-saving benefits.

Practices available to pavement managers, designers, and specification developers that might be optimized to help meet AB 32 objectives include, but are not limited to:

- Programming of maintenance and rehabilitation treatments to rough sections of pavement with high traffic,
- Development of specifications for improved smoothness during construction,
- Use of recycling strategies (in-place, plant, secondary materials, consideration of transportation distance and type),

- Selection of design life (shorter-life designs [looked at in this report] versus long-life designs including lane replacement),
- Selection of pavement structure type (i.e., flexible, semi-rigid, jointed plain concrete, continuously reinforced concrete), and
- Selection of construction closure type (continuous versus nighttime construction), which will impact road user traffic delay.

The initial practices to be addressed, and which are included in this report, focus on (1) the effects of application of relatively inexpensive pavement M&R treatments applied to rough pavement versus not applying the treatment, and (2) the effects of setting smoothness specifications for M&R treatment construction. The differences in impact of these practices for pavement segments with different traffic levels were included in the study. (These are the objectives of the study shown in this report, which are detailed in Section 3.1). The effects of these two practices are compared with the expected GHG-emissions impacts from policies to improve vehicle fuel economy and to reduce vehicle-miles traveled.

These two practices (relatively inexpensive M&R treatments and smoothness specifications) were selected for this initial study for the following reasons:

- They were expected to have a relatively large potential impact.
- They can be implemented relatively quickly: smoothness specifications are already being implemented, and these M&R treatments require identification of rough, high traffic volume sections in the pavement management system and additional funding; they do not require upgrading of non-pavement features of the road.
- They do not require models for pavement deflection effects, detailed modeling of pavement performance with recycled materials, creation of recycled material allocation rules, or models for fuel consumption from construction traffic delay, which require additional research work before they are ready for implementation.

Other practices in the list above can potentially be addressed in the future, depending on the objectives set by the program funders. If there is funding, the intention is to also further develop the models so that they may be used to address other sustainability goals, such as those for reducing criteria air pollutant emissions.

1.4 Overall Project Objectives

These are the objectives of Partnered Pavement Research Center (PPRC) Strategic Plan Element 4.26, "Studies to Support Global Climate Change Initiative":

- Develop an initial LCA framework, including standard assumptions, system boundaries, and documentation requirements, and review, critique, and modify it with an expert group through a workshop to produce a final version.
- Develop data, methods, and models for use within the final LCA framework for simulation of greenhouse gas emissions and energy use on the state highway network as a function of the application of several typical treatments and the change in pavement surface characteristics (smoothness and macrotexture) due to that construction.
- Produce initial case studies for two typical Caltrans Capital Preventive Maintenance treatments (one for concrete pavement and one for asphalt pavement) applying the framework and data, methods, and models, in order to demonstrate their use and to provide a preliminary indication of the net effects (considering the entire life cycle of the treatment as defined by the framework, including material production, construction, and vehicle use) on greenhouse gas emissions and energy use of changes in pavement smoothness and surface texture from pavement maintenance or rehabilitation.

The initial M&R practices selected for evaluation are part of the Caltrans pavement preservation program: Concrete Pavement Restoration B (CPR B) for concrete and pavement preservation overlays for asphalt, both of which are performed using nighttime closures. CPR B consists of diamond grinding with two to five percent slab replacement. Pavement preservation overlays are relatively thin overlays that often include milling of a portion of the existing asphalt surface prior to placement of the overlay. Both treatments are a type of preservation treatment called Capital Preventive Maintenance (CAPM), described in more detail in Chapters 3 and 4.

A technical memorandum (*22, 23*) completed the first objective. This report completes the second objective for two treatments commonly used by Caltrans and the third objective.

1.5 Relationship of This Project to MIRIAM, UC Research, and Industry

Funding for this work was provided by the California Department of Transportation (Caltrans), Division of Research and Innovation, with additional funding from the University of California Institute of Transportation Studies (Berkeley and Davis) through grants from the UC Multi-campus Research Programs and Initiatives (MRPI) program. The funding from the MRPI project has paid for part of the development work for the LCA models and for extrapolation of the results to consider local government issues.

The entire project has been done in partnership with the MIRIAM (Models for rolling resistance In Road Infrastructure Asset Management systems) pooled-effort project (each partner has their own funding sources), whose partners include Caltrans and eight European national highway research laboratories and which is led by the Danish Road Institute (Ministry of Transportation). As part of MIRIAM, the methodology and results included in this report were reviewed by staff of the Swedish Road and Transport Research Institute (VTI), and the Slovenian National Building and Civil Engineering Institute (ZAG), whose comments and critique are greatly appreciated.

The results presented in this report include comments, critique, and information provided by the Portland Cement Association (PCA), the Southwest Concrete Pavement Association, the California Asphalt Pavement Association, the Rubber Pavement Association, and some industry sources outside of these organizations. This report was reviewed by concrete and asphalt industry experts through their California respective industry organizations, and written comments were provided. Mix designs and other technical information were supplied as part of the review process. Errors and omissions in the original draft have been addressed based on those comments, which are gratefully acknowledged. Responses to each comment were returned in writing to industry along with the revised report for review and additional comment.

Development of the *UCPRC Pavement LCA Guideline* was done in collaboration with the International Society for Asphalt Pavements (Asphalt Pavement and the Environment Technical Committee, ISAP APE) and the International Society for Concrete Pavement (ISCP).

The results presented in this report are solely those of the authors, and do not necessarily reflect the views or opinions of these organizations.

1.6 Scope and Purpose of This Report

This report first presents the methods, approach, tools, and models developed to calculate the net life cycle impact of the pavement preservation treatments—as initial examples—considering the Material Production, Construction, Use, and End-of-Life phases. The report then presents four case studies to demonstrate the ability of the models to assess the change in the outcome (net analysis period energy and GHG emissions) for those example treatments. The results of the case studies also provide a preliminary indication of the relative effect on the outcome of the following variables:

- Automobile and truck traffic levels
- Constructed smoothness of the M&R treatment
- Material used for the M&R treatment (type of concrete or asphalt)

An effort was also made to compare pavement management strategies with two GHG-reduction strategies identified by CARB for the transportation sector: improved fuel efficiency for passenger vehicles and reductions in vehicle miles travelled (VMT) growth. Scenarios were run on the four example case studies considering improvements in the fleet average fuel efficiency compared to no changes to average fleet fuel efficiency, and extrapolation of historical annual growth in VMT versus no growth. These comparisons were made to determine whether the potential impacts of pavement management decisions warranted further evaluation for an entire factorial of cases representing the full network. These comparisons are outside the decision-making scope of Caltrans, but are of interest for other decision-makers in state and regional government who fund pavement improvements.

2. LIFE CYCLE ASSESSMENT FRAMEWORK

On May 5 to 7, 2010, the University of California Pavement Research Center (UCPRC) hosted a Pavement Life Cycle Assessment Workshop in Davis, CA (U.S.). The primary goal of this workshop was to discuss an initial LCA framework, including standard assumptions, system boundaries, and documentation requirements, and to review, critique, and modify it to produce a final version for use in future UCPRC pavement LCA studies. The workshop included a discussion of some key questions for practicing LCA of pavement, and documentation of the resulting decisions regarding their application to UCPRC pavement LCA studies (*22*). With the feedback from the workshop, the *UCPRC Pavement LCA Guideline* (*23*) was updated and then used for the LCA case studies presented in this report. The work performed in this study follows the *UCPRC Pavement LCA Guideline*.

2.1 Approach for Later Application to the State Pavement Network

The long-term goal of this research program is to develop a pavement LCA model and apply it to support pavement management and decision-making for the state highway pavement network. To address the heterogeneity of the traffic and geographic conditions that will affect the LCA models when they are extended to M&R of the overall state pavement network, the following approach will be used in the future:

1. The highway network will be divided into categories based on the factorials discussed in Section 2.2.
2. For each category, case studies will be performed based on conditions typical for that category in order to develop representative data and to develop any needed adjustments to the models.
3. Results from the categorical case studies will be applied to the network, and additional sensitivity analyses will be performed as needed depending on the issue to be addressed, such as, but not limited to:
    - Range of smoothness or rolling resistance and surface characteristics
    - Ranges of pavement damage rates depending on design life, climate, and truck traffic, and characterized by pavement performance models, which control the frequency of required maintenance and rehabilitation (design life is selected by agency policy)
    - Alternative treatments and design lives for the treatments
    - Alternative materials (including type, production method, etc.)
    - Hauling distance for materials and/or recycled materials
    - Traffic levels and fleet composition (cars, truck types), and inclusion of new vehicle technologies (e.g., hybrid, electric vehicles)
    - Extent of congestion
    - Traffic closure strategies during construction

4. Where a network-wide result is the goal, the results for the network will be summarized. Where guidance for project-level decisions is the goal, the results will be used to provide recommendations based on each project category.

M&R of existing pavements is the primary initial focus of this research because the majority of state and local pavement funding in the U.S. and particularly in California is devoted to preservation, maintenance, rehabilitation, and reconstruction of existing pavement on the current alignment, not to construction of new lanes. In addition, most treatment selection decisions are based on life cycle cost analysis (LCCA), rather than environmental impact. The selection process of treatment type among the various types of asphalt and concrete alternatives reflects questions about effectiveness and efficiency and is of understandable concern in competition for commercial market share.. The researchers performing this study believe that there is currently sufficient information to study alternatives within each material type, but the lack of a validated implementable deflection mechanism model that can be applied across the range of traffic, pavement structure types, and climates in the state prevents addressing differences between asphalt and concrete at this time. The current state of deflection models was discussed in Section 1.2 of this report, and it is clear to the researchers that the potential for deflection mechanisms to significantly affect conclusions warrants caution until the models are better sorted out and have better validation for the range of variables affecting their results.

For these reasons, this initial study assumes that the pavement surface type is the same before and after M&R; in other words, concrete pavement will remain concrete pavement and flexible pavement will remain flexible pavement. This allows for a more open critique and adjustment of the models and data, and eliminates considerations about the potential impact on market share for competing products, although that still remains when choices of materials within a pavement type are considered. Once these models are sufficiently developed and critiqued, however, the environmental impacts of changes to pavement surface type can be included in future studies.

2.2 Factorial and Sensitivity Analysis

Two main factors are considered in constructing the factorial to characterize the state pavement network: *traffic condition* and *pavement condition.* Traffic condition includes road type, road gradient, road access type, and traffic level. Pavement condition currently includes the pavement surface type and pavement surface characteristics, and in the future it may consider pavement structure type. The factorial and values defining the categories are shown in Table 2.1 and are explained as follows:

1. Road type: urban road or rural road.
   This factor mostly affects the speed profile of vehicles. Studies have shown that vehicles running on urban roads and rural roads have different driving behavior, mostly due to congestion and trip length.
2. Road access type: restricted access or unrestricted access.
   This factor affects the speed profile of vehicles. Restricted access roads are freeways and expressways, and unrestricted access roads include all other types of road. On restricted access roads, vehicles have less speed fluctuation because there are no stop lights or stop signs and access is through ramps, while on unrestricted access roads vehicles could encounter stops and frequent cycles of acceleration and deceleration.
3. Road grade: mountainous road or flat road.
   This factor affects engine power because on mountainous roads vehicle engines need to overcome extra resistance when going uphill or the assistance of gravity when going downhill. It is not certain whether there is an interaction in the models used between roughness, texture, and grade (this will be explored in later studies).
4. Traffic level: Average Annual Daily Traffic (AADT) and Average Annual Daily Truck Traffic (AADTT).
   This factor essentially determines the multiplier effect for fuel consumption during the Use Phase, since the net impact of pavement condition is dependent on the number and type of vehicles using the road.
5. Pavement surface type: asphalt or concrete.
   Determines the M&R treatment to be applied.
6. Pavement surface characteristics: smoothness (International Roughness Index [IRI] and Mean Profile Depth [MPD] or Mean Texture Depth [MTD]).
   IRI is the primary pavement surface factor affecting vehicle fuel consumption while macrotexture plays a smaller role. Together with deflection (not included yet, but the same if pavement structure type doesn't change) they control the effective rolling resistance that the vehicle engine needs to overcome. MPD is used to characterize asphalt surfaces and MTD is used to characterize concrete surfaces. The Use Phase model used converts MTD to MPD using an empirical equation.
7. Treatment: pavement treatment options, such as concrete pavement restoration (CPR) for concrete pavement or asphalt overlay for asphalt pavement.
   This factor includes the options for possible M&R strategies. Each option includes a material production process, construction process, and resulting pavement surface characteristics.

As a first demonstration of the models developed for this study, only a few selected variables are considered in the example case studies included in this report.

Table 2.1: Factorial Analysis for Case Study Selection

Attributes	Possible Value
Road type	Rural road; urban road
Road access type	Restricted access; unrestricted access
Road grade	Flat road; mountainous road
Traffic level	Different levels of AADT and AADTT, categorized
Pavement surface type	Asphalt pavement; cement concrete pavement
Pavement surface characteristics	Different levels of roughness and macrotexture
Treatment	Different pavement treatment options

3. LIFE CYCLE ASSESSMENT GOAL AND SCOPE DEFINITION

3.1 Goal

As noted in Section 1.3, the goal of the Caltrans-funded pavement LCA studies, once the LCA models are sufficiently able to model the range of cases present in the state highway network, is to apply them to the full network through evaluations of factorials covering the range of conditions across the network. The goals of the initial LCA study and example case studies documented in this report are to produce example results regarding the effects of the following items on GHG emissions and energy use:

- The application of two types of M&R treatment to rough pavement versus not applying the treatment (highly dependent on M&R funding levels)—with one treatment applicable to concrete pavement and one applicable to asphalt pavement and with two materials options for each treatment. The treatment selected for the example for existing jointed plain concrete pavement is called "Concrete Pavement Restoration B (CPR B)" and it involves pavement grinding, moderate slab replacement, spall repair, and joint seal repair. It is for projects where between 2 and 5 percent (3 percent was assumed in the examples in this report) of the total number of slabs in the lane exhibited third-stage cracking (shattered slab) or were previously replaced. Dowel bar retrofit is used for some projects but is not nearly as common as CPR B. The treatment for existing asphalt pavement, which consists of milling and overlay, is called "asphalt overlay." These treatments are listed in the Caltrans LCCA Manual (*24*) as the first choices for use on projects using funding from the Caltrans pavement preservation program. Pavement preservation examples were selected as the first examples because Caltrans uses pavement preservation treatments on pavements with "Minor Structural Distress," which are pavements that have moderate cracking and may have a poor ride (*25*). Pavement preservation projects only address pavement issues and do not address other roadway issues, which reduces the project delivery time and increases the portion of the total project funding devoted to the pavement compared to longer-life projects. Most pavement preservation work is done under nighttime closures, and traffic is put back on the pavement in the morning.
- Different levels of smoothness during construction for those two treatments, comparing good and poor initial smoothness.
- Application of the example pavement preservation treatments compared to doing nothing, compared with the effects of expected changes in fleet fuel efficiency (one prediction of those changes) versus no change, and historical annual growth in vehicle miles traveled versus no growth.

The results are intended to provide both a calculation of the GHG emissions and energy use for each of these alternatives, and a comparison of the differences between them.

Table 3.1 shows the categories included in the four example case studies, which are based on the factorial laid out in Table 2.1. Other categories will be evaluated in later studies.

Table 3.1: Factorial Attributes of Four Case Studies

Attributes	Categories for Case Studies Underlined
Road type	Rural road; urban road
Road access type	Restricted access; unrestricted access
Road grade	Flat road; mountainous road
Traffic level	Two levels of AADT/AADTT
Pavement surface type	Asphalt pavement; cement concrete pavement (not compared with each other)
Pavement surface characteristics	Two (asphalt) or three (concrete) levels of constructed roughness versus doing nothing; one level of constructed macrotexture versus doing nothing
Treatment	One treatment type for each pavement type; two materials types for each treatment

3.2 Scope of the LCA

At this current stage, the scope of the LCA presented in this report is limited to four example case studies which each involve the most typical Caltrans pavement preservation treatments and materials used for those treatments. In addition, the LCA is limited to the changes in the pavement itself caused by the M&R and the vehicles that use it and assumes no changes beyond those.

3.2.1 Functional Unit

The functional unit requires defining both the physical dimensions and the performance characteristics of the pavement. Performance characteristics of the pavement preservation treatments are the design life, the constructed smoothness and texture, and the changes of smoothness and texture over the analysis period. When a pavement LCA is performed, the analysis period is determined based on the design life of the pavement preservation treatment. The functional unit is different for each case study evaluated; thus, a unique functional unit is described in detail for each case study in Section 7.1 of this report.

3.2.2 System Boundary

The framework for pavement LCA used by the UCPRC is displayed in Figure 3.1. This framework was adopted from the *UCPRC Pavement LCA Guideline* (*23*), which recommends that a pavement LCA include any pavement structure characteristics that interact with the environment. However, at this stage only pavement roughness and texture are included. Some characteristics of the pavement structure that have direct or indirect environmental implications, such as the albedo of the pavement surface and the viscoelastic response of the pavement, will be included in future research when modeling is better validated and extended to the range of conditions in California, and will likely have some effect on the relative assessment of different pavement type and materials selection, with the size of the effect dependent on climate region, location of the pavement in an urban or rural area, etc. Table 3.2 lists the processes and subprocesses that are included in the system boundary of the UCPRC Pavement LCA model. The table also identifies the items that are considered in this stage and those that are not currently considered but are planned for inclusion in the future. It should be especially noted that the end-of-life (EOL) phase is not considered in the current model, but will be considered in the future. For the pavement preservation treatments in the four example case studies presented here, an assumption has been made that the EOL phase is the same for the four alternatives, and this eliminates the need for a net result comparison.

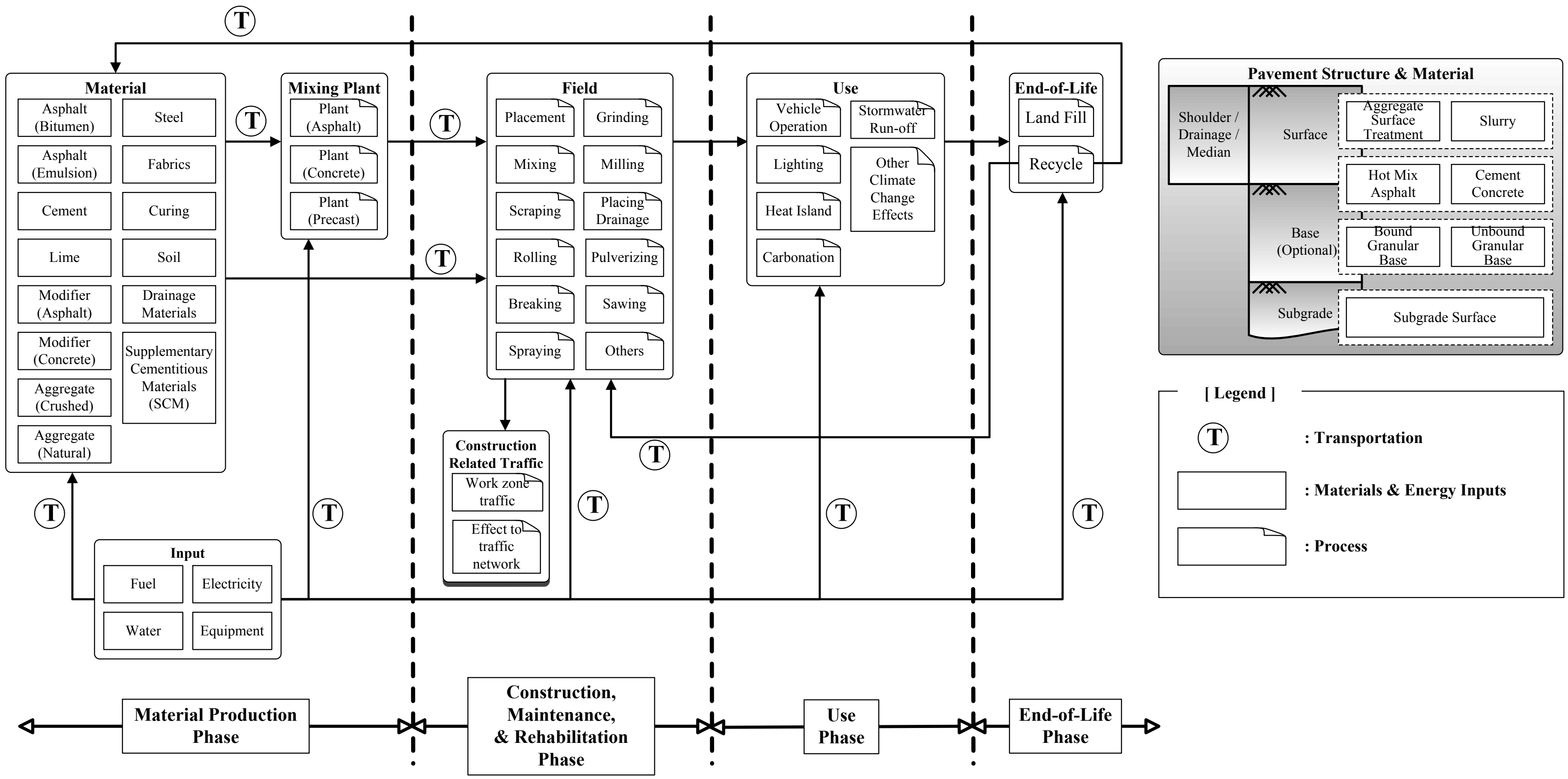

Figure 3.1: UCPRC Pavement LCA Framework.

Table 3.2: Processes and Subprocesses Included in the System Boundary

	Material Production	*Construction*	*Use*	*End-of-Life*
ENERGY				
Process Energy (Fuel & Electricity)	***Included***	***Included***	***Included***	Included
Feedstock Energy	***Included***	***Included***	***N/A***	N/A
Labor	Excluded	Excluded	Excluded	Excluded
MATERIAL				
Raw Material	***Included***	***Included***	***N/A***	N/A
Fossil/Non-renewable Material	***Included***	***Included***	***Included***	Included
Water	Included	Included	Included	Included
Land	Excluded	Excluded	Excluded	Excluded
ENVIRONMENTAL IMPACT				
Greenhouse Gases	***Included***	***Included***	***Included***	Included
Criteria Pollutants	Included	Included	Included	Included
Other Environmental Impacts	Included	Included	Included	Included
OFF-ROAD PROCESS				
Mining Operation (Material Acquisition)	***Included***	***N/A***	***N/A***	N/A
Plant/Factory Operation (Material Production)	***Included***	***Included***	***Included***	N/A
Mixing Plant Operation	***Included***	***N/A***	***N/A***	N/A
Construction Equipment Operation	***Included***	***N/A***	***N/A***	Included
Roadway Facilities Installation	N/A	Included	N/A	N/A
Roadway Facilities Operation	N/A	Included	Included	Included
Capital Investment on Production Facilities	Excluded	Excluded	Excluded	Excluded
Equipment Manufacturing	Excluded	Excluded	Excluded	Excluded
Technology Improvement	***Included***	***Included***	***Included***	Included
ON-ROAD PROCESS				
Truck Operation (Through Traffic)	***N/A***	***N/A***	***Included***	N/A
Truck Operation (Material Transport)	***Included***	***Included***	***N/A***	Included
Truck Operation (Equipment Transport)	***Excluded***	***Excluded***	***N/A***	Excluded
Transport Distance	Included	Included	N/A	Included
Traffic Congestion	N/A	Included	Included	Included
Fleet Average Passenger Vehicle Fuel Economy Improvement	***Included***	***Included***	***Included***	Included
PAVEMENT STRUCTURE				
Pavement Deterioration	***N/A***	***N/A***	***Included***	N/A
Heat Island	N/A	N/A	Included	N/A
Carbonation	N/A	N/A	Included	N/A

Note: Italicized, boldfaced items are explained in this report and considered in the four example case studies. "Included" items that are not shown in boldface and italic are planned for inclusion in future work. "Excluded" refers to items that have been excluded from this study but may be included in future studies,

3.3 UCPRC Pavement LCA Model

Figure 3.2 shows an overview of the pavement LCA model developed in this study. It consists of a user-defined Pavement module and three life cycle inventory (LCI) modules, representing the three phases currently considered in the pavement life cycle: the Material Production Phase LCI module (labeled "Material Phase LCI" in Figure 3.2), the Construction Phase LCI module, and the Use Phase LCI module. Each module consists of several submodules, some of which are used by multiple modules (e.g., the LCI database). Submodules, such as *EMFAC*, *OFFROAD*, *CA4PRS*, and *MOVES,* are discussed later in this report. In this section only the main modules are discussed.

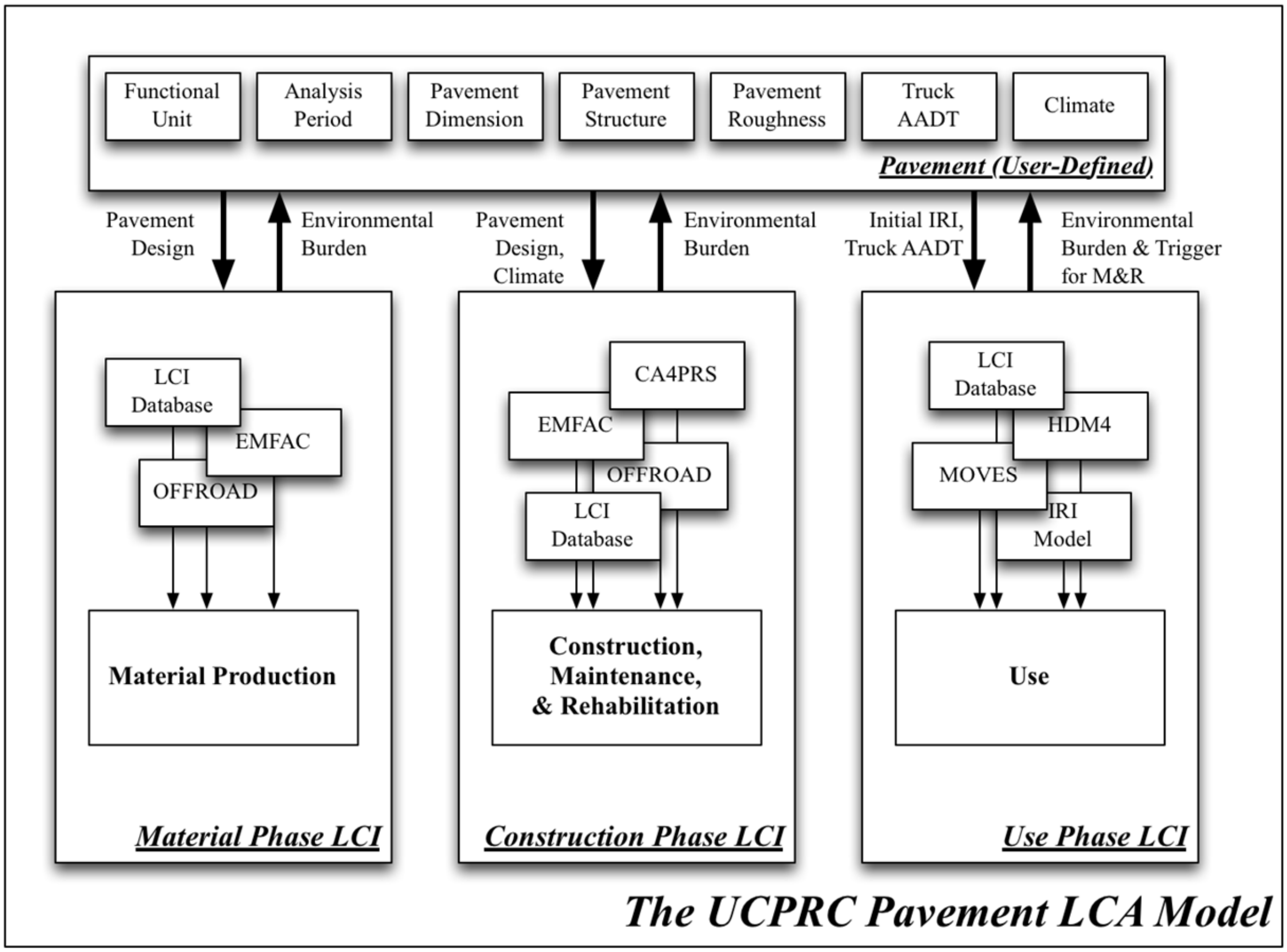

Figure 3.2: Overview of UCPRC Pavement LCA model.

The user-defined Pavement module is responsible for defining the entire project. The Pavement module includes detailed information related to the pavement and its surroundings, such as the functional unit, pavement design dimension, analysis period, annual average daily truck traffic, climate, and pavement roughness. The Pavement module passes relevant information to each module and collects the output of each module.

The Material Production Phase LCI module is responsible for calculating environmental burdens related to materials demanded within the life cycle of the pavement. This module takes inputs (mainly the amount of required materials) from the Pavement module and returns the life cycle energy consumption and environmental loads associated with material production.

The Construction Phase LCI module is responsible for calculating environmental burdens related to the construction of M&R treatments or of new pavement within the life cycle of the pavement. The Construction Phase LCI module selects a construction strategy and a construction schedule based on the pavement design information from the Pavement module. Then the module calculates operating hours for on-road and off-road construction equipment, and calculates life cycle energy consumption and environmental flows related to equipment operation.

The Use Phase LCI module is responsible for calculating environmental burdens related to traffic operation on the user-defined pavement section over its life cycle. The Use Phase LCI module takes pavement surface characteristics and traffic information from the Pavement module and calculates pavement deterioration, traffic growth, and the related life cycle environmental burdens associated with the pavement's effect on vehicle operation. The life cycle environmental burdens associated with the pavement effects in the Use Phase are reported as the difference between the burden of the business-as-usual (*Do Nothing*) scenario and the M&R treatment scenario.

4. METHOD FOR MODELING THE MATERIAL PRODUCTION PHASE LIFE CYCLE INVENTORY

4.1 Life Cycle Inventory (LCI) Analysis Overview

A life cycle inventory (LCI) tracks all the quantified environmental flows in an LCA. While a typical LCA tracks many inputs to and outputs from a system, the analysis conducted here has been limited to energy inputs in the form of their natural state (as characterized by total primary energy) and greenhouse gas (GHG) outputs. This limited scope reflects the goal of the study, which is focused on characterizing climate change impacts for state highways (typically a small land area covered in an urban area). However, future work should expand the scope to include other potentially important environmental impacts, for example air pollutants with direct effects on human health.

ISO 14040 briefly describes a general method for developing LCIs (*17*). A methodology more relevant to the UCPRC Pavement LCA model is described starting in Section 4.2 (for the Material Production Phase) and continues in Chapters 5 and 6 (for the Construction and Use phases, respectively). The discussion in this section focuses on the overall development of LCIs and specifically refers to the Material Production Phase. The methods used to generate these LCIs are also applicable to LCIs used generally for the Construction and Use phases.

The first step in developing a Material Production Phase LCI is to construct flow diagrams for each material production process. Flow diagrams for this already exist for most pavement material production processes. In this report, flow diagrams from the U.S. EPA's *Compilation of Air Pollutant Emissions Factors, Volume I: Stationary Point and Area Sources* (AP-42) have been adopted (*26*). The most recent edition (5th) has been used.

The second step for developing a Material Production Phase LCI is to collect and document available data for each material production process. An LCI of each material is required; that is, each input to the production process must have its own life cycle characterized from "cradle-to-gate," meaning from raw material acquisition to delivery to the next phase of the life cycle. For example, an LCI of bitumen (also referred to as asphalt) would include an allocated portion of all the emissions associated with extracting crude oil, delivering the crude oil to a refinery, and producing refined bitumen, and end at the point when a truck or rail car leaves the refinery gate.

The third step for developing LCIs is to tailor the collected data to the region and technology of interest. In the case of the Material Production Phase LCIs being discussed here, upstream profiles of electricity generation, fuel production, and transport distance between points of production and points of consumption are common factors that reflect regional conditions and would be tailored in this step. Best practices include customizing the collected data to technical conditions as well. In order to tailor the collected data to regional conditions (California in this study), an upstream profile of electricity generation in the available LCI sources was replaced with an upstream profile of electricity generation reflecting California's power mix. One problem with this approach was that many LCI sources either do not provide detail sufficient to allow tailoring or they collect data that represent generic product manufacturing processes with unspecified technology. For example, Stripple provides an LCI of cement production, but does not provide detailed information about the cement type or the cement plant technology (*27*).

Once it is customized, the LCI should be validated. Validation in this study was provided through review of data by experts in the asphalt and concrete materials and construction fields.

4.2 Material Production Phase LCI Overview

The *UCPRC Pavement LCA Guideline* suggests that the system boundary of the Material Production Phase should include raw material acquisition and production/refining, the mixing processes at asphalt or concrete plants, and the transport of materials between each production step. Feedstock energy is also reported as part of the accounting of energy flows. Feedstock energy refers to the chemical energy contained in a material that is not used as a fuel or energy resource. In this report the system boundary of the Material Production Phase includes material acquisition; material production or processing prior to delivery to the mixing plant; mixing processes at the mixing plants; and material transport between the mixing plant and construction site by truck operation. Warm-mix asphalt was not considered because it is not used routinely, it is often used as a compaction aid rather than a means to reduce mixing energy, and there are a number of products on the market in California with different potential environmental impacts in their production and use. Mixing plants for both materials are assumed to be on the construction site; thus, cement and asphalt are assumed to be transported from the nearest production facility to the construction site. Specific distances are reported in the case study descriptions since they will vary by construction site.

4.2.1 Primary Energy

For LCA, energy consumption is typically reported in units of *primary energy*. Primary energy refers to the full life cycle energy, meaning that the energy required to process and to deliver are both included. Energy use includes the consumption of energy resources such as fuels and other energy carriers (such as electricity), but also the energy that is available in the product itself if it were to be used as a fuel source (the *feedstock energy* noted previously). In order to translate between the amount of materials and the amount of energy, it is important to understand the feedstock energy (or the heating value) of a material.

Feedstock energy is a characteristic of each material and is characterized by its heating value (e.g., MJ/kg or MJ/m^3). When a fuel is burned, some of its energy is involved in vaporizing the water blended in the fuel which ends up as a latent heat in the water vapor. That water vapor usually exits an exhaust pipe along with the other combustion gases, and therefore its energy value is lost. In thermodynamic terms, the *gross energy* (or higher heating value [HHV]) includes the latent heat of vaporization, while the *net energy* (lower heating value [LHV]) does not include the latent heat of vaporization. LCA methods do not include a recommendation on whether the HHV or LHV should be used to characterize feedstock energy. In this study, net energy, or LHV, is used and takes heating values mainly from EcoInvent (*28*), which are shown in Table 4.1. If the heating value of a fuel was unavailable from EcoInvent, it was taken from an alternative source, as shown in the table.

Table 4.1: Characteristics of Fuels

	Gross Energy (HHV)	**Net Energy (LHV)**	**Density**	**Carbon Content ***	**Source**
Liquid Fuels:	**MJ/kg**	**MJ/kg**	**kg/L**	**% by weight**	
Conventional gasoline	46.54	43.45	0.74	86.3	GREET (*29*)
Crude oil	45.3	42.33	0.86	85.3	EcoInvent (*28*)
Liquefied petroleum gas (LPG)	50.15	46.61	0.51	82.0	GREET (*29*)
Residual oil	42.21	39.47	0.99	86.8	GREET (*29*)
U.S. conventional diesel	45.77	42.79	0.84	86.5	GREET (*29*)
Gaseous Fuels:	**MJ/kg**	**MJ/kg**	**kg/m^3**		
Natural gas	48.88	44.08	0.81	72.4	EcoInvent (*28*)
Solid Fuels:	**MJ/kg**	**MJ/kg**			
Hard coal	27.35	26.31		75.0	EcoInvent (*28*)
Lignite	13.43	11.88		49.1	EcoInvent (*28*)
Pet coke	31.31	29.51		79.9	GREET (*29*)
Uranium natural	559,503	559,500		N/A	EcoInvent (*28*)

* Carbon contents listed in this table are to provide information only. These values are not used in this study.

4.2.2 Greenhouse Gases

GHGs cause radiative forcing in the atmosphere, absorbing thermal (infrared) radiation and disturbing the balance between the energy absorbed by and radiated from the earth. This is the primary mechanism by which GHGs cause global warming. GHGs may be short-lived (e.g., CO and NO_x) or long-lived (e.g., CO_2, N_2O, SF_6) in the atmosphere. Global warming calculations and so-called "carbon footprints" typically track long-lived GHGs. The primary greenhouse gases of concern in most LCAs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), although many other GHGs exist. This study assesses only CO_2, CH_4, and N_2O. Because the processes modeled in this study are dominated by combustion of fossil fuels, CO_2 makes up the large majority of emissions. Other GHG emissions categories (e.g., chlorofluorocarbons, halons, hydrofluorocarbons, perfluorinated compounds, fluorinated ethers, etc.) are expected to contribute little, if at all, to the CO_2-e emissions from the analyzed systems. In future analyses the scope of GHGs included could be expanded, as the data permits.

During the impact assessment step in LCA, inventory flows are translated into measures of environmental impact. For GHGs, global warming potential (GWP) serves as the most common impact assessment category. GWP is a relative measure developed by the Intergovernmental Panel on Climate Change (IPCC) that allows for all GHGs to be expressed as CO_2-equivalents (CO_2-e) (*30*).

GWPs are calculated based on two important characteristics of each GHG: first, a gas's capacity to trap thermal radiation (also called its "radiative efficiency") and second, its lifetime in the atmosphere. GWP is the ratio of cumulative radiative forcing of a GHG relative to CO_2, and because it is a measure of cumulative effect a time horizon for integration is required. In LCA studies, and in domestic policies (e.g., the U.S. Greenhouse Gas Inventory) and international policies (e.g., the Kyoto Protocol) that also use IPCC GWPs, 100-year time horizons are most often used. GWPs from the IPCC's most recent report are listed in Table 4.2 for time horizons of 20, 100, and 500 years.

Table 4.2: GWP for Given Time Horizon (*30*)

	Global Warming Potential for Given Time Horizon		
	20-yr	***100-yr***	**500-yr**
Carbon Dioxide (CO_2)	1	***1***	1
Methane (CH_4)	72	***25***	7.6
Nitrous Oxide (N_2O)	289	***298***	153

PAS2050, a carbon footprinting standard used in the U.K., suggests that CO_2 emissions that are extracted from the atmosphere and released from biogenic carbon sources within a 100-year time period should be treated differently and excluded from the final calculations of GHG intensity assessment (*31*). EcoInvent reports CO_2 emissions released from biogenic carbon sources and these emissions are excluded from calculating total GWP. EcoInvent also reports CH_4 emissions released from biogenic carbon sources, but these emissions are still included in the calculation of total GWP, after a correction for the impact of the actual CO_2 absorption, which puts the GWP at 22.

4.3 LCI Sources

In this report an LCI database is developed that is based on various LCI sources. Five of these sources are mainly used: EcoInvent (abbreviated as "Eco" in figures) (28), Stripple, Hakkinen (32), Athena (33), and Portland Cement Association (PCA) in the U.S. (*34, 35*). Table 4.3 shows which LCI sources are applicable for each material and basic information related to the main LCI sources. In this report, the sources are labeled in the following manner: "process, location, source/upstream profile." For example, "electricity, at grid, Eco/US-Cal mix" indicates that the data come from an LCI of electricity at grid and that the LCI was developed based on EcoInvent but tailored using the California electricity mix. As another example, for "concrete, US, PCA/US-Cal mix&Eco" indicates that the data represent an LCI of a concrete mixing plant in the United States and that the LCI was developed based on PCA with added upstream profiles of the California electricity mix and process fuels from EcoInvent.

Table 4.4 lists the area codes used in Table 4.3 and later in this report.

Table 4.3: Overview of LCI Sources for Construction Materials

Source	EcoInvent	Stripple	Hakkinen	Athena	PCA	Others
Type	Commercial LCI	LCA Report	LCA Report	LCA Report	LCA Report	
Location*	GLO, RER, UCTE, CH	SE	FI	CA	US	
Year:		2001	1996	2006	2006	
Energy Value	MASS**	LHV	HHV	HHV	HHV	
UPSTREAM PROFILE						
Capital Investment	Included	Excluded	Excluded	Excluded	Excluded	
Electricity	Included	Included***	Included	Included	Excluded	
Fuel	Included	Included****	Included	Included	Excluded	
MATERIAL						
Crushed Aggregate	Yes	Yes	Yes	Yes	Yes	
Natural Aggregate	Yes	Yes	Yes	Yes	Yes	
Bitumen	Yes	Yes	Yes	Yes	No	Eurobitume (*36*) USLCI (*37*)
Crumb Rubber Modifier	No	No	No	No	No	Corti (*38*)
Extender Oil	Yes	No	No	No	No	
Recycled Asphalt Pavement	No	No	No	Yes	No	
HMA Mixing Plant	No	Yes	No	Yes	No	
Cement	Yes	Yes	Yes	Yes	Yes	
Concrete Admixture	No	No	No	No	No	EFCA (*39*)
Dowel Bar	No	No	No	No	No	World Steel Association (*40*)
Concrete Mixing Plant	Yes	No	No	Yes	Yes	

* See Table 4.4 for a description of geographical codes.
** Reported in mass of primary resource flows. Energy consumption is calculated by multiplying by HHV or LHV.
*** Upstream profile of generating electricity is included. However, upstream profiles of producing fuels, which are required for generating electricity, are excluded.
**** Upstream profiles of producing fuels, which are combusted for transport equipment, are included.

Table 4.4: Geographical Codes for Inventories

Area	Area Code
Canada	CA
Switzerland	CH
Finland	FI
Global	GLO
Europe	RER
North America	RNA
Sweden	SE
Union for the Co-ordination of Transmission of Electricity (Europe))	UCTE
United States	US
United States, California	US-Cal
United States, Eastern Interconnection	US-East
United States, Western Interconnection	US-West
United States, Texas Interconnection	US-Texas

4.4 LCI Scenario Analysis

For most of the materials, only a few LCI sources were publicly available, and for some materials in this report only one source was available. However, aggregate, bitumen, and cement have a number of reliable LCI sources, differentiated by region. Because no datasets are available for the region of study, California, datasets from other regions have been customized to better reflect California conditions. Customization includes, for example, substitution of electricity data that reflects the California grid's fuel mix.

4.4.1 Electricity

Figure 4.1 shows energy consumption and GHG emissions from generating 1 MJ of electricity in different power plants. Generating electricity from fossil fuels, such as coal, natural gas, or oil, not only consumes large amounts of energy but also releases large amounts of GHGs. Nuclear power plants produce large amounts of energy, but release very little GHGs because combustion processes are not used. Generating electricity from biomass (wood) may release a large amount of GHGs, however, based on PAS2050, CO_2 emissions released from biogenic carbon sources are excluded from the calculation of GWP, and therefore biomass power plants have low GWP. Electricity generated from hydropower and renewable resources are efficient from the standpoint of both energy consumption and GHG emission.

Electricity supplied to the grid is not solely from one type of power plant, and therefore it is important to understand the power mix of electricity for a specified region. As listed in Table 4.5, about half of California's electricity is generated by fossil-fueled power plants, largely natural gas. For comparison, the overall United States' average electricity is generated mainly with coal, natural gas, and nuclear power plants. Among LCI sources only three out of five (EcoInvent, US LCI, and Stripple) report an LCI for electricity, and therefore Table 4.5 lists the average U.S., California, and Swedish power mixes for comparison. Sweden's electricity is produced mainly from hydropower plants and nuclear power plants.

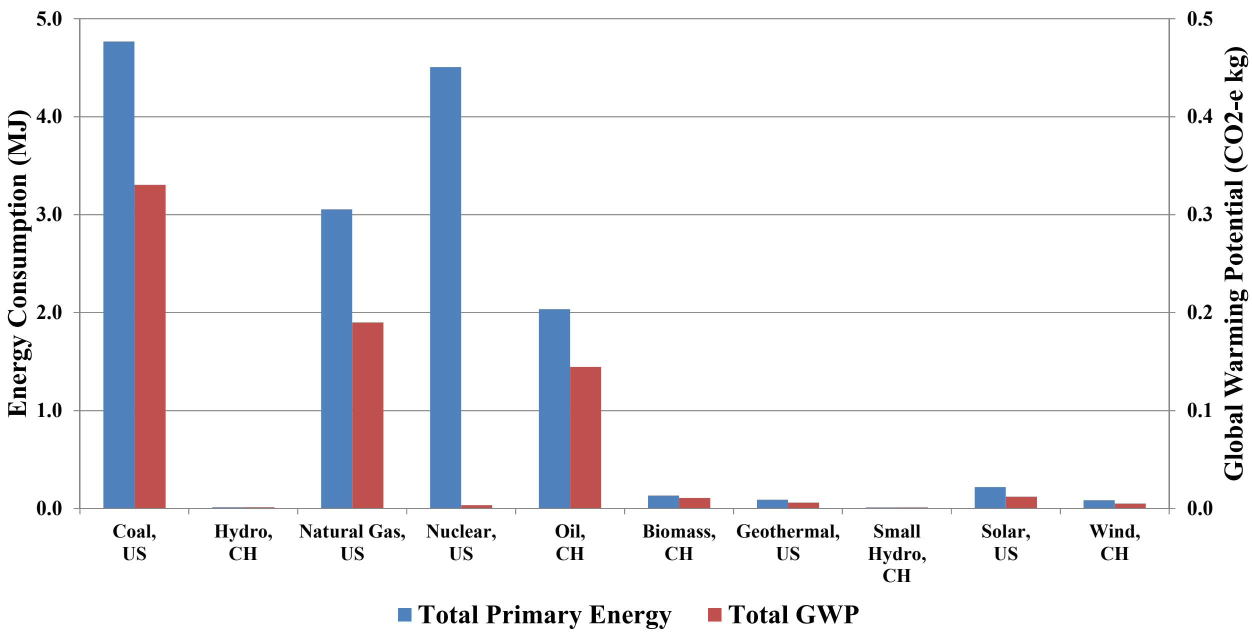

Figure 4.1: Electricity generation, at plant (1 MJ). (Source: EcoInvent)

Table 4.5: Electricity Mix in California and Sweden (and codes for electricity mixes)

	Coal	Hydro	Natural Gas	Nuclear	Oil	Renewable	Other
California (US-Cal mix) (*41*)	7.73%	10.75%	41.85%	13.93%	0.02%	13.71%	12.01%
United States (US mix) (*42*)	44.4%	6.9%	23.3%	20.2%	1.0%	3.8%	0.5%
Sweden (SE mix) (*27*)	1.79%	21.05%	0.42%	71.66%	2.87%	2.02%	0.20%

Figure 4.2 shows the energy consumed and GHGs emitted to deliver 1 MJ of electricity to the grid. "US-Cal, Eco/US-Cal mix," "US, Eco/US mix," and "SE, Eco/SE mix" are electricity LCIs calculated based on EcoInvent with power mixes adopted from Table 4.5. Other LCIs in Figure 4.2 are derived directly from EcoInvent, US LCI, and Stripple, as indicated in the bar chart labels. Unlike the other datasets shown here, Stripple did not include the total life cycle burdens (energy consumption and GHG emissions) of electricity generation; instead, he ignored the precombustion phases for fuels used in electricity generation. In general, more energy is consumed and more GHGs are emitted in the Unites States than in Europe to deliver 1 MJ of electricity to the

grid. However, the difference in GHG emissions is greater than the difference in energy consumption. "US-Cal, Eco/US-Cal mix" (shown at far right in Figure 4.2) is the electricity LCI used in this report: 2.83 MJ of primary energy is consumed and 0.13 kg of GHGs are emitted to deliver 1 MJ of electricity to the grid with the loss of transmission over the grid being 8 percent.

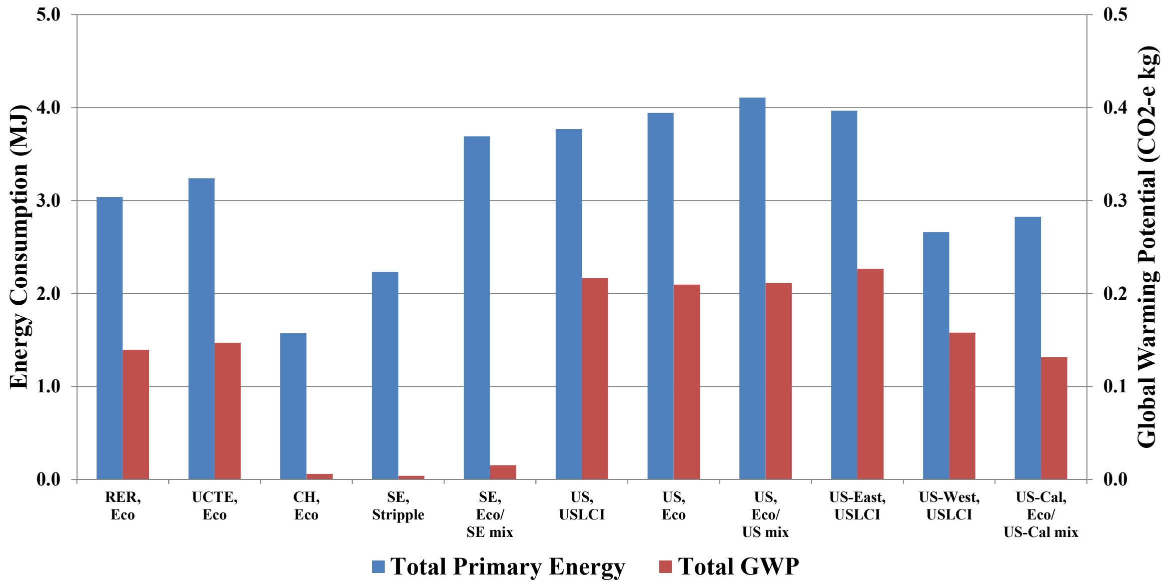

Figure 4.2: Electricity generation & distribution, at grid (1 MJ).

4.4.2 Aggregate

In the U.S. Geological Survey terminology assumed to be used in most aggregate inventories, crushed stone is taken from hard rock quarries (often by blasting) and then further crushed to desired sizes. The three most prevalent types of crushed stone produced and used in California are limestone, which is primarily used to manufacture cement; granite, which is primarily used in road base, concrete, and asphalt mixes; and trap rock (such as basalt), which is primarily used for the same purposes as granite (*43*). California production of crushed stone in 2010 was 75 million metric tons from 338 operations (*44*), about half of the production in 2003. Construction sands and gravels are mined from alluvial sources, usually by scraping or bucketing directly from the deposits. Sands and gravels are often, but not always, then crushed to various degrees to obtain the desired sizes and surface textures for road base and asphalt and concrete mixes. In California, construction sand and gravel are used primarily for the production of concrete mixes, road base, and asphalt mixes. California production of construction sands and gravels in 2010 was 32 million metric tons from 168 operations (*43*), about 60 percent of the production in 2005 (*44*). California has a wide range of sources of both crushed stone and sand and gravel. The geology of the state is such that both types often compete against each other in the same markets, and both are often included in the same mixture depending on economics and specifications since many companies own quarries for both types.

Aggregates are also categorized by size as coarse or fine. Typically, coarse aggregates are those retained on the 4.26 mm (No. 4) sieve, and fine aggregates are those that pass that same sieve. For asphalt mix production, dust is defined as material passing the 0.075 mm (No. 200) sieve. For concrete mix production, aggregates smaller than sand size are eliminated from the gradation.

Crushed aggregates, whether from crushed stone (hard rock mining) or construction sand and gravel (alluvial mining), are more angular than aggregates that are taken from sand and gravel deposits and not crushed. Crushed faces on aggregates are required for use in asphalt mixes and are also used for higher strength in concrete mixes. In concrete mixes, uncrushed sand and gravel often provides better workability, and is acceptable for use in concrete provided that the required strength and other specified property requirements are met. The inventories used in this study do not provide much documentation regarding the degree of crushing of sand and gravel that was assumed, or whether they assumed that all crushed stone was from hard rock mining. As a result, for flexible-surfaced pavements, both coarse and fine aggregates are assumed to be sourced 100 percent from crushed stone, although the majority of aggregate used for asphalt mixes in California is sand and gravel from alluvial deposits that has been subjected to crushing, not crushed stone mined from hard rock quarries. For rigid-surfaced pavements, coarse aggregate is assumed to be 50 percent crushed stone and 50 percent sand and gravel, and fine aggregate is assumed to be comprised of 100 percent sand and gravel aggregates. It was felt by the researchers that these were reasonable assumptions in light of the lack of documentation in the inventories, the range of crushing applied to different sources in the state, and the relatively low strengths required of concrete mixes used for highways compared with other applications.

In general, crushed aggregates consume more energy and release more GHGs during extraction and production than sand and gravel aggregates. This is because manufacturing crushed stone requires drilling, blasting, and crushing, while production of sand and gravel aggregates does not.

However, one LCI source, Athena, reports the opposite result (*33*). Athena provides both fuel and electricity consumption for coarse and fine aggregates, and reports fuel consumption for both to be the same, which indicates that the activities for mining equipment are the same. Fine aggregate consumes more electricity, which is likely the result of the additional crushing and sieving activities involved in meeting specifications. As a result, in the Athena data set shown in this report, fine aggregate is considered as crushed stone and coarse aggregate is considered as sand and gravel for all mixtures.

Manufactured aggregates, which are defined as aggregates created from source materials that are not natural stone (such as blast furnace slag or expanded clay), are seldom used in California at this time.

Figure 4.3 summarizes the environmental burdens of crushed aggregates and natural aggregates. Energy consumption and GHG emissions included in this report are calculated based on LHV and California electricity mix. Each of these sources was considered in later analyses to provide an assessment of sensitivity to the data source.

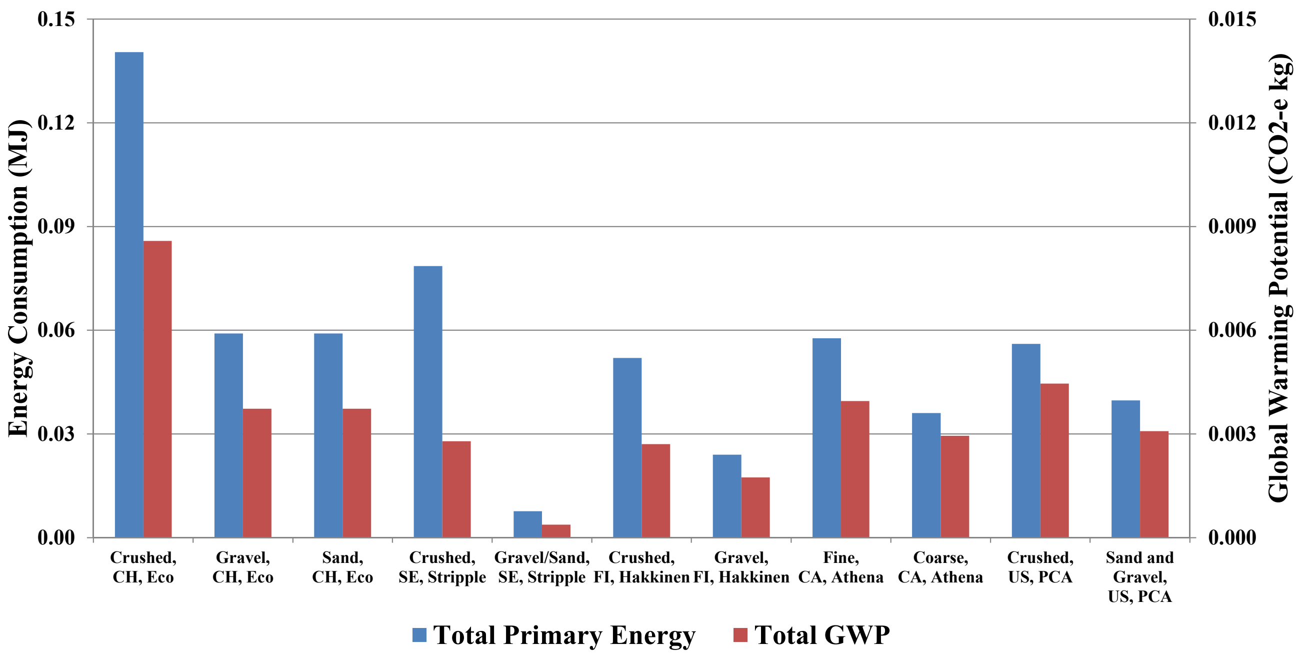

Figure 4.3: Aggregate production, at quarry (1 kg).

4.4.3 Asphalt

This report uses the terms "asphalt" and "bitumen" interchangeably. In the U.S., asphalt is produced during the refining of crude oil, although the majority of refineries in the U.S. do not produce asphalt. Crude oil refining processes generally consist of separation, treatment, conversion, and blending. Most bitumen is produced during the separation process, where crude oil is heated and fed into atmospheric and vacuum distillation towers. Bitumen is a heavier component of crude oil that stays at the bottom of those distillation towers. After collection, bitumen may be blended with additives, often polymers also created from petroleum stocks, in order to meet specifications. In this report, no additives were considered for hot-mix asphalt (HMA), but crumb rubber modifier (a mix of recycled scrap tires with some natural rubber) and extender oil were considered for rubberized hot-mix asphalt (RHMA).

Petroleum refineries are complex systems and each of them is unique, and therefore allocating energy consumption and environmental loads only associated with bitumen is not simple. ISO/TR 14049 provides allocation examples for bitumen using both economic value and mass. However, none of the bitumen datasets examined in this project report using economic value. Of the LCI sources shown in Figure 4.4 that reported their allocation methods, all use mass-based allocation. (*45*)

Figure 4.4 shows the life cycle energy and CO_2-e emissions from producing 1 kg of bitumen. All of the LCI sources include crude oil extraction, transport of crude oil to a refinery, and bitumen production within their system boundary. Feedstock energy is shown separately from other primary energy usage. Stripple and Eurobitume considered transport of bitumen to storage tanks and storage of bitumen in their system boundary, while the other LCI sources did not specify whether or not they include storing the bitumen. In this example case study, however, transport of bitumen to storage tanks and storage of bitumen were excluded from the system boundary when the numbers summarized in Figure 4.4 were calculated so that an equitable comparison could be made among the LCI sources. Any LCIs produced based on HHV have been adjusted to LHV, and electricity consumption was replaced with the California power mix whenever the substitution was possible. As was the case for aggregates, all available LCI sources were used in later analyses to provide an indication of sensitivity to the data sources available. As noted previously, this approach was taken because California-specific data were unavailable.

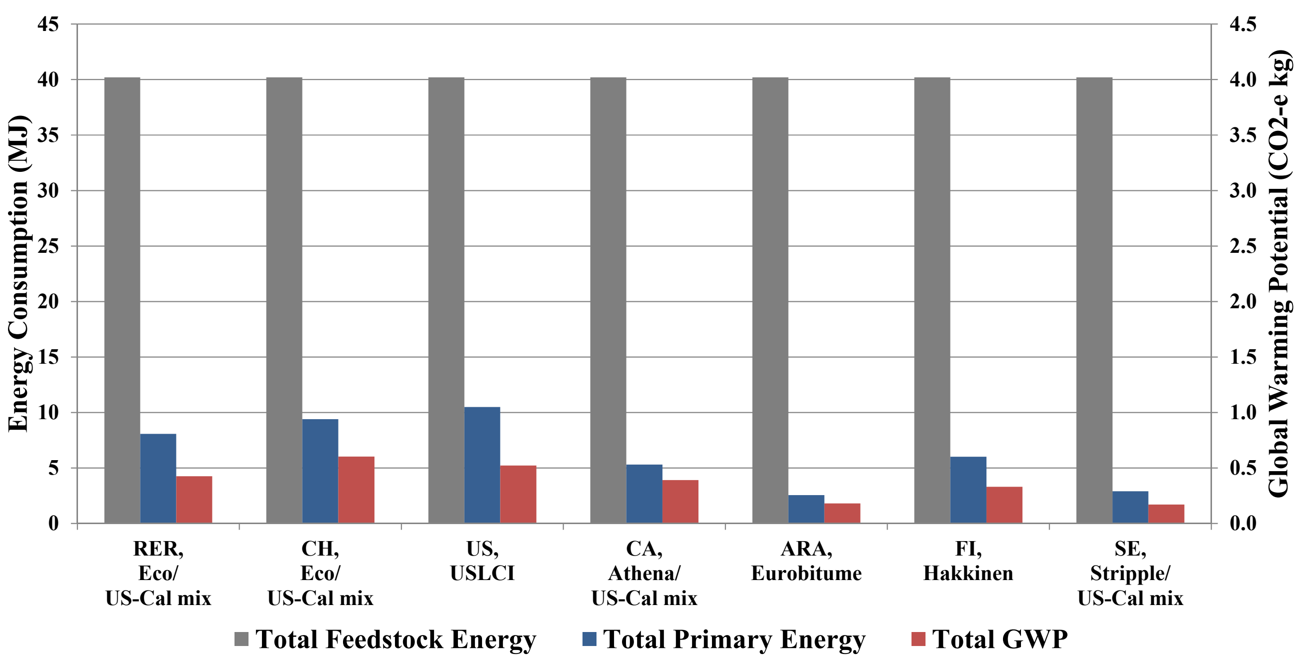

Figure 4.4: Bitumen production, at refinery (1 kg).

4.4.4 Crumb Rubber Modifier

Crumb rubber modifier (CRM) is a general term for recycled tire rubber that is ground into fine particles. It is added to asphalt concrete for certain types of asphalt mixes. The resulting product is called "rubberized hot-mix asphalt (RHMA)" in California. CRM is produced in two steps. First, waste tires are shredded into relatively large pieces and then ground to finer pieces. There are several ways to grind the shredded tire; however, Caltrans specifies that CRM be ground at ambient temperature.

CRM can be introduced to produce RHMA by one of three processes. In the dry process, CRM is mixed with aggregate before it is added to the asphalt. Therefore, in the dry process CRM functions like an aggregate. The dry process is not used by Caltrans. In the wet process, which is assumed for this report, CRM is reacted with bitumen at high temperatures at the HMA mixing plant. In the terminal blend process, CRM is mixed with bitumen and reaction occurs at the refinery. The blended binder is then shipped to the asphalt mixing plant in a truck. The size of the rubber particles is smaller in terminal blend mixes and they do not remain as discernible particles in the binder. The reaction process is also different between the wet and the terminal blend processes.

In October 2005, California Assembly Bill 338 was signed into law, and in its original form it called for the use of increasing amounts of wet-process–produced asphalt rubber in hot-mix asphalt (HMA): 20 percent of total HMA tonnage in 2007, 25 percent in 2010, and 35 percent in 2013. The language of the bill has recently been broadened to allow the use of other types of rubberized asphalt including terminal blends (*46*).

In the 2006-07 fiscal year, the last year for which data are readily available, Caltrans treated 157 lane-miles with RHMA and 390 lane-miles with HMA through its pavement preservation program, which intends to give design lives on the order of five years. Through the thin blanket overlay maintenance program, Caltrans treated 545 lane-miles with RHMA and 147 lane-miles with HMA in the same year (*46*).

Caltrans requires that CRM include 75.0+/-2.0 percent of scrap tire CRM and 25.0+/-2.0 percent of high natural CRM by total weight of CRM. Scrap tire CRM is manufactured with discarded (scrap) tires, which are composed mainly of styrene butadiene rubber (SBR), polyisoprene, and carbon black. High natural CRM is manufactured from discarded heavy truck tires, which contain a higher percentage of natural rubber. Caltrans also requires the use of extender oil. The purpose of using high natural CRM and extender oil is to enhance CRM dispersion and the stability of blended binder.

Mixing CRM into asphalt results in higher binder content, viscosity, softening point, and resilience, and a thicker binder film. These changes in asphalt properties reduces temperature susceptibility and improves the durability and performance of pavements, such as resistance to surface-initiated cracking, fatigue/reflective cracking, aging, oxidation, and rutting (*47*).

Very limited environmental impact data is available for CRM production. However, since CRM is produced from scrap tires, which are assumed to otherwise be collected and disposed of in a landfill, the impacts of producing new tires and collecting them after retirement are not included in the CRM LCI. Processing of scrap tires into CRM should be included in an LCI of CRM production. Corti and Lombardi performed a comparative LCA of alternative scrap tire applications and report process energy (electricity) for CRM production (*38*). Corti and Lombardi's reported electricity consumption was linked to the California power mix electricity LCI to yield an LCI of CRM production.

4.4.5 Extender Oil

Extender oil is aromatic oil used to enhance the interaction between bitumen and CRM. Extender oil is absorbed and causes expansion of CRM particles, and helps CRM to disperse in the asphalt/rubber binder blend.

Data on the composition of chemical compounds such as extender oil can be hard to identify. However, information is publicly available based on the Chemical Abstracts Service (CAS) registry number. The CAS number can be found on the Material Safety Data Sheet (MSDS) of the product. Raffex 120[1] is extender oil tested by Caltrans for use in RHMA. Raffex 120 is made from a heavy naphthenic distillate solvent extract (CAS No. 64742-11-6), which is also known as mineral oil, petroleum extract, liquid paraffin, and liquid petroleum. LCIs of solvent, mineral oil, and paraffin were searched for within EcoInvent, US LCI, and other LCA databases and studies, and only a few relevant LCI sources were found. "Paraffin, at plant, RER, EcoInvent" was selected as the representative extender oil in this report. The paraffin LCI was adjusted with the California electricity mix.

4.4.6 Recycled Asphalt Pavement

Recycled asphalt pavement (RAP) is a general term for a recycled pavement layer containing milled (with a milling machine) or pulverized (with a full-depth reclamation machine) asphalt pavement.

RAP is most often produced by milling an existing asphalt pavement, and then screening the material for use in a new asphalt mix or for use as aggregate base. RAP is used in two typical ways as part of a maintenance, rehabilitation, or reconstruction activity. The first and most common method is to process and mix RAP as an addition to new HMA at a mixing plant. The second method is in-place recycling or full depth reclamation. In-place recycling of less than the full depth of the asphalt layers can consist of either the top surface of the existing

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[1] Registered product of San Joaquin Refining Co., Inc. Use of Raffex 120 as extender oil was confirmed via personal communication with Caltrans personnel.

pavement undergoing cold in-place recycling with the addition of asphalt emulsion and cement, or hot in-place recycling with addition of new asphalt. The full-depth reclamation form of in-place recycling consists of pulverization of all the asphalt layers and using the resulting granular material as is or stabilizing it with cement, either with or without foamed asphalt or asphalt emulsion. This research will focus on the first method, where RAP is processed and mixed at an off-site mixing plant.

As described earlier, RAP is extracted from the construction site, transported to a mixing plant, and mixed there with virgin asphalt binder and aggregates into new HMA. The RAP used on an overlay project is usually not the RAP taken from the same location by milling, since RAP stockpiles are often blended from a number of locations. Milling is seldom included in a design specifically to produce RAP. Milling is usually included as part of the overlay design because it will improve performance, it improves IRI, it is required for grade elevation maintenance, or any combination of these three reasons.

Extraction processes at the construction site are included in the Construction Phase and the transport and mixing processes are included in the Material Production Phase. However, the mixing process is linked to a separate LCI for the HMA mixing plant. As a consequence, RAP production in this model only includes transportation of RAP from the construction site to the mixing plant, and it is assumed that the RAP is mixed into HMA following the HMA mix design. Currently, Caltrans specifications do not permit use of RAP in RHMA and set a maximum of 15 percent by mass in HMA, except for a few recent pilot projects with greater RAP contents. If RAP is not used in the HMA mix, milled pavement material will be used as aggregate base, aggregate subbase, fill or shoulder backing, or disposed of at a dump site. This activity is included in the EOL phase, which is not considered in this report.

4.4.7 HMA Mixing Plant

HMA is manufactured in California in drum mix plants, a type of continuous mixing plant. The main source of energy consumption and GHG emissions associated with drum mix plants is the dryer burner, which is attached to the drum mixer. The dryer burner consumes a significant amount of fuel (i.e., natural gas or fuel oil) in order to dry and heat the raw materials fed into the drum mixer. For HMA, the aggregate materials need to be heated to 135°C to 165°C (275°F to 329°F). For RHMA, the aggregate materials are heated to about 175°C (347°F) and for HMA with RAP the virgin aggregates are super-heated to 215°C to 425°C (420°F to 800°F) so that when the unheated or partially heated RAP is added there is sufficient heat for mixing of the virgin binder and aged asphalt on the RAP (*48*). Manufacturing RHMA and HMA with RAP consumes more fuel than producing HMA. This report assumes that the relationship between heating temperature and fuel consumption is linear. The heating temperatures are assumed to be 165°C (329°F) for HMA, 175°C (347°F) for RHMA, and 260°C (500°F) (*49*) for HMA with RAP.

Two LCI sources for HMA mixing plants available were examined: Athena and Stripple. Athena reports energy consumption distinguished by fuel type and GHG emissions for the entire production process, but Stripple reports energy consumption distinguished by electricity and heating energy. For Athena, it was assumed that diesel consumption is associated with mobile equipment operation and other fuel consumption, dominated by natural gas, is associated with heating the drum. The LCI of the HMA mixing plant for HMA, HMA with RAP, and RHMA was calculated based on these two LCI sources and the results are summarized in Figure 4.5. Athena yields lower energy consumption, but Stripple returns lower GHG emissions. This study uses values calculated from Athena because of the more detailed fuel type information.

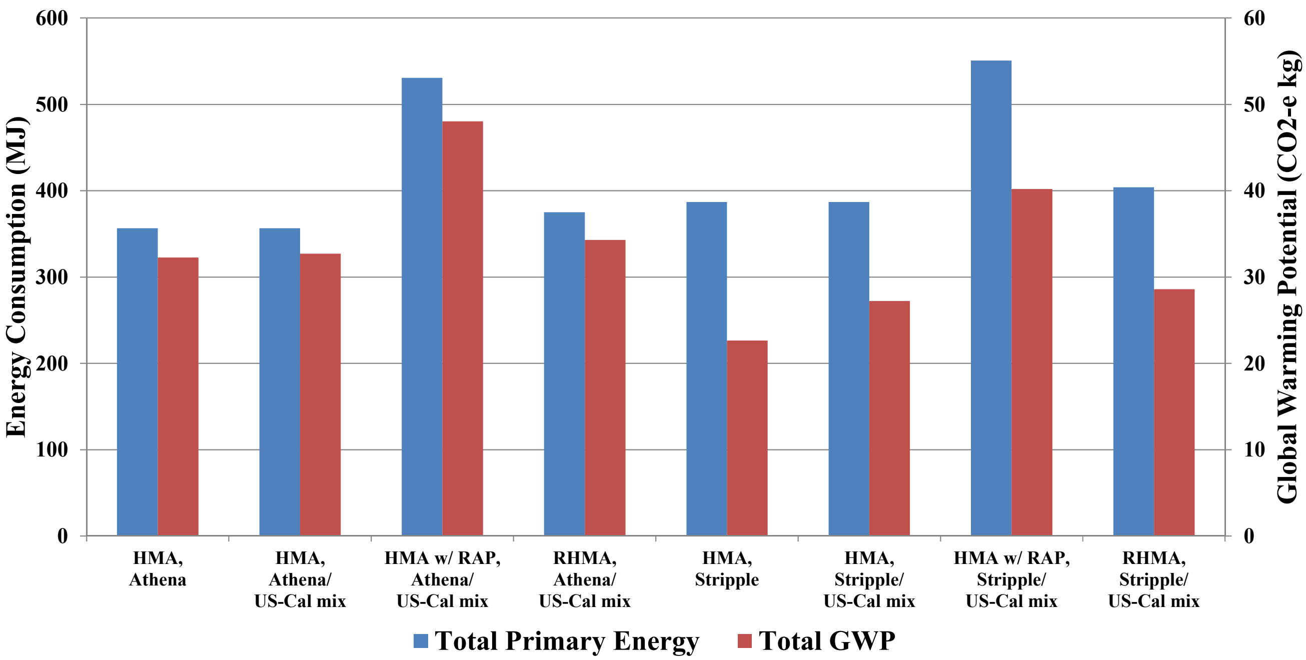

Figure 4.5: HMA mixing, at plant per metric tonne of asphalt mix produced.
Note that one tonne of asphalt has a volume of approximately 0.36 to 0.5 m^3.

The results shown in Figure 4.5 indicate that HMA with RAP consumes more energy per metric tonne than does HMA without RAP, the primary source of the difference being the higher temperatures that the aggregate must be heated to for mixing with RAP. The RHMA has less energy consumption per metric tonne than does the HMA with RAP, and slightly more energy consumption than the HMA without RAP.

Warm mix asphalt was not considered in the initial LCA model and case studies included in this report for the following reasons:

- WMA is often used in California as a compaction aid for long hauls and cooler temperature paving, which does not reduce plant mixing temperatures; better information is needed to consider sensitivity analysis for this factor.
- There are a number of very different products being used in California, all of which will require different LCIs, and many of which are currently not available.

4.4.8 Cement

This current study examined cement concrete surface pavements receiving pavement preservation CPR B treatment, which involves diamond grinding and 2 to 5 percent slab replacements, and which almost exclusively occurs during nine-hour nighttime traffic closures. Because this construction window is relatively short, high-early strength concrete is necessary. Reviewing the types of cement used for these closures in California with both industry and Caltrans, it was found that Rapid Set Concrete (RSC) mixes that use either Type III portland cement or calcium sulfoaluminate (CSA) cement are almost exclusively used in California for these closures because of their high early strength. Therefore, these two cements were analyzed for the initial case studies. However, because inventories were unavailable for these two types of cement, existing and extensive inventories for Type I and Type II cements were adjusted using additional information available about Type III and CSA cements, and also for expected cement production technologies and energy sources used in California. The Type I/II inventories will be used later when concrete lane reconstruction, which cannot be performed through the pavement preservation program and cannot be constructed with nighttime closures, is added to the LCA model. In addition, it was learned from industry sources that since 2006 California mostly uses cement produced in the state, whereas when California and worldwide cement demand was higher prior to 2006 a significant amount of cement was imported, therefore California cement production practices can be exclusively assumed.

Cement production can be broken into four steps: quarrying raw materials, preparing raw feeds, producing clinker in a rotary kiln (pyroprocessing), and producing finished cement by grinding clinker with gypsum and other processing additions. The fuel and electricity consumption distribution among these four steps have been estimated by PCA as shown in Reference (*34*). The PCA estimates listed in Figure 4.6 applied to LCIs that did not provide a fuel and electricity breakdown. These LCIs include Hakkinen, Stripple, and Athena.

Table 4.6: Percentage Distribution of Fuel and Electricity Use by Process Step (*34*)

Fuel and Electricity	Quarry (%)	Raw Feed Preparation (%)	Pyroprocess (%)	Finish Grind (%)
Gasoline	25	25	25	25
Middle distillates*	70	10	10	10
Electricity	8.5	14.1	27.9	49.5
Coal, petroleum coke, etc.**	0	0	100	0

*: Middle distillates include diesel oil and light fuel oil.
**: The other fuels are LPG, natural gas, residual oil, and various wastes.

There are several types of rotary kiln: wet, semi-dry, dry, preheater, and precalciner, and unfortunately, only PCA reports LCIs for each kiln type. However, the primary focus of interest for this LCI was on a rotary kiln with a preheater and precalciner because it is the dominant technology in California. In a preheater kiln, hot kiln exit gases are utilized to heat the raw feeds that are entering the kiln, and the precalciner consists of an additional fuel burner attached to the lower part of the preheater tower. The fuel burner promotes kiln feed to calcine more than a simple preheater tower.

Many pavement LCA studies include LCIs of cement, yet most of them do not specify the type of cement analyzed, which is generally assumed to be Type I portland cement. Because the case studies analyzed here use either Type III portland cement or CSA cement, this study calculated new LCIs of Type III portland cement and CSA cements based on modifications of the LCIs of Type I portland cement. This was accomplished by adopting LCIs of the common processes of the different cement types and adjusting the LCIs of the different processes.

For many materials, fuel and electricity consumption are the major two sources of carbon dioxide (CO_2) emissions during the Material Production Phase. However, for cement production, calcination of limestone at the pyroprocessing step is a nearly equal source of CO_2 emissions to fuel and electricity consumption. Limestone and other raw feeds undergo a series of mineral phase transitions when heated, and calcium carbonate ($CaCO_3$, the primary mineral compound in limestone) is converted to calcium oxide (CaO) by driving CO_2 out of the compound in a process called calcination. The Cement Reporting Protocol is a method provided by the California Climate Action Registry (established by California Senate Bills 1771 and 527 in 2001 as a non-profit voluntary registry for GHG emissions) for estimating CO_2 emissions from cement production, including direct GHG emissions (including mobile and stationary combustion, process, and fugitive) and total significant indirect GHG emissions (from electricity usage, co-generation, steam imports, and district heating and cooling) (*50*).

The amount of CO_2 released during the pyroprocessing step can also be calculated based on the composition of the mineral phases of the clinker. The composition of the mineral phases of a clinker differs for every product. Portland cement (PC) and CSA cement have different mineral phase compositions, and this report uses numbers from Quillin (*51*), which are shown in Table 4.7. The main components of portland cement are alite and belite and the main components of CSA cement are belite and calcium sulfoaluminate. The amount of CO_2 released from calcination during the formation of 1 kg of each mineral phase is listed in Table 4.8, showing that the amount of CO_2 released by calcinations is highly dependent on the mineral phases in the clinker used to make a kilogram of cement.

Table 4.7: Mineral Phase Composition of Portland Cement (Type I & III) and Calcium Sulfoaluminate Cement (*51*)

Mineral Phases of Clinker	Alite	Belite	Aluminate	Ferrite	Calcium Sulfoaluminate
Portland cement	64%	16.5%	3.5%	9.5%	0%
CSA cement	0%	38%	0%	8%	35%

Table 4.8: CO_2 Release of Forming 1 kg of Mineral Phases During Pyroprocessing Based on Chemical Compositions

Mineral Phases of Clinker	Alite	Belite	Aluminate	Ferrite	Calcium Sulfoaluminate
CO_2 release	579 g	512 g	489 g	362 g	216 g

The composition of the mineral phases of PC and CSA cement also changes the temperatures used to produce them, which affects the energy use for the pyroprocessing phase. Alite, the main component of portland cement, starts to form at temperatures around 1,300°C and belite starts to form at 1,200°C. Thus, portland cement is manufactured at 1,450°C while CSA cement is produced at about 1,300°C. As a consequence, manufacturing CSA cement requires less heat energy than producing portland cement.

Another important factor that affects the composition of mineral phases is the mix of raw feeds. Calcium oxide (CaO, quicklime), silicon dioxide (SiO_2, silica), aluminum oxide (Al_2O_3, alumina), iron oxide (Fe_2O_3), and sulfur trioxide (SO_3) are major chemical compounds that participate in the formation of the mineral phases. These chemical compounds are acquired from natural resources, such as limestone, clay, and sand. In general, natural resources exist as a mixture of chemical compounds, and therefore a chemical analysis of the raw materials should be performed. However, for the purposes of the initial case studies presented in this report, each raw material was assumed to be pure (without any foreign substances), and the chemical analysis of raw material was calculated based on the molar mass, with the results shown in Table 4.9.

Table 4.9: Percent by Mass of Chemical Compounds Existing in 1 kg of Each Raw Material

	Clay $Al_2(SiO_3)_3$	Limestone $CaCO_3$	Sand SiO_2	Gypsum Mixture	Bauxite $Al(OH)_3$
CaO		56.0%		32.0%	
SiO_2	63.8%		100.0%		
Al_2O_3	36.2%				79.1%
Fe_2O_3					
SO_3				43.0%	
Total	100.0%	56.0%*	100.0%	75.0%*	79.1%**

*: Shortage due to CO_2 decarbonated from calcite.
**: Shortage due to H_2O loss during heating.

The mineral phase compositions of Type I and Type III portland cement are similar (as noted in Table 4.7), however the Type III PC is more finely ground. While Type I is ground to a surface area of 330 to 380 m^2/kg, Type III is ground to 400 to 450 m^2/kg. It was assumed for this study that the difference between Type I and Type III only exists in the surface area, and therefore the only differences in the LCI are from the grinding process. The grinding is usually performed in a ball mill, which is operated by electricity. The surface areas of Type I and Type III were assumed to be 330 m^2/kg and 400 m^2/kg, respectively, and it was assumed that electricity consumption is linearly related to the surface area. However, the literature has shown that because energy consumption is not linear when the specific surface area exceeds 300 m^2/kg (*52*), the linear approximation used in this study may underestimate the grinding energy for Type III. However, currently there is no way to estimate the impact from this approximation.

Figure 4.6 displays the original LCI of cement production for Type I cement and the estimated LCI for production of Type III and CSA based on the Type I information. CSA cement is known as low energy cement, yet one result in Figure 4.6 disagrees. The LCI of CSA calculated based on EcoInvent shows that the energy consumption of CSA cement is larger than that of Type I portland cement and similar to that of Type III. This higher energy consumption is due to the energy required for the raw material production of CSA cement. Figure 4.7 summarizes the LCIs of raw material production for cement, and shows that bauxite production, which is a main ingredient of CSA cement, has greater environmental burdens than those of the raw materials used in portland cement production. If the raw material production is ignored, CSA cement's energy consumption is lower than portland cement because of the lower temperatures required during pyroprocessing. However, the GHG emissions from CSA cement production are still significantly lower than for portland cement because bauxite does not undergo calcination, which is a significant contributor of CO_2 during portland cement production (*52*).

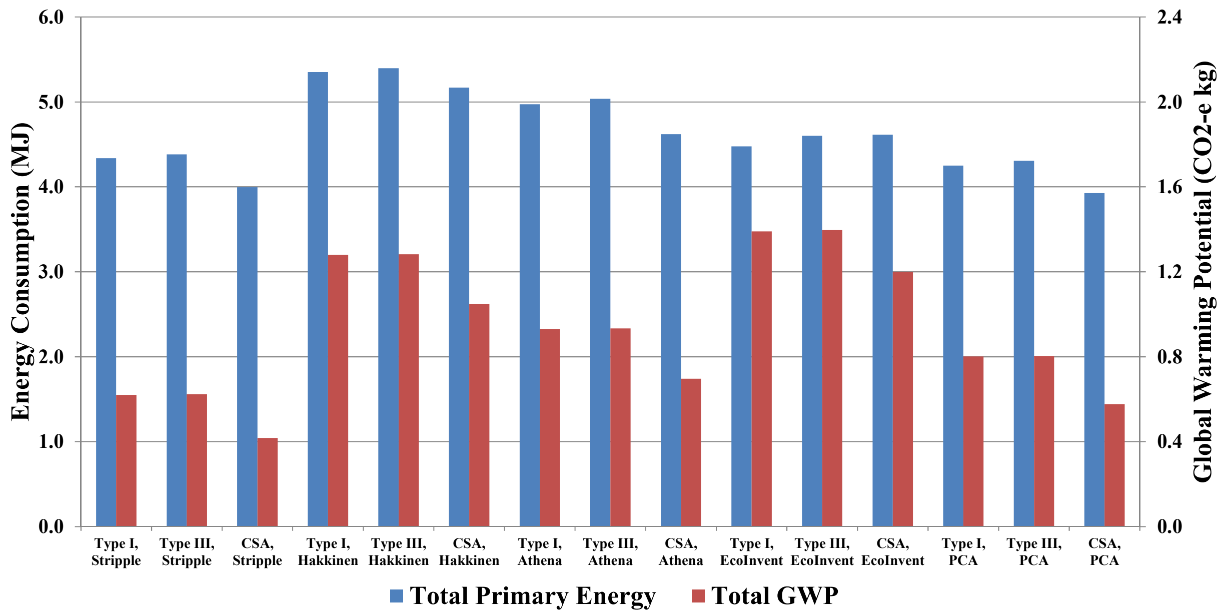

Figure 4.6: Cement production, at plant (1 kg), for Type I cement and estimated for Type III and CSA based on Type I LCI.

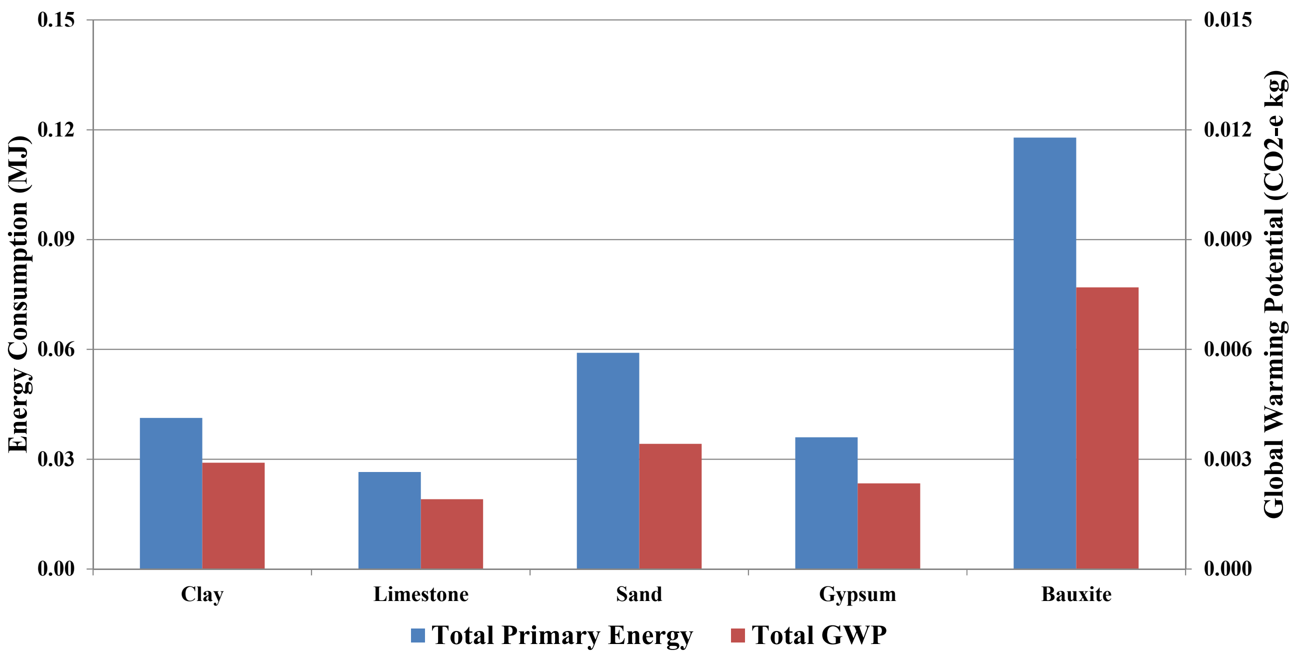

Figure 4.7: Raw material (for cement) production, at quarry (1 kg). (Source: EcoInvent/US-Cal mix)

4.4.9 Concrete Admixtures

ASTM C 125 (*53*) defines an admixture this way:

> *A material other than water, aggregates, hydraulic cement, and fiber reinforcement that is used as an ingredient of concrete or mortar and is added to the batch immediately before or during its mixing.*

Admixtures are either chemical admixtures or supplementary cementitious materials (SCM). In this report, only chemical admixtures are considered and no SCMs are analyzed. Various types of chemical admixtures are available, and they are categorized into three broad categories: air-entraining agents, set-controlling admixtures, and plasticizing admixtures. All of the chemical admixture LCIs used in this report are produced by the European Federation of Concrete Admixture Associations (EFCA) because they are the only LCIs for these materials that could be found (*39*). The system boundary of chemical admixture LCIs covers the upstream profile of fuel and electricity, raw material production, transport of raw material, and admixture production. Figure 4.8 shows the LCIs for concrete admixture production.

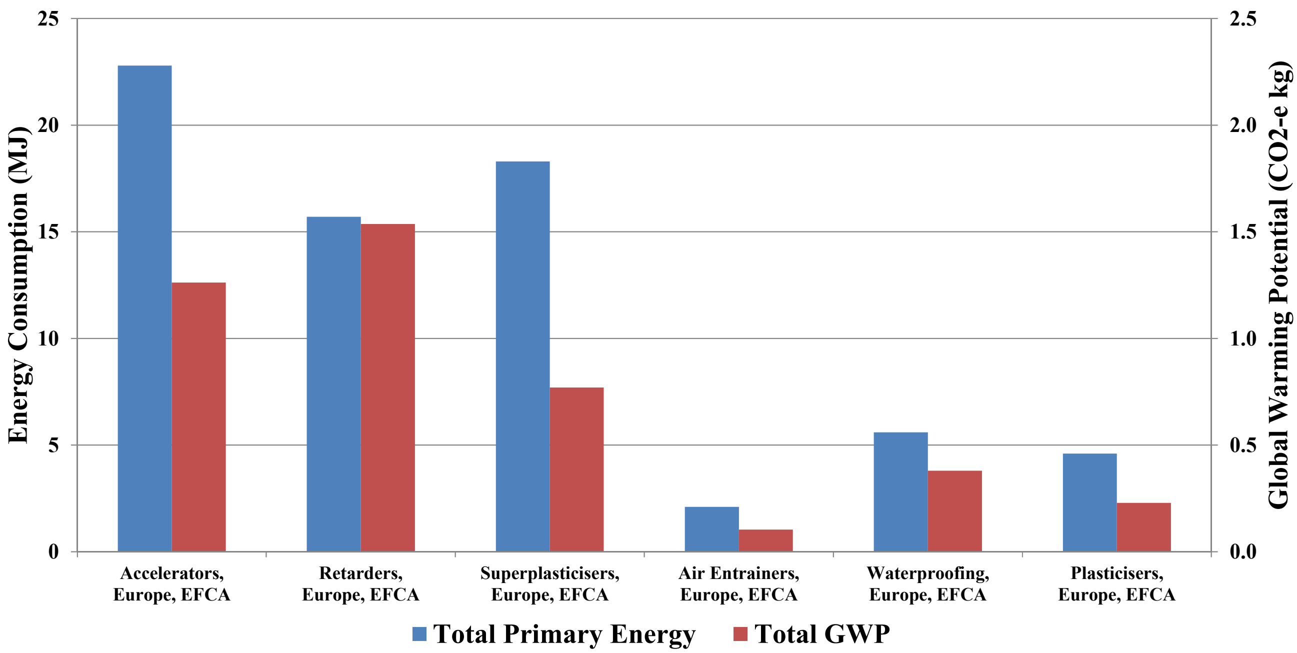

Figure 4.8: Concrete admixtures production, at plant (1 kg).

4.4.10 Concrete Mixing Plant

The general process steps for a concrete mixing plant are storage, conveyance, measurement, mixing, and discharge into delivery trucks.

There are several ways to handle concrete at mixing plants: volumetric-mix (dry), central-mix (wet), transit-mix, and shrink-mix. The volumetric-mix method does not blend water into the concrete mix at the mixing plant but instead adds the dry ingredients at the plant, and then adds water and mixes the materials at the construction site. Volumetric-mixed concrete is preferred when a construction site is far from a mixing plant and with high early strength mixes (to minimize the risk of the mix setting up in the truck on the way to the construction site). For central-mixed concrete, all the ingredients are mixed at the mixing plant because the proportions and quality of the mix are better controlled there. Transit-mixed and shrink-mixed concretes are partially mixed at the mixing plant and transported to the construction site. However, none of the LCIs reviewed for this study specifies the type of concrete mixing plant. Central-mixing was assumed.

The LCI for concrete mixing plants from the PCA was analyzed (*35*). The system boundary of the PCA LCI does not include the upstream profile of fuels and electricity. However, for this initial case study, the system boundary of the PCA LCI was expanded to consider upstream fuels and electricity by adding the electricity consumption based on the California electricity LCI and the fuel consumption based on the diesel and natural gas LCI from EcoInvent. The energy value was adjusted to the LHV as well.

Figure 4.9 displays how energy consumption and GHG emissions change as the original PCA LCI system boundary was expanded to include upstream fuels and electricity. “Concrete, HHV” is the original LCI from the PCA. “Concrete, LHV” is the energy-value–adjusted LCI. Only energy values were adjusted, and therefore the amount of GHG emissions did not change. The values for “Concrete, LHV/US-Cal mix,” reflect the addition of upstream electricity based on the California electricity mix. The values for “Concrete, LHV/US-Cal mix/Fuel” reflect addition of the upstream profiles of both fuel and electricity. This report uses the “Concrete, LHV/US-Cal mix/Fuel” value.

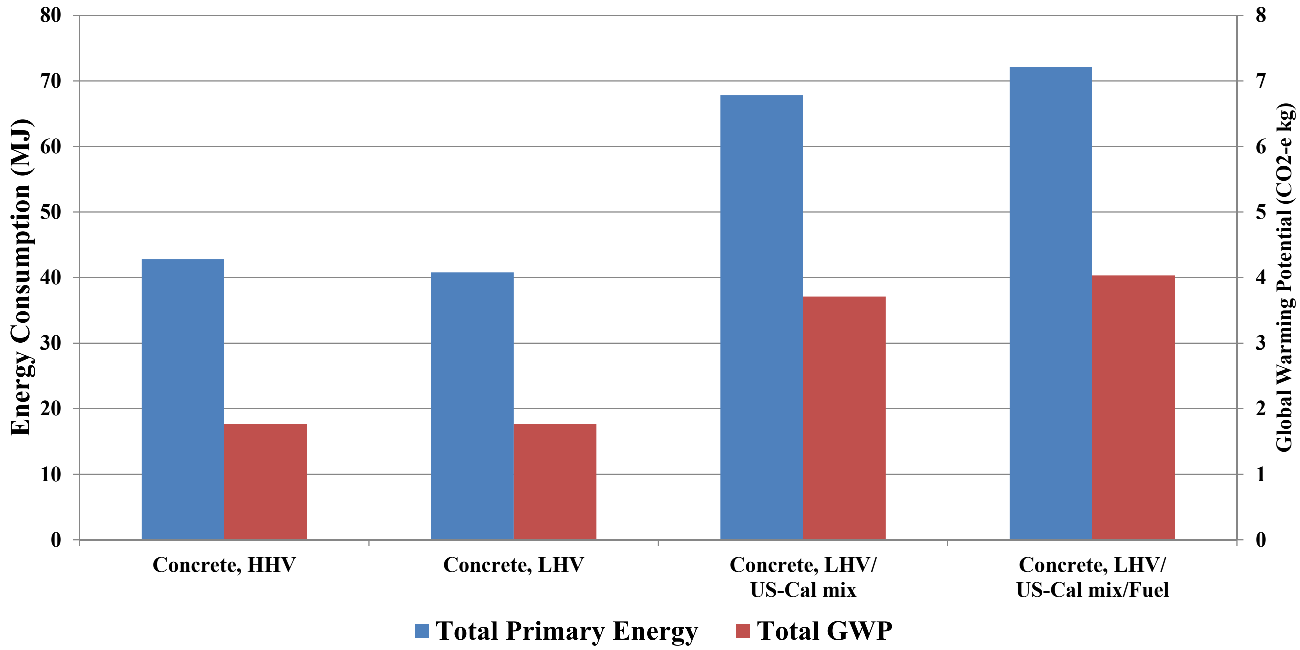

Figure 4.9: Concrete mixing, at plant, per 1 m^3 of concrete mix produced. (*35*)
(Note that 1 m^3 of concrete has a mass of approximately 2.2 to 2.6 metric tonnes.)

5. METHODS FOR MODELING THE CONSTRUCTION PHASE LIFE CYCLE INVENTORY

5.1 Overview

In the Construction Phase, fuel is used and emissions are produced by construction equipment, including trucks engaged in the construction process and construction-related traffic delay. The system boundary for the Construction Phase used for the case studies presented in this report includes most of the processes suggested in the *UCPRC Pavement LCA Guideline* with two exceptions—water use is not an impact considered because water is not tracked in many of the datasets used, and traffic congestion is not analyzed because nighttime closures are used. Congestion will be included where necessary in future project phases, once appropriate inputs for typical traffic closure scenarios are developed for different treatments under different conditions.

The impact from construction-related traffic delay is not included in this study because the inputs to the traffic delay model in *CA4PRS* have not yet been developed for the factorial of cases shown in Section 2.2 of this report. This study assumes that all construction work was to be performed at night and, given the rural location of the case studies presented, that there would be minimal work zone traffic delay.

Figure 5.1 shows the general procedures adopted in this study for analysis of the Construction Phase. The first step is to consider the design of the pavement structure, including its dimensions and materials. The quantities of material to be removed and new materials introduced are calculated based on the pavement dimensions and materials designs. The distance between mines/plants and the site are also identified in this step, in order to calculate the total travel distance of transport trucks.

In the next step, the software *CA4PRS* (*54*) is employed to calculate operation hours of construction equipment based on different construction strategies. *CA4PRS* calculates the construction schedule based on equipment production rates, material quantities, the distance between mines/plants and construction site, equipment capacities, closure tactics, mobilization/demobilization requirements, and the time that materials need to gain sufficient strength to open to traffic.

The last step is to run the emissions models. Three categories of equipment are involved: truck, construction equipment, and mixing plants. The models used, *EMFAC* (*55*) and *OFFROAD* (*56*), are emissions models[2] for on-road and off-road mobile sources provided by the California Air Resources Board. Emissions from mixing

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[2] Official emissions model for particulate matter, but not official for CO_2 and CH_4 emissions.

plants are calculated by following the steps described in Chapter 4 that describe the Material Production Phase. The basic principle of evaluating fuel use and emissions is summarized in Formula (5.1) and Formula (5.2):

$$Fuel\ use = \sum Fuel\_factor \times Activity \quad \textbf{(5.1)}$$

$$Emission = \sum Emission\_factor \times Activity \quad \textbf{(5.2)}$$

Where *Fuel_factor* and *Emission_factor* represent the fuel use and emissions of each type of equipment per hour, respectively; *Activity* represents the total amount of working hours for each type of equipment.

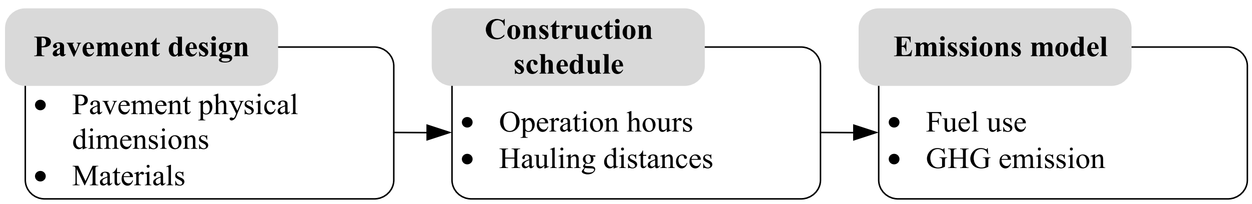

Figure 5.1: Overview of Construction Phase LCI.

5.2 Construction Schedule Analyses

This study uses the software *CA4PRS* to quantify the total operation hours of construction equipment (*54*). *CA4PRS* incorporates three interactive analytical modules: a Schedule module that estimates project duration, a Traffic module that quantifies the delay caused by work zone lane closures, and a Cost module (not used in this study) that compares project costs among alternatives. For the Construction LCI for this study, only the Schedule module was used. The Traffic module will be used for future studies that consider traffic delay, after work characterizing typical inputs to the Traffic module for different types of cases has been completed.

One of the main inputs of *CA4PRS* schedule analysis is the construction timing for lane closures, referred to as the “construction window.” In this study, for example, the pavement preservation overlays for the asphalt case study on a flat rural freeway were assumed to be constructed during the nighttime with partial lane closures for nine hours (9 p.m. to 6 a.m.). During a typical nine-hour nighttime closure, about three hours are nonworking hours: one hour is used for the contractor’s mobilization and about two hours are used for either demobilization and cooling of the asphalt or curing of the concrete prior to opening to traffic.

5.3 Equipment Usage and Operation Hours

Typical characteristics of equipment for the milling and HMA overlay work—such as the milling machine, paving machine, and demolition hauling and HMA delivery trucks—were taken from the historical data in the

CA4PRS resources database. The equipment and values used in these case studies were then checked by respective construction industry groups.

Some minor equipment types not included in the *CA4PRS* database were added based on the specific pavement preservation practice. Specific equipment engine information, such as horsepower and fuel consumption, were collected from industry references and manufacturer's information. Information regarding hourly engine fuel consumption was used directly in the California Air Resources Board's *OFFROAD* model (*56*), with some adjustments based on specific engine information from the manufacturer. Table 5.1 and Table 5.2 show the equipment used and their horsepower and energy consumption information for the asphalt and concrete pavement preservation constructions, respectively, that were considered in the case studies in this report. For the asphalt pavement preservation, the equipment types are categorized into milling, HMA mixing and paving, and general activity. For the concrete pavement preservation, they are categorized into demolition, concrete paving, grinding, and general activity including the vacuuming of all grinding slurry to protect surface waters. Figure 5.2 illustrates a general relationship between engine horsepower and hourly fuel (diesel) consumption for some of the equipment considered in this study.

Table 5.1: List of Construction Equipment Used for Asphalt Pavement Preservation Construction

Activity	Equipment	Engine power (hp)	Hourly Fuel Consumption (Gal/hour)
Milling	Milling machine	700	20.0
	Demo hauling truck	500	5.3
	Payloader	250	10.7
	Grader	250	13.0
	Compactor	100	3.5
HMA Mixing and Paving	AC paver (with pickup)	250	10.6
	HMA delivery truck	500	6.5
	Roller (vibratory/static steel)	150	8.1
	Roller (pneumatic tire)	120	4.9
General Activity	General truck (Tac-coat, water, sweeper, multi)	350	7.2
	Generator (lighting) (3 at site)	200	13.7

Table 5.2: List of Construction Equipment Used for Concrete Pavement Preservation Construction

Activity	Equipment	Engine power (hp)	Hourly Fuel Consumption (Gal/hour)
Demolition	Saw cutters (demo & paving)	80	2.0
	Excavator	500	10.0
	Demo hauling truck	500	4.4
	Payloader	250	5.0
	Compactor	100	5.0
Concrete Paving	Paver (Roller-screed)	90	3.0
	Concrete delivery truck	500	4.9
Grinding & Dowels	Diamond grinder	275	5.0
	Grinder slurry tanker	500	4.9
General Activity	General truck	350	4.9
	Generator (lighting) (3 at site)	200	13.7

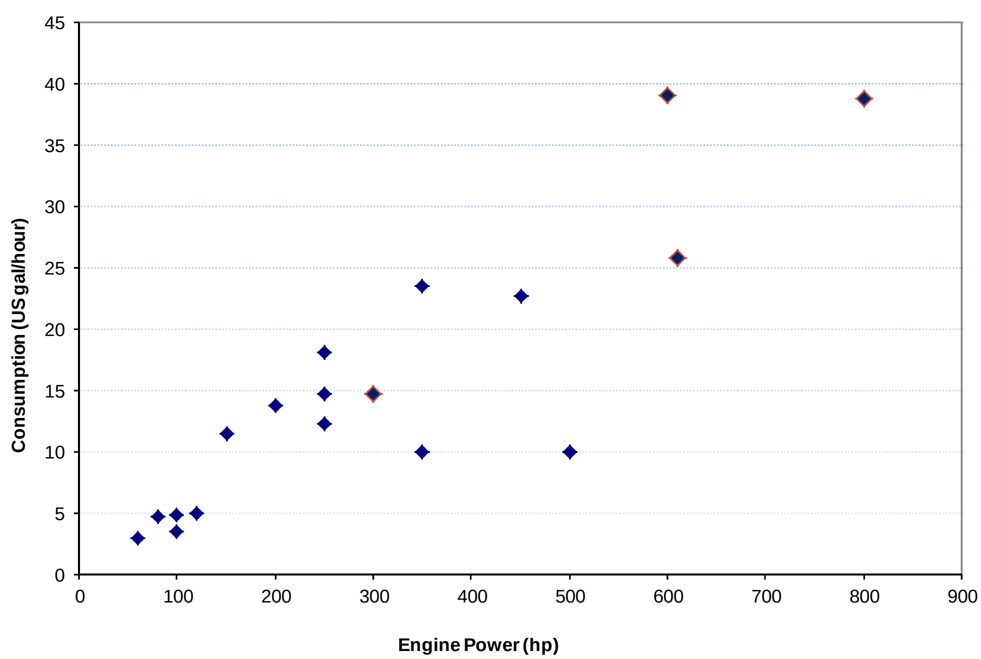

Figure 5.2: General relationship between equipment engine horsepower and hourly fuel (diesel) consumption across all equipment considered.

CA4PRS considers the number of pieces of each type of equipment as a resource input for the schedule (productivity) analysis. The schedule analysis output shows a typical duration of each major construction activity per each closure. Duration is the operation hours of equipment related to that activity. For example, the schedule analysis output shows that the milling activity and the HMA paving activity each take about three hours per nine-hour nighttime closure. An extra one or two hours (depending on the equipment type) were added to the closure operation hours to cover their mobilization and demobilization. In the case of the demolition trucks and HMA delivery trucks, approximately two hours of extra operation time were added per closure for their commute time to the site or the plant. The total operation hours for each type of equipment are calculated as the product of the operation hours per closure and the total number of closures needed to complete the project.

5.4 Emissions Inventory

The California Air Resources Board's *EMFAC* model (*55*) was adopted to calculate direct emissions of on-road hauling trucks, and the *OFFROAD* model from CARB (*56*) was adopted to calculate direct emissions from construction equipment. Both models report emissions factors for various engine sizes and include an inventory of activity for different types of equipment. Emissions factors in the models are based on laboratory testing and defined by engine horsepower and fuel type. Both models are based on the same emissions data.

The emissions inventories of both models include hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2), particulate matter (PM), sulfur dioxide (SO_2), and fuel consumption. While most of the emissions data are based on laboratory tests, SO_2 and fuel consumption are calculated based on other measured pollutants. When the models are run, users can choose how HC are reported among these items: total organic gases (TOG), reactive organic gases (ROG), total hydrocarbon[3] (THC), or methane[4] (CH_4). TOG includes all organic gases. ROG is an equivalent of EPA's volatile organic compounds (VOC). THC includes compounds with H and C atoms only. For *OFFROAD*, CH_4 is collected in order to calculate GWP.

5.4.1 EMFAC

EMFAC contains emissions factors and vehicle activity data for model years from 1965 to estimates up to 2040. This information is important when considering technology improvement. In the LCA model used in this study, technology improvement is dealt with by limiting the span of model years in the analysis. For example, this study assumed that trucks older than ten years are retired or re-powered (have their engines replaced) based on input from industry. Hence, if the analysis year is 2012, only trucks from 2003 to 2012 are included. *EMFAC*

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[3] Option for *EMFAC*, not available for *OFFROAD*.
[4] Option for *EMFAC*, default and reported separately for *OFFROAD*.

groups vehicles into thirteen classes. Material transport trucks are assumed to all be vehicle Class 8 (T7, Heavy-Heavy-Duty Trucks [HHDT]), which weigh over 15 metric tons (33,000 lbs). All of the trucks included in the analysis are assumed to run on diesel.

5.4.2 OFFROAD

The *OFFROAD* model generates three output files by default: exhaust emissions, evaporative emissions, and toxics emissions reports. This report and its initial case studies use the results of the exhaust emissions report, which includes the emissions inventory, equipment population, equipment average activity, and fuel consumption. The emissions inventory from *OFFROAD* is a product of the emissions factor (g/hour), population (total number of each equipment type in use), activity (hours per year per equipment type [hr/yr-pop]), and other factors. The emissions inventory is converted to emissions per hour of operation for use in the UCPRC Pavement LCA model.

One challenge associated with using *OFFROAD* is that the equipment types included in the *OFFROAD* database do not all directly match the equipment defined in *CA4PRS*. Instead of matching equipment types based on their titles, equipment types were matched based on their maximum engine horsepower.

6. METHODS FOR MODELING THE USE PHASE LIFE CYCLE INVENTORY

The Use Phase system boundary recommended in the *UCPRC Pavement LCA Guideline* (*23*) includes additional fuel use by vehicles operating on the pavement attributed to pavement deterioration, the pavement heat island effect, non-GHG climate change effects from pavement albedo, the effect of roadway lighting due to pavement albedo, carbonation of concrete pavement, and water pollution from leachate and runoff. Also discussed in the guideline is consideration of fuel use and GHG emissions from energy consumed that can be attributed to pavement deterioration that damages vehicles, damages freight, and changes tire wear. However, since the goal of the case studies presented in this report is limited to evaluating the effects of pavement deterioration and maintenance, only the effects that these two factors have directly on fuel economy—without consideration of vehicle damage, freight damage, or tire wear—have been included in the Use Phase. This is considered reasonable given the assumptions that pavement type, the effects of heat island, the non-GHG climate change effect from pavement albedo, roadway lighting, and carbonation will all remain the same, and therefore they are not expected to differ among the alternatives examined for each case study. LCIs for vehicle damage, freight damage, and tire wear are too complex and/or incomplete to consider at this time. In addition, the case studies do not consider the effects of water pollution.

6.1 Methodology

6.1.1 Pavement and Fuel Consumption

Pavements directly affect vehicle fuel economy through the phenomenon of rolling resistance. The effects are caused by a combination of three factors: pavement structure, roughness, and macrotexture. These can be managed by pavement design and maintenance practices.

Many of the existing studies that focus on pavement structure have indicated that concrete pavements, which are stiff and elastic, have less rolling resistance than asphalt-surfaced pavement (also referred to as "flexible pavement" if there is no cemented base beneath the asphalt) (*57, 58*). The explanation provided is that asphalt's viscoelastic response rather than its elastic response (i.e., its properties that dissipate energy as opposed to its properties that return stored energy to the system) predominates when a vehicle passes—consuming energy that could otherwise have been used for propulsion (*57*). However, a recent empirical field study with a fleet consisting of several types of light and heavy vehicles showed that the effect of pavement type (concrete and asphalt) is not statistically significant *except* under conditions where asphalt pavement exhibits its most viscous behavior: when an asphalt pavement surface is used by heavy vehicles traveling at low speed when the pavement is hot (*16*). In all of these studies there is very little detailed information provided about the asphalt pavements, such as cross sections and specific asphalt material types, to enable direct application for asphalt pavement structures and materials in other case studies. The studies do not provide the viscoelastic master curves showing stiffnesses and phase angles for different traffic speeds and temperatures nor the underlying base type (cement-treated or aggregate), factors which were not considered in their analyses or conclusions. If an asphalt mix is aged and/or subjected to cooler temperatures, either due to climate or depth below the surface, or subjected to faster traffic, then it will behave more elastically. The response of an asphalt mix also depends on the type and grade of the asphalt binder. Types include conventional, polymer-modified, or rubberized, which can have very different viscoelastic master curves. Grades are measured in terms of their stiffness at extreme high and low temperatures. Also, the viscoelastic deformation will be controlled to some degree by the stiffness of the layer beneath it, with concrete or cement-treated base expected to result in smaller deformations in the asphalt than an aggregate base.

For the case studies presented in this report, it was assumed that pavement type would not change because of the treatment: asphalt pavement would remain asphalt pavement and concrete would remain concrete. This fits with the goal of this study, which is to compare the effects of performing maintenance that changes the surface characteristics of the pavement versus not performing this maintenance—which doesn't change the pavement type—rather than comparing the effects of rehabilitation or reconstruction where the pavement type changes.

Pavement roughness (also referred to as *smoothness)* is defined as the deviation of a road surface from a true planar surface with wavelengths of deviations that can range between 0.5 and 50 m (1.6 and 164 ft [(*59*)]). Pavement unevenness in these wavelengths dissipates energy in the vehicle suspension, which includes deformation of the tire body. International Roughness Index (IRI) is a roughness parameter developed by the World Bank to provide a stable and portable measurement standard for worldwide use. However, IRI was not developed to provide a parameter that captures the full effect of pavement/vehicle interaction on fuel economy. Instead, it was developed to characterize the effect of pavements on vehicle dynamics, and was calibrated for human comfort by simulating the vertical movements of a passenger in a car adjusted for the human perception of frequency and amplitude of that vertical movement. IRI was also intended for use in characterizing improvements in the longitudinal profiles of the wheelpaths in order to reduce vehicle operating costs, including fuel economy and vehicle wear (*60*). IRI is presented in terms of the accumulated vertical displacements per distance traveled of a vehicle mass calculated by computer simulation of the mass, a car suspension and a wheel operating on the longitudinal profile measured in the wheelpath, with units of inches/mile or m/km.

Macrotexture is defined as the deviation of a pavement surface from a true planar surface with the wavelengths of the deviations between 0.5 and 50 mm (0.02 and 2 in. [(*61*)]). It is typically measured on asphalt-surfaced pavement as Mean Profile Depth (MPD) with units of millimeters. A similar measure, called Mean Texture Depth (MTD), is typically used on concrete-surfaced pavement. MTD does a better job of accounting for directional texture that has been cut into the surface of the concrete, such as longitudinal tining or grooving, than does MPD. Macrotexture dissipates energy through the viscoelastic response of the rubber in the tire tread as it rolls over the surface.

Some studies have shown that roughness (unevenness) and macrotexture are the most important components affecting rolling resistance and fuel consumption (*8*). The results suggest that a change in IRI from 1 m/km (60 in./mi., smooth) to 10 m/km (600 in./mi., extremely rough, maximum speed about 60 km/hr or 38 mph) can increase rolling resistance between 8 percent and 64 percent, while a change in MPD from 0.3 mm to 3 mm can increase the rolling resistance between 8 percent and 84 percent. Another study showed that changes in IRI and MPD in the same ranges can lead to increases in rolling resistance of 47 percent and 60 percent, respectively (*62*). Other studies focused on the direct relationship between IRI and fuel economy (*58, 63, 64*). These studies agree that pavement roughness is positively correlated with vehicle fuel consumption, but they differ in the quantitative relationship determined, which is to be expected considering that different methods of measuring rolling resistance were used as well as different vehicles. There are at least four different methods for measuring rolling resistance (*7*) which may relate differently to both IRI and macrotexture. These methods consist of direct measurement through fuel flow meters, coast-down tests, direct measurements of rolling resistance with instrumented trailers, and drum dynamometer measurements.

A recent study calibrated the fuel consumption model in the World Bank's *HDM-4* (Highway Development and Management software ver. 4) under U.S. conditions (*65*), in which IRI and MPD are used to predict vehicle fuel use. The results indicate that that a change in IRI from 1 to 5 m/km (60 to 300 in./mi.) can increase the fuel use of cars by 4 percent. This result matches the previous conclusion if we consider that a 10 percent change in rolling resistance can lead to a 1 to 2 percent change in fuel economy. However, this study also shows that the effect of macrotexture on fuel consumption is small except for heavy trucks at low speed (35 mph) (*16*). Therefore further research may be needed to identify the importance of macrotexture in fuel consumption.

6.1.2 Addressing Rolling Resistance Under Different Traffic Situations

Currently, almost all studies that address the effect from rolling resistance on fuel consumption are performed at a steady speed. However, it is unknown whether a speed fluctuation will impact the process by which rolling resistance affects fuel consumption. In the Pavement LCA Workshop held at UC Davis in 2010, it was agreed by the participants that the effect from speed fluctuation under conditions such as congested traffic should also be included in the rolling resistance analysis (*66*). Therefore, the development of a model that can address both pavement condition (roughness and texture) and different traffic conditions is important in the Use Phase of a pavement LCA. The traffic condition needs to include different levels of service, including vehicles travelling at a constant free-flow speed and traffic under congested, stop-and-go conditions.

Currently there are several types of vehicle emissions models: some do not consider pavement and traffic conditions, while others can either fully or partially characterize the relationship between pavement condition and fuel consumption/emissions under different traffic conditions. These four types of models and examples of each are shown in Table 6.1.

Table 6.1: Description of the Four Types of Fuel Economy/Emissions Models

Type	Is pavement roughness considered?	Speed Condition	Examples
A	No	Only steady speed	*EMFAC (55), MOBILE (67)*
B	No	Speed fluctuation included	*CMEM (68)*
C	With pavement information	Only steady speed	*HDM-4 (15)*
D	With pavement information	Speed fluctuation included	*MOVES (69)*

Type A models only assume that vehicles travel at a steady speed and do not include pavement rolling resistance. The model results represent either an average rolling resistance from pavement or no effect of rolling resistance from pavement. However, because no mechanistic component is involved in the modeling process, it is impossible to add the effects of pavement to the model. Furthermore, because the speed fluctuation is not addressed, the model can only analyze the stabilized running exhaust emissions based on average speed, and the results may underestimate real-world emissions, especially during peak-hour congested traffic conditions. When using this type of model, a macroscopic or mesoscopic approach is usually adopted to acquire the traffic information. By using a Demand-Capacity model or other macroscopic traffic analysis method, the aggregated vehicle activities, such as the distribution of mileage under different speed ranges, can be acquired, and then the emissions factors (usually only based on speed) can be applied to those activities to obtain the fuel consumption and emissions.

Type B models use a more comprehensive approach than Type A models to address vehicle emissions based on vehicle operation conditions. An example of this type of model, *CMEM,* can simulate engine activity based on the vehicle classification and second-by-second vehicle operation mode, and simulate instantaneous fuel consumption and emissions. The vehicle operation mode is usually a function of vehicle speed, acceleration, and roadway grades. This information is usually gathered by using probe vehicles equipped with GPS devices operating in traffic, or through microscopic traffic simulation. However, currently this type of model cannot fully address the impact of pavement on vehicles. *CMEM* is based on dynamometer test results and does not consider any pavement information, and it is not practical to revise this parameter. The developer of *CMEM* does not update the model to reflect changes in vehicle technology and their impact on emission factors. Furthermore, the structure of this model does not allow it to be run at large scales of time and space, such as for multiple road segments during multiple years, because the user needs to input the second-by-second speed of each vehicle.

Type C models are also steady-speed models, but they incorporate pavement information. This type of model adopts a mechanistic-empirical approach. The mechanistic part is that the model analyzes the different types of resistance that the engine has to overcome, converts the resistance force to engine power, and calculates the instant fuel consumption based on that engine power. The types of resistance usually include aerodynamic resistance, rolling resistance, gradient resistance, inertial resistance, and curvature resistance. The empirical part consists of determining many of the coefficients for the different types of resistance based on experiments and observations. An example of this type of model is the fuel consumption model in *HDM-4*. Although pavement information is integrated into this model, problems with this model are that (1) it only deals with steady speed; (2) it does not address pollutant emissions, only fuel economy; and (3) it only handles current vehicle technologies and there is currently no organization maintaining the model to keep it up to date with advanced vehicle technologies. Therefore it is difficult to consider policy and technology changes that will affect fuel economy and GHG emissions from pavement maintenance over a future time horizon.

Type D models can address both speed fluctuation and different pavement conditions, and were the preferred candidate for this study. Similar to Type B models, Type D models first use an engine model to simulate the engine running status, and then convert this status to emissions and fuel consumption. During the modeling of engine status, the rolling resistance forces, aerodynamic forces, inertial forces (when accelerating), and gravitational forces when driving on a vertical curvature are calculated and then converted to engine power. Engine power, speed, and vehicle mass are then combined to create an indicator of engine running status, and this indicator is used to calculate the base emissions factors. Type D models differ from Type B models in that the former are able to include the pavement effect on rolling resistance, and to calculate the emissions for large time and space scales. Furthermore, because the results are calculated on a second-by-second basis, Type D models have the capability to capture the additional emissions from speed fluctuation and can be easily implemented with the effects of technology improvement on emission factors and fuel consumption. *MOVES*, which was developed by the U.S. Environmental Protection Agency (U.S. EPA), is an example of a Type D model. A detailed description of *MOVES* and the method developed by the UCPRC for this study to update the rolling resistance term in its engine model will be discussed in Section 6.2.2.

6.1.3 *Vehicle Operation Process Model Adopted by UCPRC*

Figure 6.1 shows the outline of the vehicle operation process model adopted by the UCPRC for this study. First, the time progression of pavement surface characteristics (roughness, macrotexture) on a road segment is generated from pavement condition survey information and performance models. At the same time, based on different M&R strategies, different scenarios can be also developed for these surface characteristics. The rolling resistance based on these surface characteristics is then calculated using the rolling resistance model, and these rolling resistance values are used to update the relevant parameters in a vehicle emissions model. The method to update the rolling resistance parameter can vary depending on the specific vehicle emissions model.

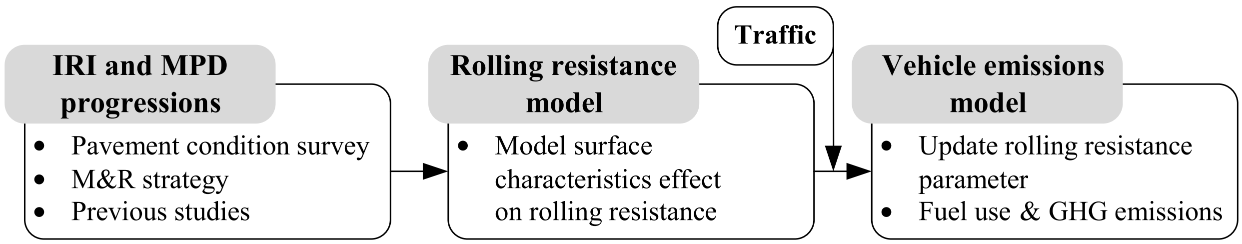

Figure 6.1: Procedure adopted by UCPRC to calculate additional fuel consumption due to pavement deterioration.

6.2 Model Description

In the approach used for this study, the *HDM-4* was adopted as the rolling resistance model and *MOVES* was adopted as the vehicle emissions model.

6.2.1 *HDM-4*

HDM-4 is a model published by PIARC (World Road Association) and developed by the World Bank to conduct cost analysis for the maintenance and rehabilitation of roads (*15*). It has a model for simulating rolling resistance from IRI and MPD for asphalt pavement and IRI and MTD for concrete pavement, and an engine model to address the effects of rolling resistance on vehicle fuel consumption. Only the relationship between surface characteristics and rolling resistance was used in the UCPRC vehicle operation process model because only steady speed is considered when *HDM-4* calculates fuel consumption.

In *HDM-4*, rolling resistance is calculated through Formulas (6.1) and (6.2). Some coefficients are shown in Table 6.2. In a recent NCHRP study (01-45), these rolling resistance equations were calibrated based on North American vehicles (*70*). The calibration factor *Kcr*2 was developed for each type of vehicle. However, this factor will be cancelled out during the calculation in this study, which will be shown in Section 6.2.2.2.

$$Fr = CR2 \times FCLIM \times \left(b11 \times Nw + CR1\left(b12 \times M + b13 \times v^2\right)\right) \quad \textbf{(6.1)}$$

$$CR2 = Kcr2\left[a0 + a1 \times Tdsp + a2 \times IRI + a3 \times DEF\right] \quad \textbf{(6.2)}$$

Where:

Fr	is rolling resistance in Newtons;
*CR*1	is a function of tire type, 1.3 for cross-ply bias, 1.0 for radial, and 0.9 for low profile tires;
*CR*2	is the factor of surface characteristics;
FCLIM	is the climate factor related to the percentage of driving done in snow and rain;
Nw	is the total number of wheels;
*b*11, *b*12, and *b*13	are the coefficients related with tire type and technologies;
*Kcr*2	is a calibration factor;
*a*0, *a*1, *a*2, and *a*3	are coefficients for different surface characteristics;
Tdsp	is the texture depth from the sand patch method in mm, which can be calculated from *MPD* as: *Tdsp* = 1.02**MPD* + 0.28 for asphalt pavement; for concrete pavement *MTD* is used to represent *Tdsp* directly.
IRI	is the International Roughness Index in m/km;
DEF	is the Benkelman Beam rebound deflection in mm, a measure of pavement elastic deflection, not used in this study;
M	is the mass of vehicles in kg; and
v	is the speed in m/s.

Table 6.2: Values of Coefficients in *HDM-4* CR2 Model

Surface Class	Operating Weight of Vehicle							
	≤2,500 kg (5,500 lb)				>2,500 kg (5,500 lb)			
	a0	***a1***	***a2***	***a3***	***a0***	***a1***	***a2***	***a3***
Bituminous	0.5	0.02	0.10	0	0.57	0.04	0.04	1.34
Concrete	0.5	0.02	0.10	0	0.57	0.04	0.04	0

Using these parameters, the rolling resistance with a specific pavement and a specific type of vehicle can be used to calculate rolling resistance.

6.2.2 MOVES

MOVES (Motor Vehicle Emissions Simulator) is the official highway vehicle emissions model developed by the U.S. Environmental Protection Agency (U.S. EPA) (*69*). It calculates vehicle fuel consumption and emissions based on emissions factors and vehicle activities. The emissions factors are adjusted from base emissions factors according to engine running status, engine technology, vehicle age, meteorology, and other factors, and vehicle activity acquired from fleet information and traffic activities. *MOVES* can be used to analyze the effect of rolling resistance on vehicle fuel consumption and emissions because it incorporates engine running status. The U.S. EPA is continuing development of *MOVES* to make its data more accurate and more functional, and also to reflect EPA's estimate of future changes in fleet average fuel economy based on new data and national policy changes affecting fleet average fuel economy. In this study *MOVES* version 2010a was used.

6.2.2.1 Modeling Engine Running Status

MOVES uses vehicle specific power (VSP) as an indicator of engine running status. *VSP* is the engine power per unit vehicle mass and it represents the power demand placed on a vehicle when the vehicle operates under different speeds and conditions. It is calculated based on the vehicle's instantaneous speed and the forces that an engine needs to overcome during normal operation, including aerodynamic drag, rolling resistance, engine inertial drag, and gradient force. For each run of the model, *MOVES* calculates the second-by-second *VSP* of vehicles and uses the *VSP* time history to calculate the emissions factors. Formula (6.3) shows the mathematical form of the *VSP*, using *A*, *B*, and *C* to denote the coefficients for the first, second, and third order terms of velocity. The "*A*" coefficient roughly corresponds to the tire rolling resistance terms. "*B*" tends to be small, and describes higher order rolling resistance factors in addition to mechanical rotating friction losses. The "*C*" coefficient represents the air drag coefficient terms.

$$\begin{aligned} VSP &= Rolling\ resistance + Air\ resistance + Inertial\ and\ Gradient\ resist \\ &= F_{rolling} \times \frac{v}{M} + F_{Aerodynamic} \times \frac{v}{M} + F_{inertial\ and\ Gradient} \times \frac{v}{M} \\ &= C_R g \times v + \frac{1}{2}\frac{\rho_a C_D A_{front}}{M}(v+v_w)^2 \times v + \left(a\left(1+\varepsilon_i\right) + g \times grade\right) \times v \\ &= A/M \times v + B/M \times v^2 + C/M \times v^3 + \left(a\left(1+\varepsilon_i\right) + g \times grade\right) \times v \end{aligned} \qquad \textbf{(6.3)}$$

Where:

$F_{rolling}$	is the rolling resistance in Newtons;
$F_{Aerodynamic}$	is the aerodynamic resistance in Newtons;
$F_{inertial\ and\ Gradient}$	is the inertial resistance (if in acceleration) and gradient resistance (if on hill) in Newtons;
C_R	is the rolling resistance coefficient;
ρ_a	is the ambient air density (1.207 kg/m^3, at 20°C);
v	is the vehicle speed in m/s;
v_w	is the speed of headwind into the vehicle in m/s;
A_{front}	is the front area of the vehicle in m^2;
C_D	is the aerodynamic drag coefficient;
ε_i	is the "mass factor," which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain;
grade	is the gradient, which is vertical rise divided by slope length;
g	is the acceleration of gravity in m^2/s;
M	is the mass of vehicles in kg;
a	is vehicle acceleration in m^2/s;
A	is the coefficient of rolling resistance component in *MOVES*;
B	is the coefficient of higher order rolling resistance factors and mechanical rotating friction losses in *MOVES*; and
C	is the coefficient of air drag term in *MOVES*.

With *VSP* calculated, the engine running status in *MOVES* is then defined by both instantaneous *VSP* and speed. This mode is binned for the development of emissions factor and fuel consumption. *MOVES* classifies the *VSP* bin for different modeling purposes: fuel consumption and emissions. Table 6.3 shows the bin definition for fuel consumption modeling in *MOVES (71)*.

Table 6.3: *MOVES* Operating Mode Bin Definitions for Fuel Consumption

Braking (Bin 0)			
Idle (Bin 1)			
***VSP* / Instantaneous Speed (mph)**	**0-25**	**25-50**	**>50**
< 0 kW/metric ton	Bin 11	Bin 21	-
0 to 3	Bin 12	Bin 22	-
3 to 6	Bin 13	Bin 23	-
6 to 9	Bin 14	Bin 24	-
9 to 12	Bin 15	Bin 25	-
12 and greater	Bin 16	Bin 26	Bin 36
6 to 12	-	-	Bin 35
< 6	-	-	Bin 33

Therefore, the emissions factors are directly related to the *VSP*, from which the pavement contribution can be included in the vehicle emissions modeling. The user can also input a *VSP* distribution directly, but under this modeling mode, the calculation can only be run at an hourly level, which does not meet the requirements of this study.

6.2.2.2 Updating the Rolling Resistance Term

According to *MOVES* documents, the default values of coefficients *A*, *B*, and *C* are derived from the track road load horsepower (*TRLHP*) at 50 mph recorded in the Mobile Source Observation Database (*MSOD*) (*72*). *MSOD* includes the emissions test data from in-use mobile air-pollution sources such as cars, trucks, and engines from trucks and off-road vehicles. Here, *TRLHP* is a value obtained through dynamometer tests of vehicles, in which a vehicle is running on a smooth surface, usually steel or steel with a sand coating. From this point of view, the rolling resistance coefficient (*A*) in the *MOVES* model only includes the rolling resistance effect from vehicles and excludes the effect from pavements, but allows the rolling resistance parameter to be proportionally increased to reflect pavement condition.

Formula (6.1), which is the original equation in *HDM-4*, implies that the effect of surface characteristics on rolling resistance is a product of the effect from pavement surface and vehicle tires because CR2 reflects the effect from pavement and $\left(b11\times Nw+CR1\left(b12\times M+b13\times v^{2}\right)\right)$ represents the effect from vehicle tires. In *MOVES*, because the *A* coefficient is derived from a wide range of dynamometer test results, it can be assumed that this coefficient has included all the averaged effects from the surface of the dynamometer, and a variety of vehicle and tires. Therefore, when calculating the rolling resistance on real pavement, if it is assumed that the rolling resistance on the dynamometer and on the pavement will follow this same rule, the *A* coefficient can be proportionally increased by increasing the effect of surface characteristics from the dynamometer surface to the real-world pavement surface. Because the dynamometer is very smooth and usually uses steel or steel with a sand coating as its surface, which has much lower macrotexture than real pavement, the *IRI* and *MDP* are assumed to be 0. Formula (6.4) shows the relationship between the updated *A* coefficient and the default *A* coefficient in the *MOVES* database. The updated *A* coefficient is used in later *MOVES* calculations for emissions and fuel consumption. Although the *B* coefficient also includes a higher order rolling resistance factor, the *B* coefficient was not revised for this study because (1) it also combines the rotating friction losses and (2) it is either 0 or very small.

$$\frac{A_{updated}}{A_{default}} = \frac{CR2_{pavement}}{CR2_{dynamometer}} = \frac{Kcr2\left[a0 + a1 \times Tdsp + a2 \times IRI + a3 \times DEF\right]}{Kcr2\left[a0 + a1 \times (1.02 \times 0 + 0.28) + a2 \times 0 + a3 \times 0\right]}$$
$$= \frac{a0 + a1 \times Tdsp + a2 \times IRI + a3 \times DEF}{a0 + a1 \times 0.28} \qquad \textbf{(6.4)}$$

6.3 Input Data for UCPRC Vehicle Operation Model

Input data for the UCPRC vehicle operation model includes pavement surface characteristics, traffic information, and other inputs required by *MOVES* over the analysis period.

6.3.1 Pavement Surface Characteristics

Currently, the surface characteristics of pavement considered are roughness (IRI) and macrotexure (MPD or MTD), but not viscoelastic deflection.

<u>IRI</u>

For asphalt pavement, a time series of IRI is required. For this study, IRI progression was estimated from the Caltrans pavement condition survey (PCS) database using locations close to those in the high traffic and low traffic case studies. When the IRI data was extracted from the database, segments with similar traffic condition (AADT and truck percentage) were selected.

For concrete pavement, a linear regression model of IRI progression after diamond grinding was developed based on data collected on Caltrans grinding projects (*73*) and from the Caltrans PCS database, using the cumulative ESALs and IRI just after grinding as explanatory variables. The model of IRI progression for concrete pavement used in the case studies is shown in Formula (6.5).

$$\sqrt{IRI\left(m/km\right)} = -1.74\times10^{-1} + 9.66\times10^{-5}\times\sqrt{CumulativeESAL} + 1.15\times\sqrt{InitialIRI\left(m/km\right)} \quad \textbf{(6.5)}$$

Where *CumulativeESAL* is the cumulative ESALs that a lane has received after the grinding project, and *InitialIRI* is the IRI value right after the grinding project. The statistical results of this regression are shown as follows:

	Value	Std. Error	t-value	P-value
(Intercept)	-1.74e-01	4.643e-02	-3.748	0.000272
Sqrt(*CumulativeESAL*)	9.657e-05	1.439e-05	6.711	6.17e-010
Sqrt(*InitialIRI*)	1.149e+00	3.515e-02	32.674	<2e-16

Total number of observations: 127; Residual standard error: 0.06811 on 124 degrees of freedom; Multiple R-Squared: 0.9022. A t-value is a statistical test value following Student's t distribution where t = mean – value of interest/sample std. dev./square root of sample size. The P-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true.

The same dataset also yields a model for the initial drop in IRI from grinding. It is also a linear regression model: the IRI drop is a function of the IRI value before the diamond grinding. The model is shown in Formula (6.6).

$$IRIchange\left(m/km\right) = -0.6839 + 0.6197\times IRI\_beforeGrinding\left(m/km\right) \quad \textbf{(6.6)}$$

Where *IRIchange* is the IRI drop after grinding; and *IRI_beforeGrinding* is the IRI value before the diamond grinding. In this model, the standard deviation of the residual is 0.285 m/km, which will be used in the case study to develop different scenarios for construction smoothness. The statistical results of this regression are shown as follows.

	Value	Std. Error	t value	P-value
(Intercept)	-0.6839	0.1677	-4.078	0.000249
Before_Grinding	0.6197	0.0751	8.252	1.00e-09

Total number of observations: 37; Residual standard error: 0.2886 on 35 degrees of freedom; Multiple R-Squared: 0.6605.

<u>Macrotexture</u>

Because the PCS does not collect MPD, the progression of MPD over time for asphalt was taken from a previous project performed by the UCPRC (*74*). The models of MPD progression for an HMA and an RHMA overlay are shown in Formula (6.7) and Formula (6.8), respectively.

$$\begin{aligned} MPD\left(micron\right)_{HMA} &= -93.7089 - 4.2910\times AirVoid\left(\%\right) + 47.8933\times Age\left(year\right) \\ &+28.2136\times FinenessModulus - 9.9487\times NMAS\left(mm\right) - 5.4209\times Thickness\left(mm\right) \\ &-0.7087\times NumberOfDays > 30C - 0.0402\times AADTTinLane \end{aligned} \quad \textbf{(6.7)}$$

$$\begin{aligned} MPD\left(micron\right)_{RHMA} &= -622.7423 - 9.1326\times AirVoid\left(\%\right) + 14.3359\times Age\left(year\right) \\ &+403.7994\times FinenessModulus - 28.119\times NMAS\left(mm\right) - 2.6337\times Thickness\left(mm\right) \\ &-0.7899\times NumberOfDays > 30C - 0.0348\times AADTTinLane \end{aligned} \quad \textbf{(6.8)}$$

Where *NMAS* is the nominal maximum aggregate size, and others terms are indicated by their names.

The UCPRC has not performed studies measuring the performance of the macrotexture of concrete pavement, therefore the progression of the macrotexture of concrete pavement was taken from a study by Rao et al (*75*), which is in terms of mean texture depth (MTD) from the sand patch method. The model is shown in Formula (6.9). MTD is then converted to MPD using Formula (6.10) based on documentation from *HDM-4*.

$$MTD(mm) = -0.152 \times (1 + 0.233 \times Freeze) \times Ln(Age) + 0.887 \quad \textbf{(6.9)}$$

$$MTD(mm) = 1.02 \times MPD(mm) + 0.28 \quad \textbf{(6.10)}$$

Where:

MTD is the mean texture depth from sand patch method in mm;
MPD is the mean profile depth from profiling method in mm;
Age is the age since grinding in years (0.5 to 16 years); and
Freeze is the dummy variable for freeze climate region: 0 for wet nonfreeze or dry nonfreeze; 1 for wet freeze or dry freeze.

6.3.2 Traffic

MOVES requires traffic flow and vehicle classification and speed information to calculate fuel consumption and emissions.

<u>Traffic Flow</u>

Traffic flow here refers to total vehicle miles traveled (VMT) on a segment for each vehicle type. *MOVES* requires the hourly VMT for each type of vehicle in the emissions calculation. VMT is the product of traffic volume and segment length on a specific roadway segment, requiring the acquisition of the traffic volume for each vehicle type from a traffic monitoring database. The on-road traffic database used in this study was the Caltrans traffic volume report and truck traffic report, including the average annual daily traffic (AADT), and truck fleet composition (*76*), which will be referred to as *CalTruck* data in this report. However, *CalTruck* has a different vehicle classification from *MOVES*, so a conversion procedure was needed to convert the *CalTruck* data to *MOVES* data.

To create the conversion matrix from *CalTruck* data to *MOVES* data, a two-step mapping process was used (a) to avoid severe data loss because a direct conversion would involve a change from 5 types to 13 types, and (b) because they are completely different classification methods. First, the *CalTruck* data was converted to another vehicle classification method used by Caltrans (here referred to as "Caltrans Classification"), which includes 13 vehicle types. Then, this 13-type classification ("Caltrans Classification") was converted to the *MOVES* classification. For the first step, a study by UCPRC provided the data to support the conversion (*77*). It used the data collected from 114 Caltrans Weight-in-Motion (WIM) sites on the California state highway network. At each WIM location, the number of vehicles is collected in both the *CalTruck* classification (5 types) and the Caltrans classification (13 types). This allowed creation of a conversion matrix from *CalTruck* to

Caltrans. For the second step, conversion of Caltrans to *MOVES*, the conversion matrix was based on experience and some state average data from the *EMFAC* database, which is the California emissions inventory for on-road traffic. Because *CalTruck* only provides the average daily traffic, it was assumed that the daily traffic hourly flow is constant across all days of the year. Table 6.4 shows the vehicle classifications of *CalTruck,* Caltrans, and *MOVES*.

Table 6.4: Vehicle Classification for *CalTruck*, Caltrans, and *MOVES*

***CalTruck* Classification**	**Caltrans Classification**	***MOVES* Classification**
Passenger Car 2-Axle Truck 3-Axle Truck 4-Axle Truck 5-or-more Axle Truck	• Motorcycles • Passenger Cars, Light Vans, Light Pick-up, Mini Vans, • 2-Axle 4-Tire, Full-Size Pick-up, Full-Size Vans, Limo, Motor Home • Bus • 2-Axle 6-Tire Single Unit Truck • 3-Axle Single Unit Truck • 4-Axle Single Unit Truck • 4-Axle-or-less Double Unit Truck • 5-Axle Double Unit • 6-or-more Axle Double Unit Truck • 5-Axle or Less Multi-unit Truck • 6 Axle Multi Unit Truck • 7 or more Axle Multi-unit Truck	• LDA o Passenger Car • LDT (Other 2-axle/4-tire vehicles) o Passenger Truck o Light Commercial Truck • M&HDT (Single Unit Trucks) o Refuse Truck o Single Unit Short-haul Truck o Single Unit Long-haul Truck o Combination Short-haul Truck o Combination Long-haul Truck) o Motor Home • Bus o Transit Bus o School Bus o Intercity Bus • MCY o Motorcycle

In addition to the conversion of truck traffic flow on a segment, it is also necessary to assign the total traffic flow from *CalTruck* to different lanes. This is important because this study focuses on the effect of pavement surface characteristics and their progression over time is different for different lanes: inner lanes will have a lower rate of deterioration because they carry fewer heavy vehicles, while the outer lanes deteriorate faster because of the high percentage of trucks. A lane distribution factor (LDF) for vehicles was introduced to address this problem during the traffic assignment process. LDF is defined as the portion of traffic that is traveling on a specific lane, and was also developed from the WIM study (*77*). Different sets of LDFs were taken for highways ranging from one to six lanes per direction. To maintain a level of practicability, the LDF from multiple WIM sites was aggregated to separate values for rural and urban highways. The LDF was then applied to the daily traffic calculated previously to obtain the daily traffic for each vehicle type in each lane.

Because *MOVES* requires traffic flow information at the hourly level, and data converted from *CalTruck* is at the daily level, these data need to be assigned to each hour in a day. Here the hourly distribution factor derived from the California Freeway PeMS (Performance Measurement System) database was used (*78*). PeMS uses loop detectors to measure the speed and traffic count on freeways. The database includes both historical and real-time freeway data in California. The hourly distribution factor is the portion of traffic of each hour within the whole day. For each PeMS station, a factor for weekdays and a factor for weekends are generated separately to meet the input requirement of *MOVES*. To ensure that any specific roadway segment will have this hourly distribution factor, the factors for each county are also aggregated to produce separate values for rural and urban highways. In the final model, if a roadway segment has a PeMS station, then the hourly distribution factor from that station will be used. Otherwise, the factor will be selected based on the county and road type (rural or urban). With the assumption that the hourly distribution is the same across all vehicle types and all lanes, these hourly distribution factors are then applied to the daily traffic in each lane to obtain the hourly traffic for each lane.

<u>Speed</u>

MOVES requires the average speed distribution for each type of vehicle for its calculations. This is the fraction of driving time in each speed bin (*MOVES* divides the speed into different speed bins, shown in Table 6.5) for each hour, day type (weekday and weekend), and vehicle type. From the *MOVES* documentation, it is known that the default data for rural roads was acquired in California, while for urban roads the default data was averaged from multiple cities across the U.S. (*72*). The four example case studies presented in this report include only rural freeways, and the default data for average speed distribution for rural freeways in *MOVES* was used. Updating of the model for application to the state highway network (including urban highways) will require further investigation and data collection.

Table 6.5: *MOVES* Speed Bin Categories

Bin	Average Speed (mph)	Average Speed Range (mph)
1	2.5	Speed < 2.5 mph
2	5	2.5 mph ≤ Speed < 7.5 mph
3	10	7.5 mph ≤ Speed < 12.5 mph
4	15	12.5 mph ≤ Speed < 17.5 mph
5	20	17.5 mph ≤ Speed < 22.5 mph
6	25	22.5 mph ≤ Speed < 27.5 mph
7	30	27.5 mph ≤ Speed < 32.5 mph
8	35	32.5 mph ≤ Speed < 37.5 mph
9	40	37.5 mph ≤ Speed < 42.5 mph
10	45	42.5 mph ≤ Speed < 47.5 mph
11	50	47.5 mph ≤ Speed < 52.5 mph
12	55	52.5 mph ≤ Speed < 57.5 mph
13	60	57.5 mph ≤ Speed < 62.5 mph
14	65	62.5 mph ≤ Speed < 67.5 mph
15	70	67.5 mph ≤ Speed < 72.5 mph
16	75	72.5 mph ≤ Speed

6.3.3 *Other Input Data Required by MOVES*

MOVES also requires other inputs including meteorological data, vehicle age distribution data, and fuel information.

6.3.3.1 Meteorological Data

The meteorological data used in *MOVES* includes the temperature and relative humidity of each hour of each month in the analysis year. The default database included with *MOVES* has these data for each county. The default meteorological data was used.

6.3.3.2 Vehicle Age Distribution

Vehicle age distribution includes the portion of vehicles from Age 0 to Age 30 for each vehicle type in the analysis year. This data was extracted from *EMFAC*, the California on-road vehicle inventory. Because *EMFAC* has a different vehicle classification than *MOVES*, a simple mapping from *EMFAC* to *MOVES* was used here for vehicle age distribution. For LDT (Light Duty Trucks), the overall vehicle age distribution was calculated from *EMFAC*, and this number was applied to both Passenger Truck and Light Commercial Truck. Similar approaches were adopted for M&HDT (Medium and Heavy Duty Truck) except Motor Home (because both *EMFAC* and *MOVES* have the category Motor Home). For other types of vehicles, because both *EMFAC* and *MOVES* have the same categories, the direct mapping was used. Table 6.6 shows this mapping process.

Table 6.6: Vehicle Mapping between *EMFAC* and *MOVES*

	***EMFAC* Classification**	***MOVES* Classification**
Light Duty Auto	Light-Duty Auto	Passenger Car
Light Duty Truck	Light-Duty Truck 1 Light-Duty Truck 2	Passenger Truck Light Commercial Truck
Medium & Heavy Duty Truck	Medium-Duty Truck Light-Heavy-Duty Truck 1 Light-Heavy-Duty Truck 2 Medium-Heavy-Duty Truck Heavy-Heavy-Duty Truck	Refuse Truck Single Unit Short-haul Truck Single Unit Long-haul Truck Combination Short-haul Truck Combination Long-haul Truck
	Motor Home	Motor Home
Bus	Urban Bus	Transit Bus
	School Bus	School Bus
	Other Bus	Intercity Bus
Motorcycle	Motorcycle	Motorcycle

6.3.3.3 Fuel Information

Fuel information used by *MOVES* includes the fuel formulation and the market share of each type of fuel. The default fuel data in *MOVES* was used for the case studies presented in this report.

6.4 Overall Procedure

The final procedure for calculating the effect of rolling resistance on fuel consumption and emissions of vehicles, which uses the pavement surface characteristics, traffic data, and other inputs for *MOVES,* is shown in Figure 6.2. For a given pavement segment, the traffic information is first extracted from the traffic database. With the LDF derived from the WIM study, the traffic on each lane of this segment can be acquired. Then, hourly traffic distribution acquired from PeMS is applied to the traffic. Using the mapping matrix between the different traffic databases and models, the original vehicle classification can be converted to the *MOVES* vehicle classification. This forms the traffic input for *MOVES.* In the meantime, with the IRI and macrotexture model and data from the PCS, the time series of IRI and macrotexture can be developed. Using the techniques described in this study and the rolling resistance model in *HDM-4*, the rolling resistance parameter in *MOVES* can be updated. With other inputs such as meteorological data, the *MOVES* model can be run with the traffic on the given segment and update the rolling resistance, and therefore calculate the energy consumption and GHG emissions.

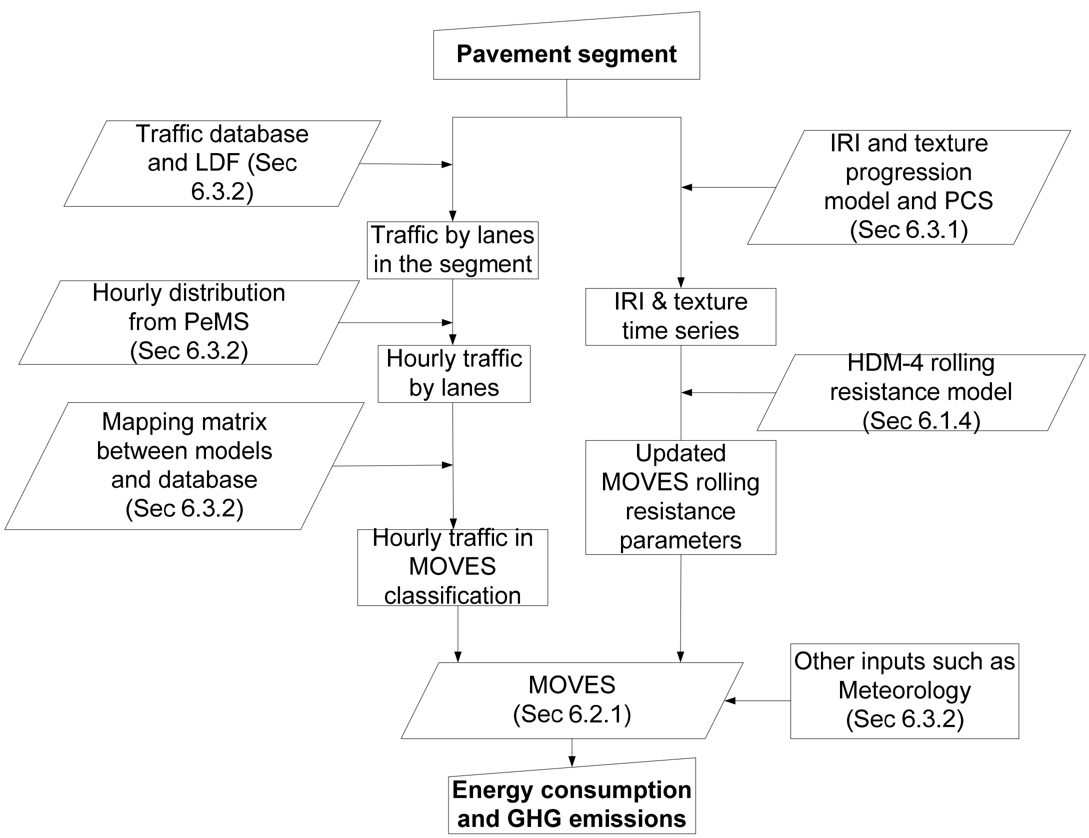

Figure 6.2: Procedure to calculate the effect of rolling resistance on vehicle fuel consumption and emissions.

7. INITIAL CASE STUDIES

Four initial case studies were performed and are described in this report. They were undertaken to demonstrate the use of the pavement LCA models and to provide a preliminary indication of the net effects from pavement maintenance. They were performed following the UCPRC pavement LCA framework, and include material production, construction, and vehicle use. The net effects include the greenhouse gas emissions and energy consumption due to changes in pavement smoothness and surface texture type from the pavement preservation treatments described earlier in this report for pavements with different traffic levels.

7.1 Functional Unit and Case Study Descriptions

All of the case studies consider Caltrans pavement preservation treatments. Two of the case studies are asphalt pavement and two are concrete pavement. The asphalt and concrete examples are separate. These case studies focus on comparing the effects that result from performing maintenance that changes the surface characteristics of the pavement versus not performing this maintenance—which doesn't change the pavement type. Comparisons of asphalt versus concrete treatments for the same pavement are not considered. The LCA phases considered in the modeling include Material Production, Construction, and Use. Because the routine maintenance and EOL phases were assumed to be the same within each pavement type, they were omitted.

The four case studies are based on the following four rural road segments (see Table 7.1 for details):

- An asphalt segment with a high traffic volume (KER-5),
- An asphalt segment with a low traffic volume (BUT-70),
- A concrete segment with a high traffic volume (LA-5), and
- A concrete segment with a low traffic volume (IMP-86).

The existing pavement condition, traffic, analysis period, and other characteristics for the concrete and asphalt case studies have been made different to focus attention on the comparison (within pavement types) of applying a treatment versus doing nothing, and between different levels of construction smoothness for each treatment. Comparisons between asphalt and concrete treatment strategies are not the purpose of this study. The case study locations were selected to provide a preliminary indication of the effects of traffic level (high and low total traffic) within each pavement type (asphalt and concrete) on the net impact of treatment, also considering constructed smoothness and two common material types within each pavement type. Other criteria were that the sections were in poor condition, and that nearby sections had been subjected to treatment to provide reasonable performance information where models were not yet available (primarily asphalt IRI progression). The traffic levels, functional units, and other details of the sections were specifically selected to be different for concrete and asphalt, to avoid direct comparison between them at this point in the research program. To provide a reasonable early indication of the effect of traffic on the results, the traffic on the sections is approximately near the upper and lower quartiles for each pavement type. The traffic levels are therefore higher for the concrete sections because of the distributions of traffic on the two pavement types across the network.

Each case study considered a potential pavement preservation treatment assumed to have been carried out in 2012. Each case also modeled two alternative materials used by Caltrans for the same treatment, multiple levels of smoothness after construction, two traffic growth rates (0 percent and 3 percent), two rates of vehicle technology improvement (none and the *MOVES* default emissions factor improvement over the years), and different LCI data sources. A *Do Nothing* scenario, in which only routine maintenance work was performed annually so the current pavement condition deteriorated at a very slow rate, was also modeled as a baseline for each case.

For asphalt pavement preservation, the old surface layer was milled and a new asphalt overlay was applied. The concrete pavement preservation is referred to as "Concrete Pavement Restoration B" (CPR B). In CPR B, about 3 percent of total slabs are replaced and all lanes are diamond ground after slab replacement (*24*). This study did not consider spall repair or joint sealing in CPR B, which were assumed for these case studies to have a very small effect. In both pavement preservation strategies, there were no changes made in the existing base layer or subgrade.

Table 7.1: Summary of the Four Case Studies

Case Study	KER-5	BUT-70	LA-5	IMP-86
County	Kern	Butte	Los Angeles	Imperial
Route	I-5 Southbound	SR-70 Westbound	I-5 Southbound	SR-86 Westbound
Surface	Asphalt concrete	Asphalt concrete	Cement concrete	Cement concrete
Analysis period	2012 ~ 2016 (5 years)	2012 ~ 2016 (5 years)	2012 ~ 2021 (10 years)	2012 ~ 2021 (10 years)
Section length	16,093 m (10 miles)	8,042 m (5 miles)	16,093 m (10 miles)	8,042 m (5 miles)
Number of lanes	2	2	4	2
Lane width	3.66 m (12 ft)	3.66 m (12 ft)	3.66 m (12 ft)	3.66 m (12 ft)
AADT	34,000	3,200	86,000	11,200
Truck percentage	35%	15%	25%	29%
Construction type	pavement preservation, mill and asphalt overlay	pavement preservation, mill and asphalt overlay	CPR B	CPR B

The two asphalt cases are KER-5 and BUT-70. The KER-5 case study considered a potential pavement preservation carried out in 2012 on a 10-mile two-lane segment of southbound I-5 in Kern County, which has an AADT of 34,000 and 35 percent trucks. Its current IRI is around 2.7 m/km (170 in./mi.), the value separating "Poor" and "Very Poor" pavement according to the Federal Highway Administration (FHWA) (*1*) and the triggering value for performing pavement preservation activities according to Caltrans (*79*): 2.5 m/km (158 in./mi.) on the inner lane (Lane 1) and 3.5 m/km (222 in./mi.) on the outer lane (Lane 2). The BUT-70 case study focused on a segment on the westbound direction of State Route 70 in Butte County. This segment is a five-mile rural non-freeway with an IRI value of about 3 m/km (190 in./mi.) on Lane 2. The AADT on this segment is 3,200 with about 15 percent trucks.

The two concrete cases are LA-5 and IMP-186. LA-5 considered a 10-mile segment on southbound I-5 in Los Angeles County. The four-lane segment is a very rough rural freeway section: the IRI value is 3 m/km (190 in./mi.) on the inner two lanes (Lane 1 and Lane 2), 3.5 m/km (222 in./mi.) on Lane 3, and 4 m/km (254 in./mi.) on the outer lane (Lane 4). The AADT on this segment is 86,000 with about 25 percent trucks. IMP-86 was on the westbound direction of State Route 86 in Imperial County. This five-mile two-lane rural non-freeway segment also has an IRI about 3 m/km (190 in./mi.). The AADT on this segment is 11,200 with about 29 percent trucks. In all of the four cases studies, because the difference of truck traffic level on different lanes significantly affects the rate of pavement deterioration, each lane was analyzed separately and the results were combined at the end.

Table 7.2 summarizes the two pavement preservation strategies for the asphalt cases—overlays with hot-mix asphalt (HMA) with conventional asphalt binder or rubberized hot-mix asphalt (RHMA)—and the baseline *Do Nothing* strategy analyzed in the study. The Caltrans life cycle cost analysis (LCCA) manual considers a pavement preservation strategy for both overlay cases to have a five-year design life based on their climate region (*24*). According to Caltrans pavement preservation guidelines (CAPM guidelines) and the *Highway Design Manual*, the HMA overlay has a 45-mm milling depth and a 75-mm new HMA layer with recycled asphalt pavement (RAP) (*79*), and the RHMA overlay has a 30-mm milling depth and a 60-mm new RHMA layer with no RAP (*80*). The precise overlay thicknesses would depend on structural evaluation of the existing pavement, but the values used in the case studies are reasonable.

The mix designs for the HMA and RHMA are shown in Table 7.3. According to Caltrans Standard Special Provisions, 15 percent of recycled asphalt pavement (RAP) can be used in the mix without changing the mix design. That amount of RAP was assumed for the HMA scenario. In the RHMA scenario, 1.5 percent by mass of crumb rubber modifier (CRM) was added to the overall mix, which is 20 percent by mass of the binder. The standard RHMA mix design also has a gap gradation and more binder than a dense-graded mix. Caltrans specifications do not permit inclusion of RAP in RHMA mix designs.

In the asphalt case studies, two levels of initial smoothness after pavement preservation were analyzed: *Smooth Rehab*, which brings the IRI down to 1 m/km (63 in./mi.); and *Less Smooth Rehab*, which brings the IRI down to 1.67 m/km (106 in./mi.). These two levels approximately span the range of a sample of initial IRI values on Caltrans pavement preservation overlays. Based on available information this sample is representative of Caltrans pavement preservation overlay projects.

Table 7.2: Construction Scenarios of KER-5 and BUT-70

Construction Strategy	Design Life	Treatment	Cross Section	Resulting Smoothness
Pavement preservation, HMA Overlay	5 years	Mill & overlay; minimum level of maintenance annually	45 mm (0.15 ft.) mill + 75 mm (0.25 ft.) HMA with 15% RAP	*Smooth Rehab:* Initial IRI = 1 m/km (63 in/mi.)
				Less smooth Rehab: Initial IRI = 1.67 m/km (106 in./mi.)
Pavement preservation, RHMA Overlay	5 years	Mill & overlay; minimum level of maintenance annually	30 mm (0.1 ft.) mill + 60 mm (0.20 ft.) RHMA	*Smooth Rehab:* Initial IRI = 1 m/km (63 in/mi.)
				Less smooth Rehab: Initial IRI = 1.67 m/km (106 in./mi.)
Do Nothing	----	Minimum level of maintenance annually	No change	Slow progression

Table 7.3: Mix Design of HMA and RHMA (By Mass of Total Mix)

	HMA with RAP	RHMA
	Percentage % by Weight	Percentage % by Weight
Aggregate	**81**	**92.5**
Coarse Aggregate	38	68
Fine Aggregate	57	27
Dust	5	5
Asphalt binder	**4**	**7.5**
Bitumen	100	77.5
Crumb Rubber Modifier	0	20
Extender Oil	0	2.5
RAP	**15**	**0**
Total	**100**	**100**

Table 7.4 summarizes the two pavement preservation strategies for the concrete case studies—CPR B treatment with 3 percent slab replacement using Type III portland cement or with calcium sulfoaluminate (CSA) cement—and the baseline *Do Nothing* strategy. Both types of cement concrete are used in California to acquire high early strength because the road segments need to be open to traffic within four to five hours of slab replacement during nine-hour nighttime construction. CPR B strategies with both types of concrete mix are considered to have a 10-year design life according to the Caltrans LCCA manual, which does not discuss different lives for Type III and CSA mixes (*24*).

Table 7.5 shows the concrete mix designs used for the Type III PCC and CSA cement concrete (the designs are per cubic meter). These mix designs are samples provided by the concrete industry as typical for overnight closures. Both mix designs were assumed to have identical construction processes because the concrete mixing plant operation and construction processes are calculated based on the volume of concrete, which is identical for the two mix designs.

Three levels of initial smoothness after construction were considered [based on Formula (6.6) in Chapter 6], as shown in Table 7.6: *Smooth Rehab*, which is the mean smoothness after construction minus two standard deviations from the initial IRI model; *Medium Smooth Rehab*, which is the mean smoothness after construction; and *Less Smooth Rehab*, which is the mean smoothness after construction plus two standard deviations from the model. The mean smoothness after construction and standard deviation are based on data from earlier Caltrans grinding projects (*73*).

Table 7.4: Construction Scenarios of LA-5 and IMP-86

Construction Strategy	Design Life	Treatment	Material (open to traffic in 2 to 4 hours, flexural strength 2.8 MPa)	Resulting Smoothness
CPR B with Type III cement concrete	10 years	3% slab replacement (0.23 m [0.75 ft.] thick); continuous grinding all lanes; minimum level of maintenance annually	Type III rapid strength portland cement concrete	*Smooth Rehab*
				Medium Smooth Rehab
				Less Smooth Rehab
CPR B with CSA cement concrete	10 years	3% slab replacement (0.23 m [0.75 ft.] thick); continuous grinding all lanes; minimum level of maintenance annually	Calcium sulfoaluminate (CSA) cement concrete	*Smooth Rehab*
				Medium Smooth Rehab
				Less smooth Rehab
Do Nothing	----	Minimum level of maintenance annually	No change	Slow progression

Table 7.5: Mix Design of Type III PCC and CSA Cement Concrete (By mass of 1 m³ or 1 cy total mix)

	Type III PCC			CSA Cement Concrete		
Flex Strength at Opening MPa (psi)	2.8 (400)			2.8 (400)		
Flex Strength at 7 Days MPa (psi)				4.2 (600)		
Cement Brand	**Hanson Type III**			**CTS Cement – Rapid Set**		
	Specific Gravity	Mass (kg per m^3 of mix)	Mass (lbs per cy of mix)	Specific Gravity	Mass (kg per m^3 of mix)	Mass (lbs per cy of mix)
Coarse Aggregate	2.60	1,128	1,901	2.68	1,064	1793
Fine Aggregate	2.60	609	1,027	2.65	794	1338
Cement	3.15	475	801	2.98	390	657
Water*	1.00	166	280	1.00	156	263
Accelerators		37.3	63		0.0	0
Retarders		0.7	1		2.1	4
Superplasticisers		2.6	4		1.2	2

* Material production of water is not included in this study.

Table 7.6: IRI After CPR B Project in LA-5 and IMP-86 (Unit in m/km, and in./mi. in parentheses)

	LA-5			IMP-86		
	Smooth Rehab	***Medium Smooth***	***Less Smooth***	***Smooth Rehab***	***Medium Smooth***	***Less Smooth***
Lane 1 (Inner)	1.3 (79.6)	1.8 (115.6)	2.4 (151.7)	1.1 (57.4)	1.6 (104.2)	2.2 (140.2)
Lane 2	1.3 (79.6)	1.8 (115.6)	2.4 (151.7)	1.1 (71.9)	1.7 (108.0)	2.3 (144.0)
Lane 3	1.5 (91.6)	2.0 (127.7)	2.6 (163.7)	N/A		
Lane 4 (Outer)	1.6 (103.7)	2.2 (139.7)	2.8 (175.8)			

7.1.1 Material Production Phase

The Material Production Phase includes the extraction and initial processing of aggregates, asphalt, cement, and other supplementary material such as CRM and admixtures to the cement concrete. Processes within this phase include raw material acquisition, transport of raw materials from/to plant, and material manufacture. The mixing processes in HMA plants and transport of materials from and to the site were attributed to the Construction Phase.

As mentioned in Chapter 4, multiple data sources for each material were included in the analysis. These data sources are from published LCI databases and other LCA reports, including the commercial LCA software *EvoInvent* (*28*), the U.S. Life Cycle Inventory (USLCI) produced by the National Renewable Energy Laboratory (*37*), the asphalt inventory produced by the Athena Institute in Canada (*33*), a pavement LCI produced by Stripple et al. in Europe (*27*), and a cement LCI study by the Portland Cement Association (PCA) in the U.S. (*34, 35*). Before inclusion in the study, each data source was disaggregated to the process level; then these processes were compared with respect to related technologies, and the results were recalculated based on the local conditions (e.g., a California-specific electricity mix) and commensurate system boundary.

7.1.2 Construction Phase

For the asphalt pavement preservation treatments, the *CA4PRS* schedule output shows that the HMA overlay should have construction progress (closure productivity) of about 0.6 lane-miles per nine-hour nighttime closure. Therefore, the schedule output indicates that this construction event needs about 36 nighttime closures for the HMA overlay alternative with the given scope of 20 lane-miles and calculated closure productivity in KER-5. Similarly, the schedule analysis shows that the RHMA overlay alternative can be constructed at a rate of about 0.7 lane-miles per night. A total of about 27 nighttime closures are therefore needed for the project scope of 20 lane-miles. A summary comparison of the construction schedules shows that the HMA overlay requires about 33 percent more time (and consequently equipment usage) for construction compared with the RHMA overlay.

Table 7.7 summarizes the total operation hours of the equipment mobilized for KER-5. The equipment output shows that milling demolition trucks and the HMA delivery trucks are the dominant resources in terms of the equipment total operation hours, primarily because about 14 trucks are required for demolition operations and 22 trucks are needed for mix delivery operations compared with one piece of equipment for the other operations. The asphalt mixing plant was assumed to be 45 miles from the construction site for both the KER-5 and BUT-70 cases, and the same distance was assumed from the construction site to the location where milled materials were dumped. The hauling and delivery trucks' total usage hours have been broken into separate operational categories because there is a significant difference between their fuel consumption in each condition; the two designated modes are *operations* (driving) mode or *idle* (standby) mode.

The construction schedule and usage of equipment for BUT-70 was calculated on a pro-rated basis from the KER-5 results.

For the concrete pavement preservation treatments, the *CA4PRS* schedule output nine-hour (8 p.m. to 5 a.m.) nighttime construction closures with partial lane closures (1-2-3-2-1 lanes closed progressively) were assumed for the construction productivity analysis. The productivity for grinding of the concrete pavements was about 1 lane-mile per nine-hour nighttime closure. The schedule is assumed to be the same for the two types of Rapid Strength Concrete, Type III PCC and CSA. The *CA4PRS* productivity and schedule analysis gave about 0.068 lane-miles of concrete slab replacement progress per nine-hour nighttime closure, which covers about 110 m or about 27 slabs replaced. It was estimated that the CPR B in this case needs a total of about 60 nighttime closures for the given scope of 40 lane-miles, with:

- Approximately 20 × nine-hour nighttime closures for slab-replacement; and
- Approximately 40 × nine-hour nighttime closures for grinding.

Table 7.7: Summary of the Equipment Total Operation Hours for KER-5

Activity	Equipment	Unit in Operation	HMA		RHMA	
			Total Operation Hour	Total Idle Hour	Total Operation Hour	Total Idle Hour
Milling	Milling machine	1	124		86	
	Demo hauling truck	14	1,761	534	1,244	377
	Payloader	1	216		162	
	Grader	1	216		162	
	Compactor	1	216		162	
Asphalt concrete production and paving	Paver (with pickup)	1	216		162	
	Mix delivery truck	22	3,098	492	2,456	390
	Roller (vibratory/static steel)	2	432		324	
	Roller (pneumatic tire)	1	216		162	
	AC plant operation	1	108		81	
General activity	General truck (tack coat, water)	4	870	138	652	104
	Generator	3	648		486	
Mix Production (metric ton)		---------	20,628		16,510	

The construction schedule uses the total net length of CPR B slab replacement (measured in lane-miles) as the input. For LA-5, 3 percent random-slab replacement for the total project boundary of 40 lane-miles yields about 1.2 lane-miles of continuous lane-replacement equivalent scope (i.e., 0.03 x 40 lane-miles). Placing the 230-mm (0.75-ft.) thick new slabs using four-hour curing time Rapid Set Concrete without base replacement, the total volume of concrete on this project is approximately 1,644 m^3 (2,150 cubic yards). As part of CPR B designs, the surface of all the concrete pavement (existing slabs and newly replaced slabs) is diamond ground (usually 0.635 cm or ¼ in. depth) after the slab replacement. The total scope of the surface grinding is 235,788 m^2 (282,000 square yards).

Table 7.8 summarizes the total construction equipment use for LA-5, calculated using the *CA4PRS* schedule analysis outputs and resources inputs. The use of hauling trucks and delivery trucks is split into operation hours and idle hours because fuel consumption rates differ. For the operation of demolition hauling trucks, this study assumed that the demolition dumping yard is located about 15 miles (one-way) from the construction site (i.e., 10 miles on freeway and 5 miles on local arterials). Similarly, for the concrete delivery truck operations, it was assumed that the concrete batch plant is located about 20 miles (one-way) from the construction site (15 miles on freeway and 5 miles on local roads).

The construction schedule and usage of equipment for IMP-86 was calculated on a pro-rated basis from the LA-5 results.

Table 7.8: Summary of the Equipment Total Operation Hours for LA-5

Activity	Equipment	Number per Closure	Operation Hours	Idling Hours
Demolition	Saw cutters (demo & paving)	2	324	
	Excavator	2	180	
	Demolition hauling truck	8	495	229
	Payloader	1	92	
	Compactor	1	90	
Cement concrete production	Cement concrete roller screed	1	72	
	Concrete delivery truck	8	436	165
Grinding & dowels	Diamond grinder	2	563	
	Grinder slurry tanker	4	789	338
General activity	General truck	2	216	108
	Generator (180kw, for lighting etc.)	3	486	

7.1.3 Use Phase

In the Use Phase, the case studies focused on the effect of pavement surface characteristics (IRI and MPD or MTD) on rolling resistance and fuel economy. Assumptions and adjustments made to simplify this initial study include:

- Routine maintenance and the End-of-Life Phase were assumed to be equal and were therefore ignored;
- IRI progression of conventional HMA and RHMA for each case study was assumed to be the same, with one progression for the low traffic case study and another for the high traffic case study taken from Caltrans Pavement Condition Survey data. A regression equation for IRI as a function of ESALs and other variables was used for the concrete case studies, and the two types of concrete mix used for slab repairs were assumed to have the same IRI progression.
- Material-specific MPD models were used for the two types of asphalt mix, which indicate that HMA starts with a lower MPD but deteriorates faster, while RHMA starts with a higher MPD but has a lower deterioration rate. For concrete, the same MTD progression model was used for both types of concrete and used for both levels of traffic;
- Traffic volume and fleet composition are the same all week;
- Hourly distribution is the same for all types of vehicles;
- Default average speed distribution on rural freeway in *MOVES* is used[5]; and
- Alternative fuel vehicles are not considered.

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[5] These data are based on studies in California (U.S. EPA, 2010).

7.1.3.1 Traffic

As mentioned earlier, a lane distribution factor (LDF) was applied to the AADT to differentiate the traffic on each lane, with different LDFs from the WIM database used for cars and trucks, as shown in Table 7.9.

Table 7.9: Lane Distribution Factor in All Cases

	KER-5		BUT-70		LA-5		IMP-86	
	Cars	**Trucks**	**Cars**	**Trucks**	**Cars**	**Trucks**	**Cars**	**Trucks**
Lane 1 (Inner)	77%	9%	61%	8%	38%	0.2%	76%	8%
Lane 2	23%	91%	39%	92%	34%	8%	24%	92%
Lane 3	N/A				16%	42%	N/A	
Lane 4 (Outer)					13%	49%		

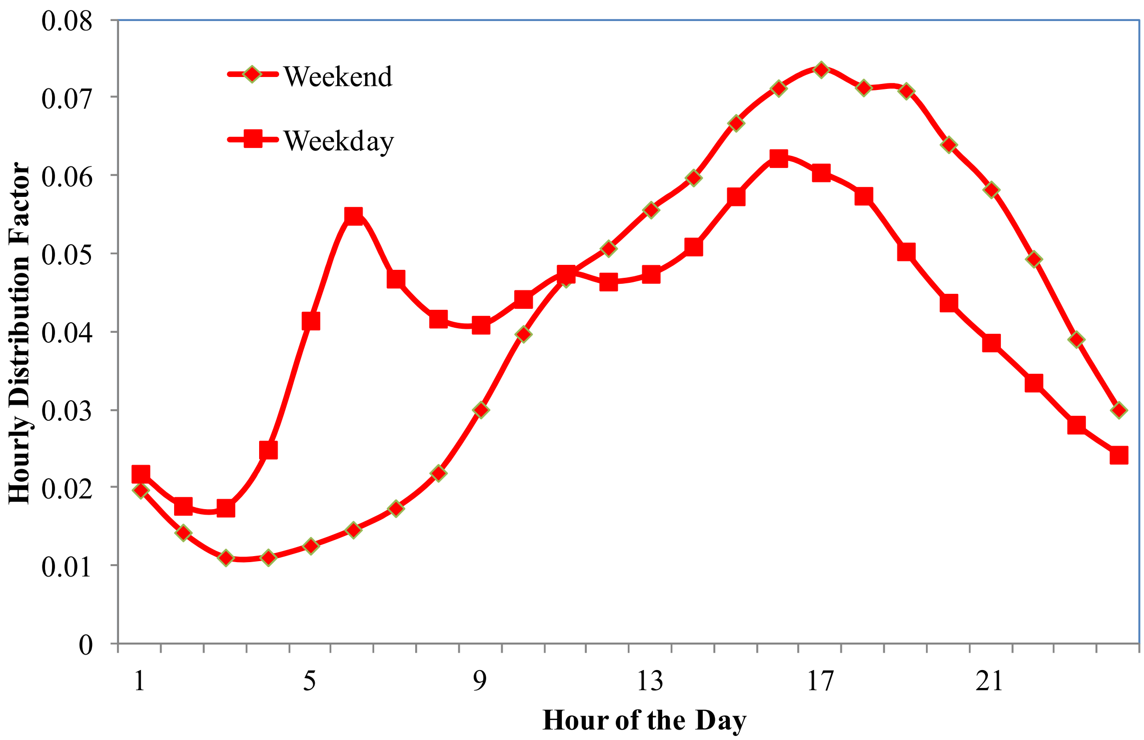


Figure 7.1: Hourly distribution factor of traffic in KER-5.

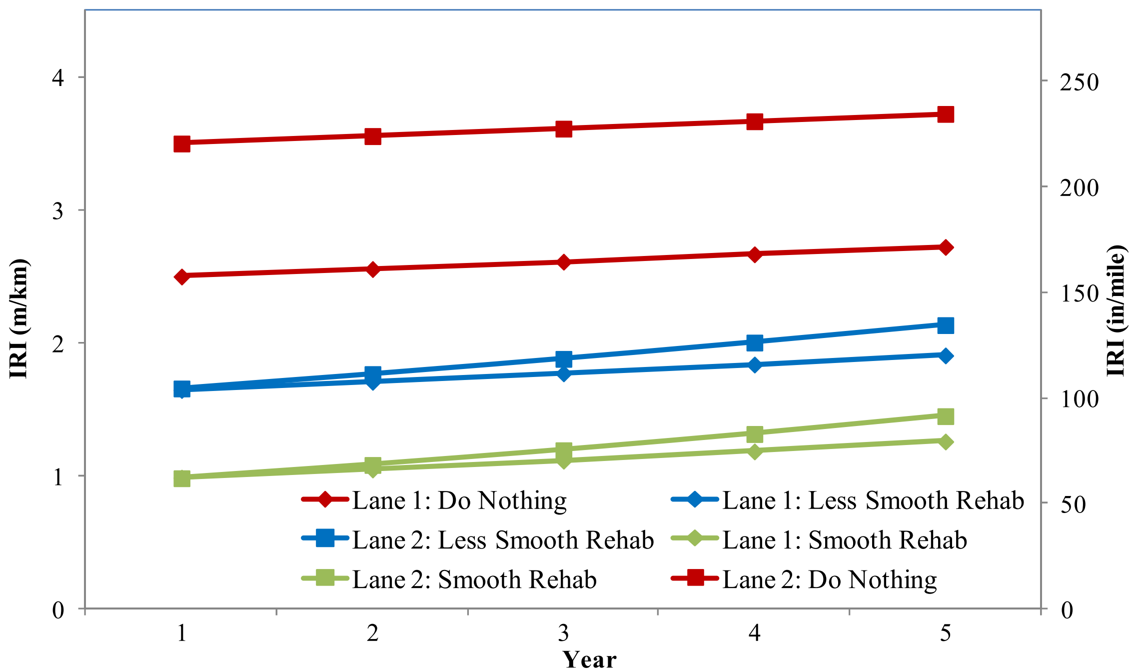
The hourly distribution factor of traffic was acquired from the PeMS database, which includes two sets of distributions: weekday distribution and weekend distribution. As an example, Figure 7.1 shows the hourly distribution factor used for KER-5. As noted, the default data in the *MOVES* database was used for other traffic information.

7.1.3.2 IRI and MPD or MTD

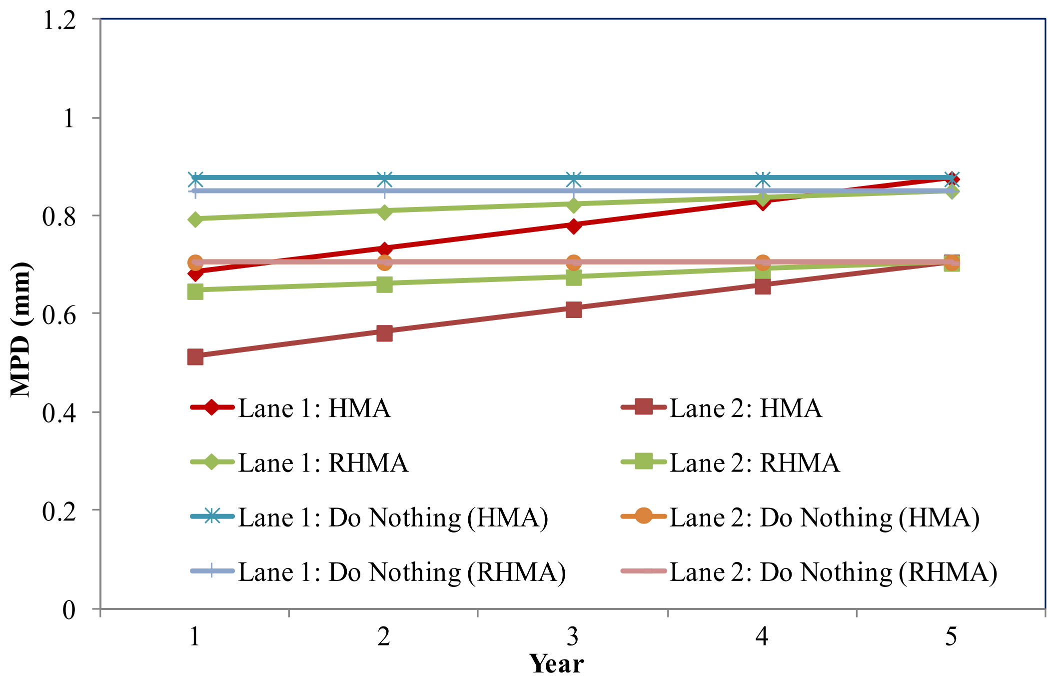
The IRI progressions for the asphalt concrete pavement examples were taken directly from the Caltrans PCS database for the example projects, as opposed to using modeled values. Since the inner lane has less truck traffic than the outer lane, IRI has a lower deterioration rate. The macrotexture change over time, represented by MPD, was modeled using the UCPRC models described previously, and is more dependent on the material (HMA or RHMA) than on the truck traffic. According to UCPRC MPD equations, truck traffic is negatively correlated with MPD. Therefore the inner lane has a higher MPD because it carries less truck traffic. HMA usually starts with a lower MPD but a faster rate of increase than RHMA, which usually starts with a higher MPD but has a slower deterioration rate. Figure 7.2 shows the IRI and MPD progression over five years for each scenario of KER-5 and BUT-70, with Figure 7.2(a) and (b) showing IRI and MPD progression for KER-5, respectively, and Figure 7.2(c) and (d) showing the same for BUT-70. In the *Do Nothing* scenario, the MPD is set to the Year 5 value during the entire analysis period.

The IRI and MTD progressions for concrete pavement were based on the models discussed in Section 6.3.1. For the *Do Nothing* scenario, the MTD is set to the Year 10 value during the entire analysis period. Figure 7.3 through Figure 7.6 show the IRI and MTD progressions for LA-5 and IMP-86. It can be seen in Figure 7.3 that on LA-5 the IRI for the truck lanes (lanes 3 and 4) slightly surpass the IRI of the *Do Nothing* scenario towards the end of the analysis period. This is based on the performance model used for IRI on concrete and the higher truck traffic levels in those lanes, which was not adjusted to avoid the crossing of the two performance trends. This is a plausible assumption since the routine maintenance of the *Do Nothing* scenario might be delayed in the last several years with the knowledge that the CAPM treatment would be repeated, provided the difference is not large.

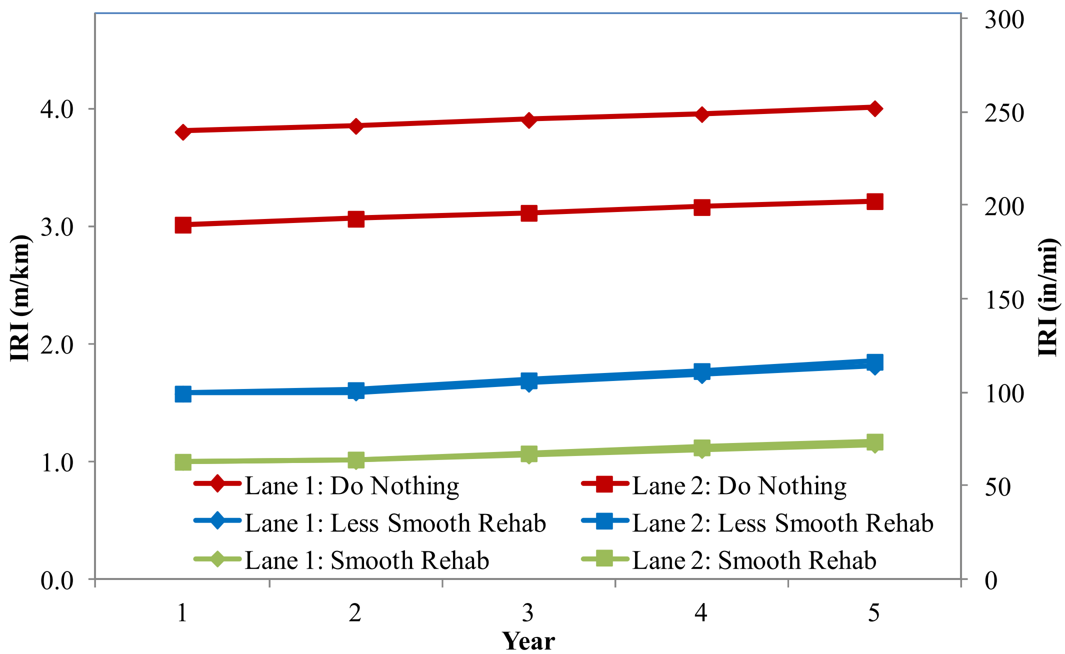
A sensitivity analysis was performed for the two high-traffic cases (KER-5 for asphalt and LA-5 for concrete) to evaluate the relative contributions to energy savings and reduced GHG emissions of the reduction of IRI and the change in macrotexture.



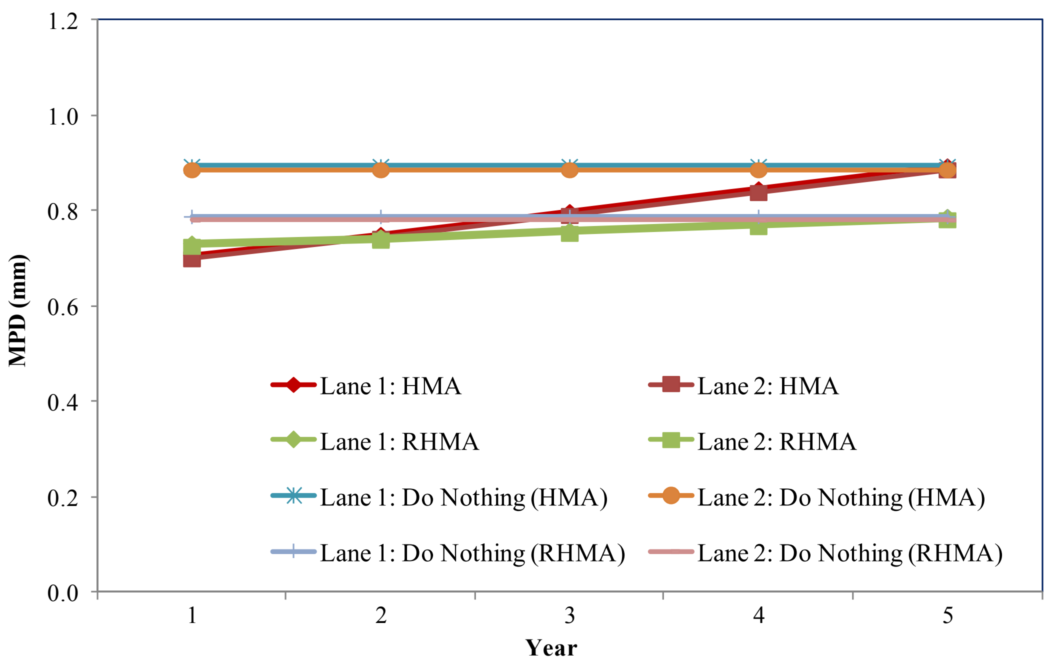
(a) KER-5 IRI



(b) KER-5 MPD



(c) BUT-70 IRI[6]



(d) BUT-70 MPD

Figure 7.2: (a) IRI progression in KER-5; (b) MPD progression in KER-5; (c) IRI progression in BUT-70; (d) MPD progression in BUT-70.
(Note: For the KER-5 and BUT-70 *Do Nothing* scenarios, MPD was set to the Year 5 values.)

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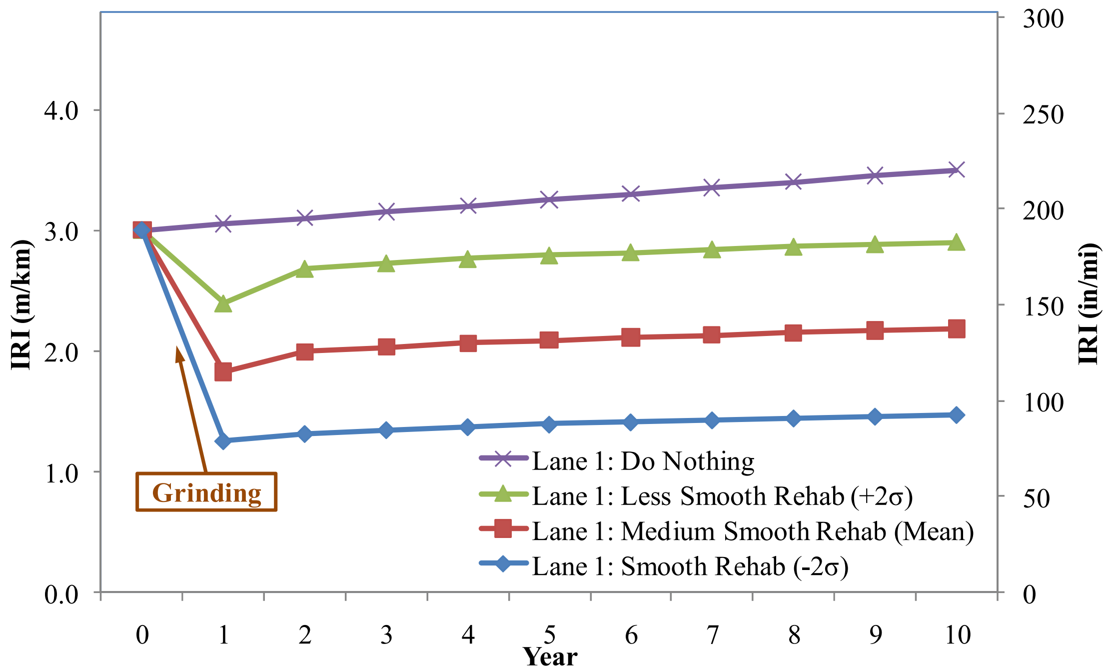
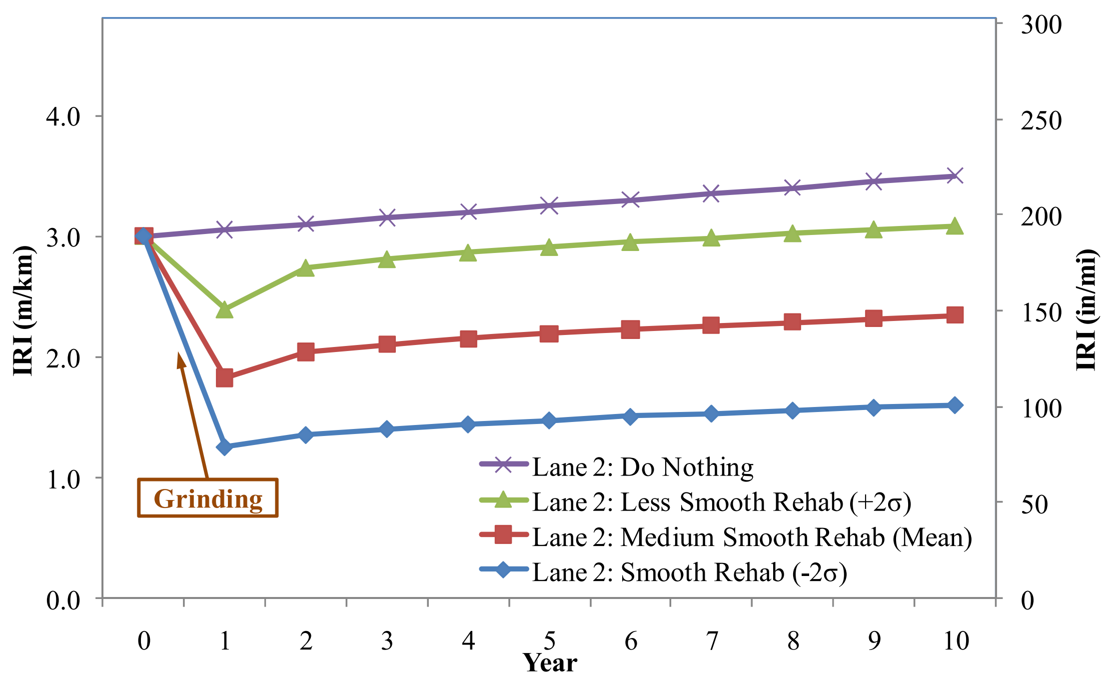
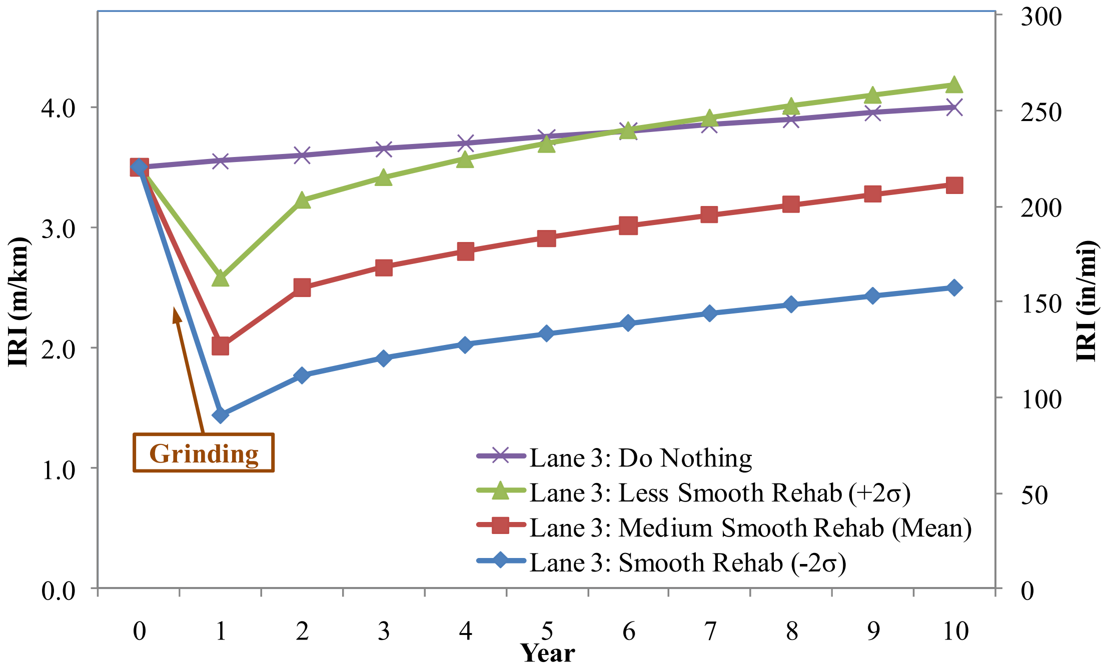
[6] In BUT-70 sections, PCS shows the inner lane has a higher IRI than the outer lane, which contrasts with common sense. However, here the value from PCS is still used.



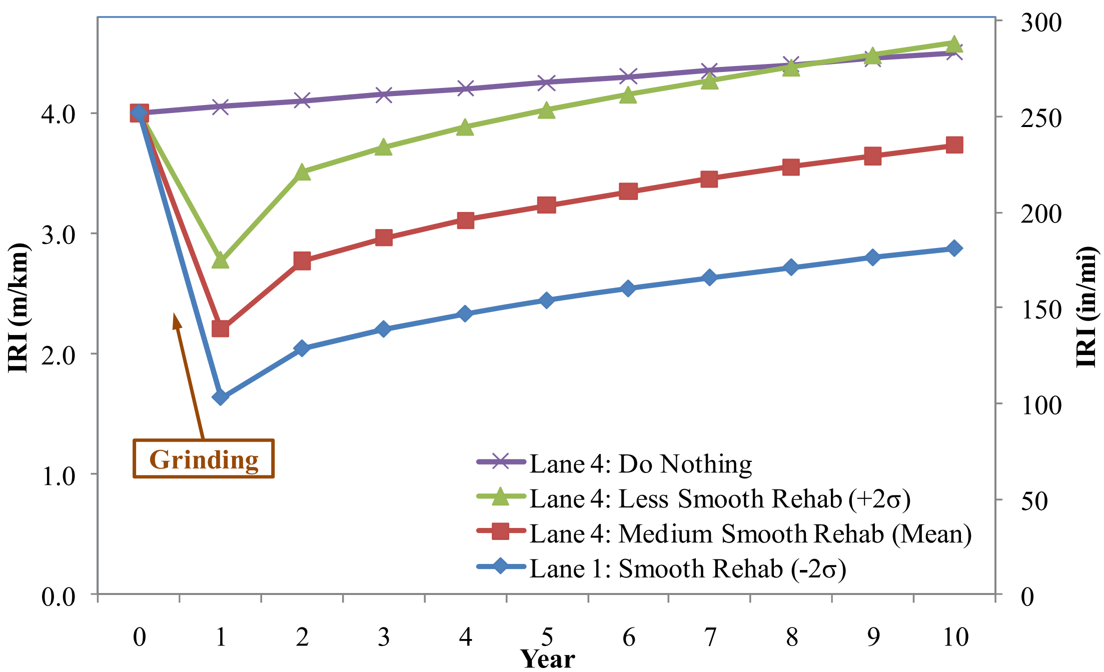
LA-5 Lane 1 (Inner lane) IRI



LA-5 Lane 2 IRI

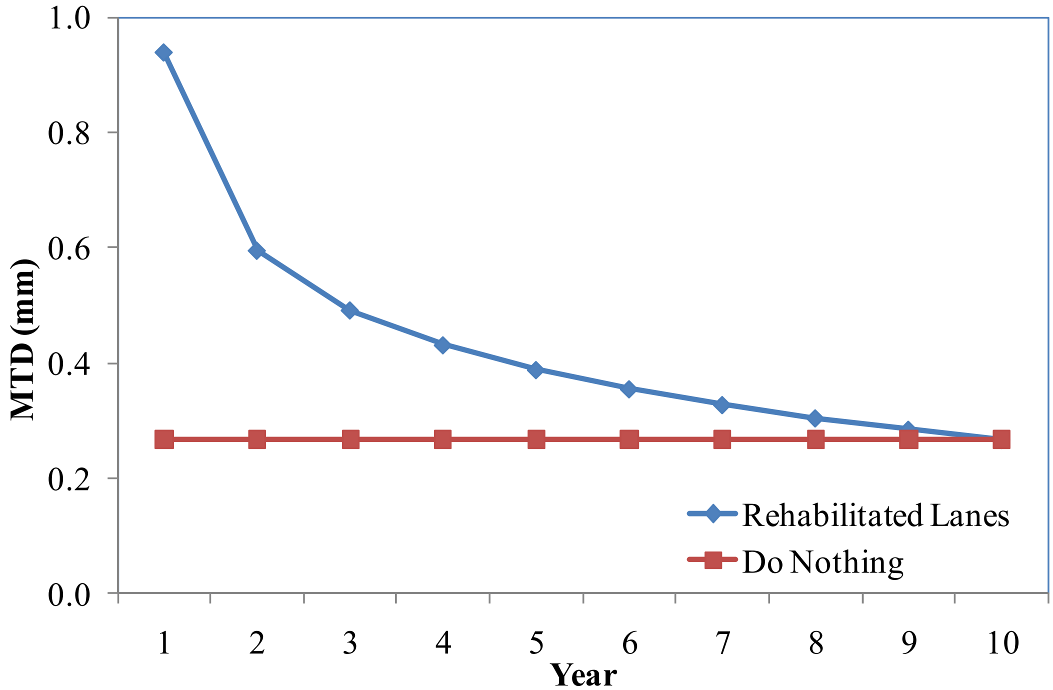


LA-5 Lane 3 IRI



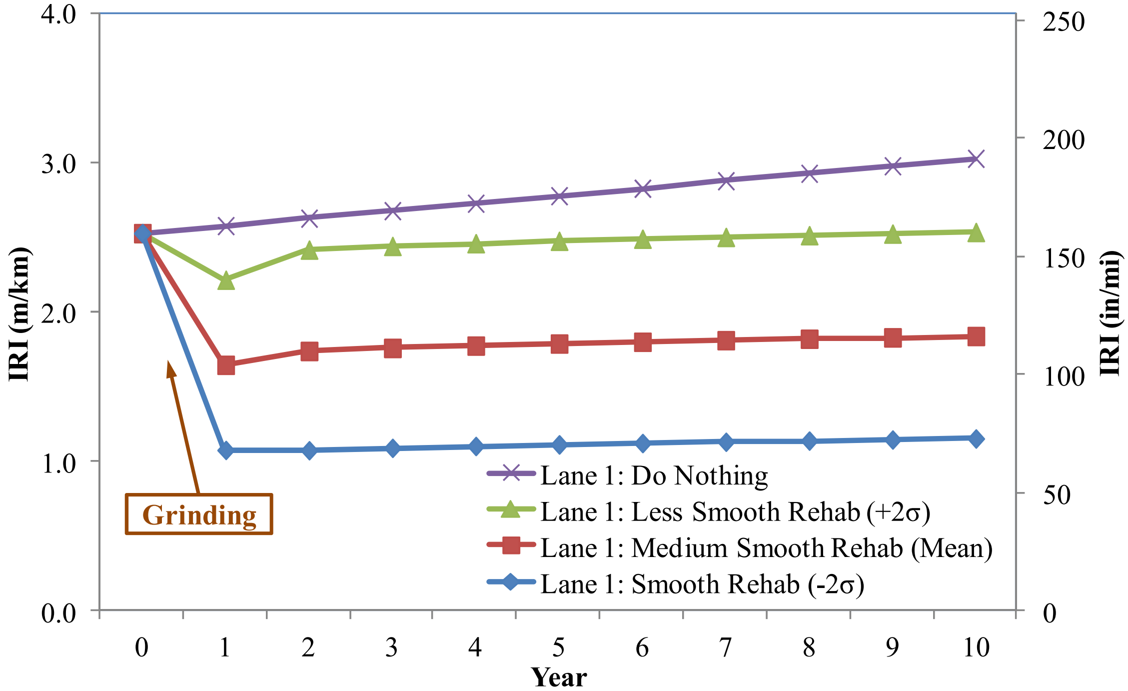
LA-5 Lane 4 (Outer lane) IRI

Figure 7.3: IRI progression in LA-5.

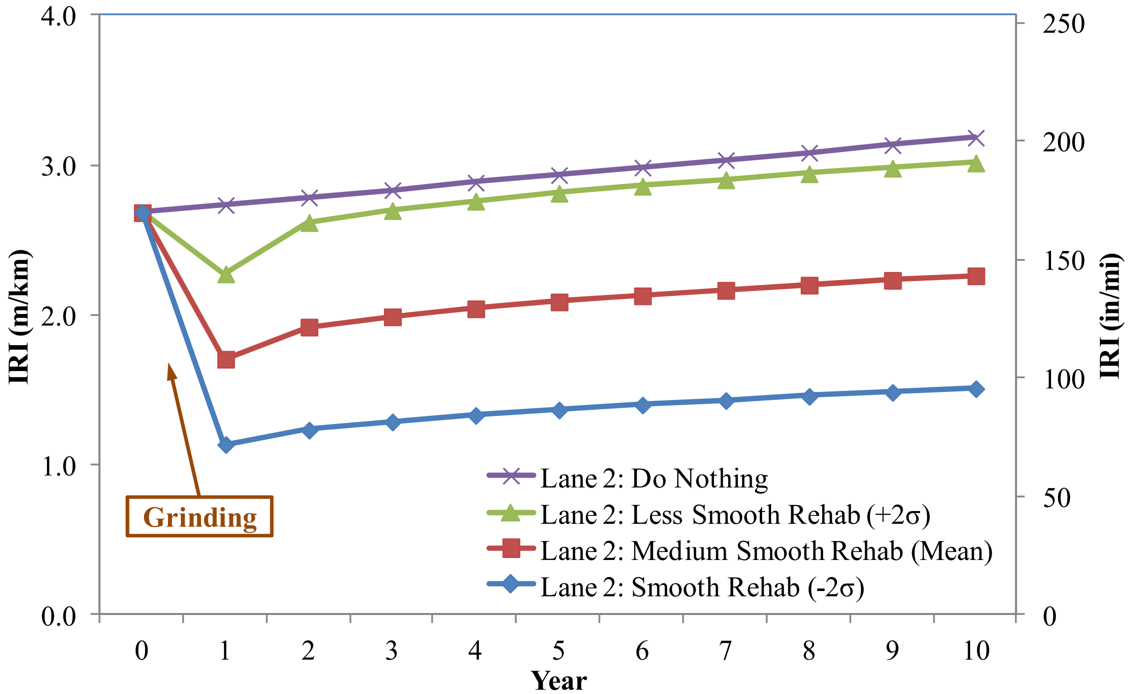


LA-5 all lanes MTD

Figure 7.4: MTD progression in LA-5 (all lanes).

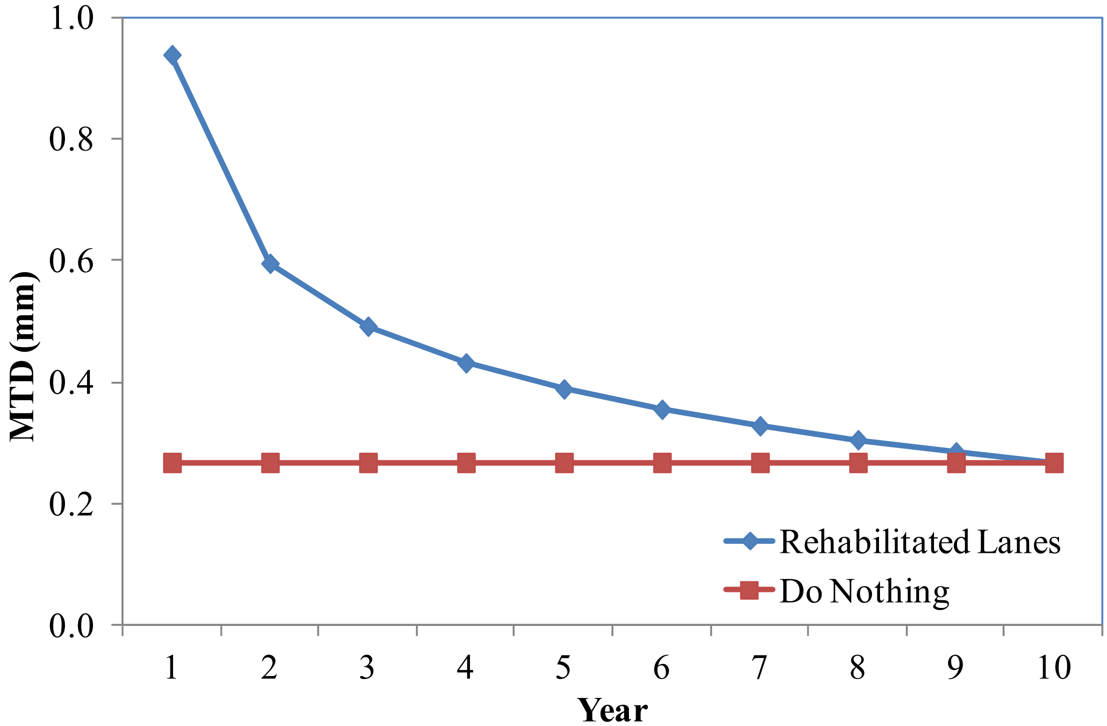


IMP-86 Lane 1 (Inner lane) IRI



IMP-86 Lane 2 (Outer lane) IRI

Figure 7.5: IRI progression in IMP-86.



IMP-86 all lanes MTD

Figure 7.6: MTD progression in IMP-86 (all lanes).

7.2 Results

Sections 7.2.1 and 7.2.2 discuss the results of the Material Production and Construction phases of the asphalt concrete and cement case study scenarios, respectively. Section 7.2.3 presents an initial analysis of the Use Phase for each case performed to provide an indication of the relative importance of changes in pavement surface characteristics relative to changes in the vehicle fleet and in vehicle miles traveled. Afterward, the net preservation treatment life cycle energy consumption and GHG emissions were analyzed, which is shown in Section 7.2.4.

7.2.1 Asphalt Concrete Production and Construction

Figure 7.7 and Figure 7.8 summarize the results of LCI analyses for the Material Production Phase for the entire KER-5 project. The results from BUT-70 (which are shown in Appendix C) show a similar trend with regard to the contribution of each phase of production and construction, with only the quantities changed. HMA requires more energy and emits more GHGs than RHMA, which can be explained by the fact that HMA mills and overlays a larger volume of material than RHMA, as indicated in Table 7.2.

For the HMA Material Production Phase, when feedstock energy is excluded, operating the HMA mixing plant requires the most primary energy. On the other hand, manufacturing binder is the most energy-consumptive process for RHMA. In both cases, transporting materials to the plant is ignored, except transporting RAP from the construction site to the plant. When material transport is considered in future studies, energy consumption will increase.

Mixing plant operation is the main source of GHG emissions for HMA. While plant operation is also the main source of GHG emissions for RHMA in three cases, binder production emits more GHGs than plant operation for the Swiss and U.S. data sources. It should be noted that plant operation requires more heating energy when RAP is introduced in the HMA.

As summarized in Figure 7.9 and Figure 7.10, the trends of energy consumption and GHGs emissions are similar. This is because the environmental burden of the Construction Phase considered in this study is based on the fuel consumption of transport equipment and construction equipment. However, the transport of paving materials is the main source of environmental burden for both HMA and RHMA. This result indicates that the distance between the HMA mixing plant and the construction site is an important factor affecting the environmental burden in the Construction Phase.

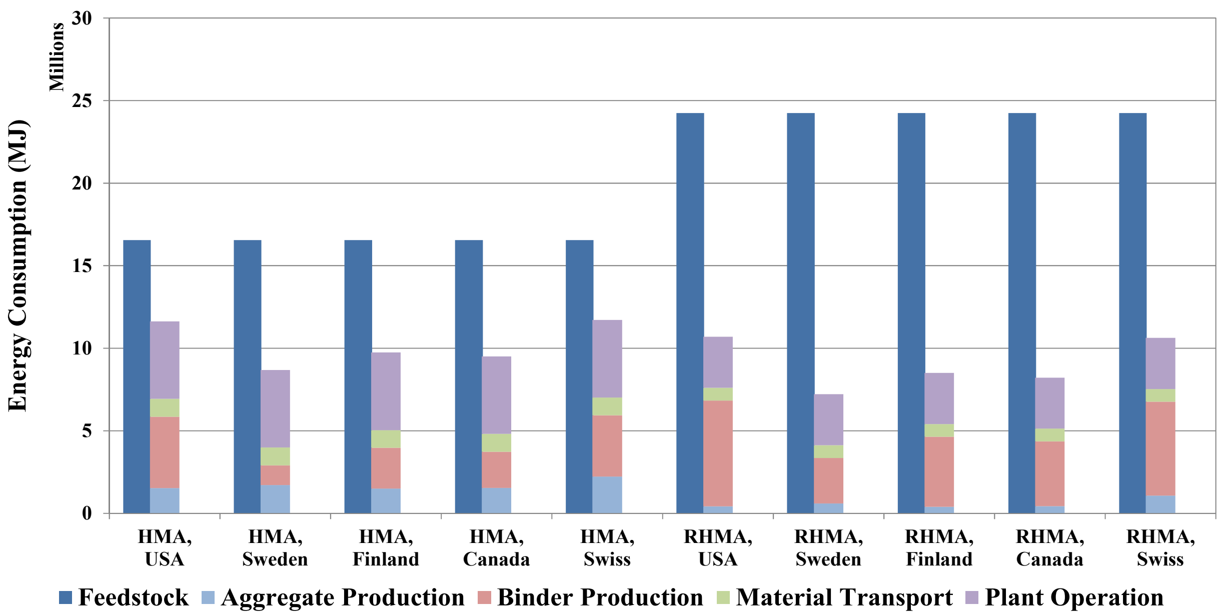


Figure 7.7: KER-5 Material Production Phase: energy consumption for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

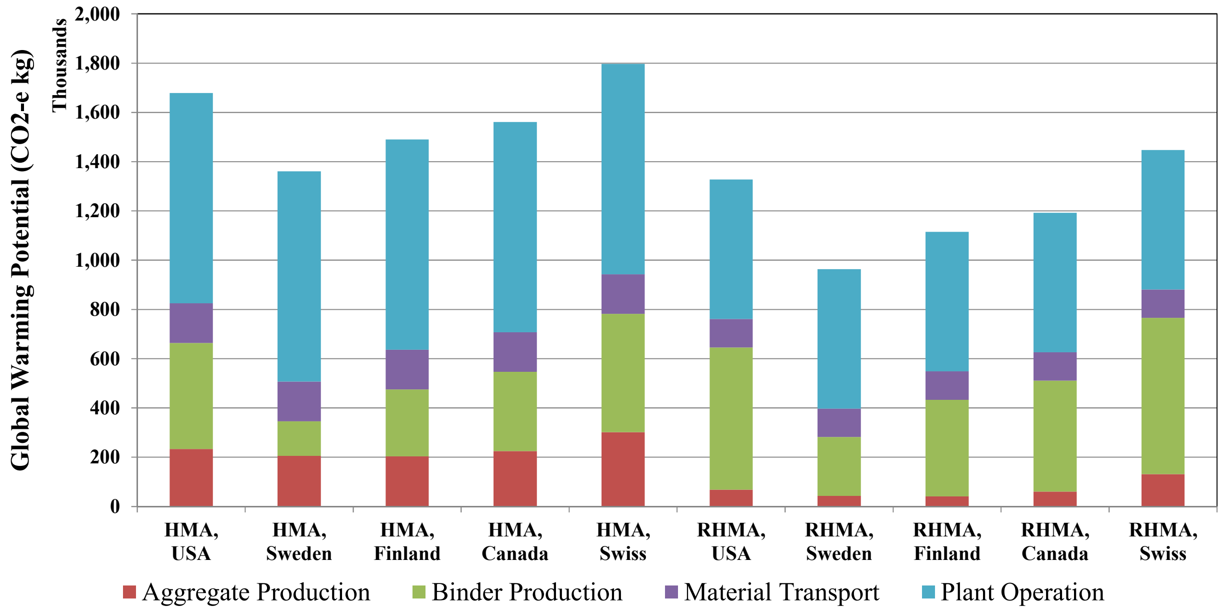


Figure 7.8: KER-5 Material Production Phase: GHG emissions for the functional unit (metric tons).
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

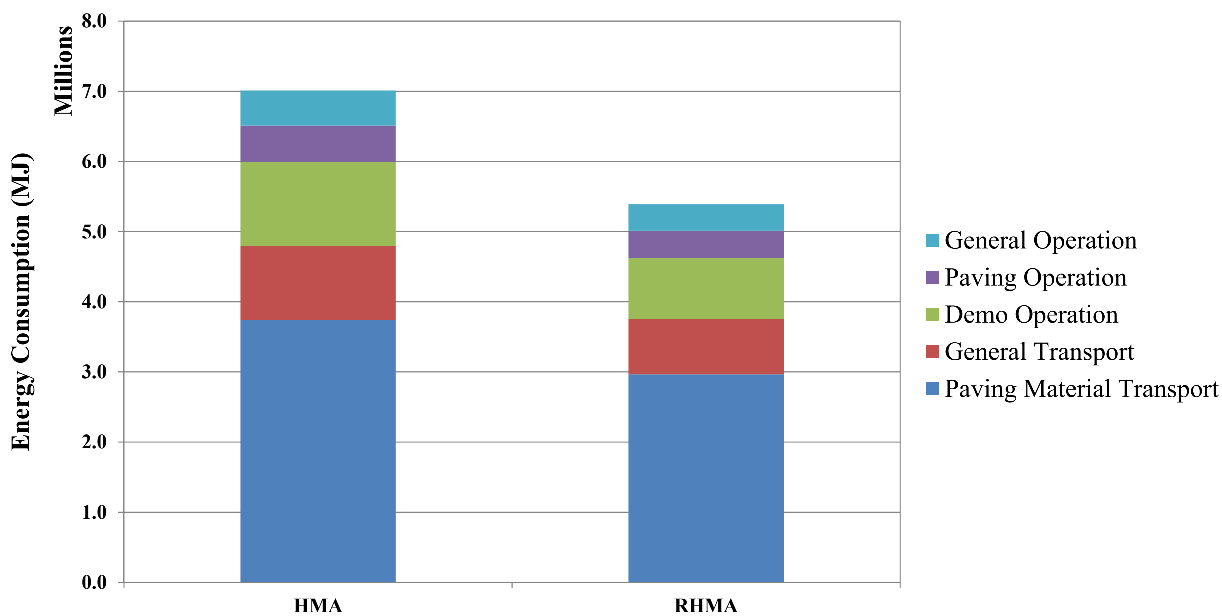


Figure 7.9: KER-5 Construction Phase: energy consumption for the functional unit.

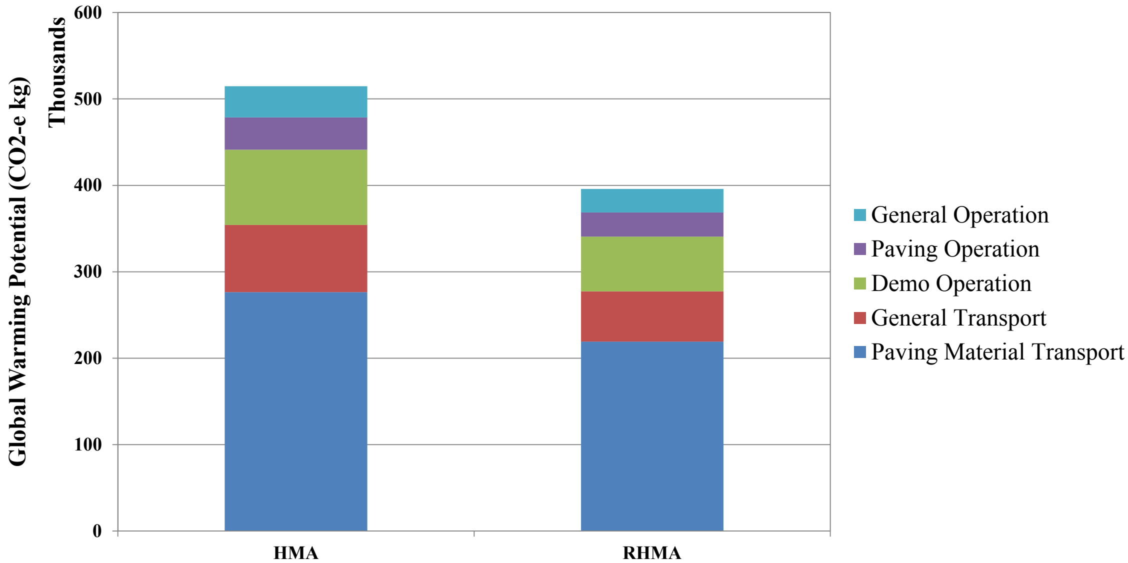


Figure 7.10: KER-5 Construction Phase: GHG emissions (metric tons).

7.2.2 Cement Concrete Production and Construction

Figure 7.11 and Figure 7.12 show energy consumption and GHG emissions from the Material Production and Construction phases for LA-5, respectively. Results from IMP-86 are (shown in Appendix C) show the same trends because its number of total lane-miles is proportional to LA-5. Because the total volume of materials for both material types is the same, the operation hours of trucks and construction equipment are also equal. Thus differences between the Type III and CSA treatments only exist in the Material Production Phase.

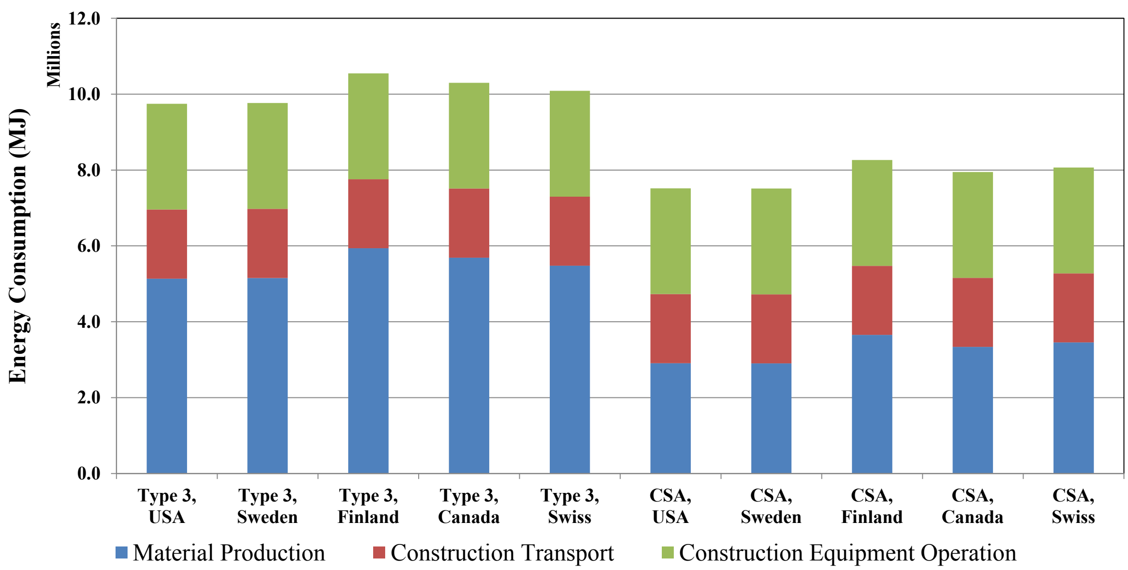


Figure 7.11: LA-5 Material Production Phase and Construction Phase: energy consumption for the functional unit.

Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

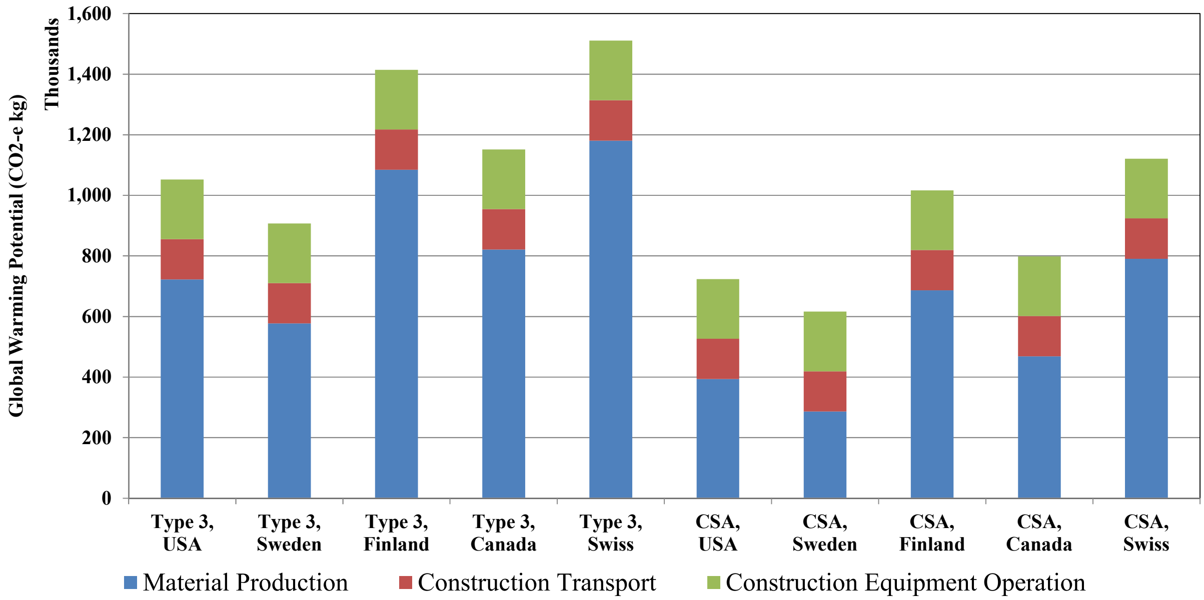


Figure 7.12: LA-5 Material Production Phase and Construction Phase: GHG emissions (metric tons) for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

Figure 7.13 and Figure 7.14 show the breakdown of energy consumption and GHG emissions for the Material Production Phase. Cement production ("Binder") is the major contributor to both, particularly GHG emissions, when compared to the other parts of the Material Production Phase.

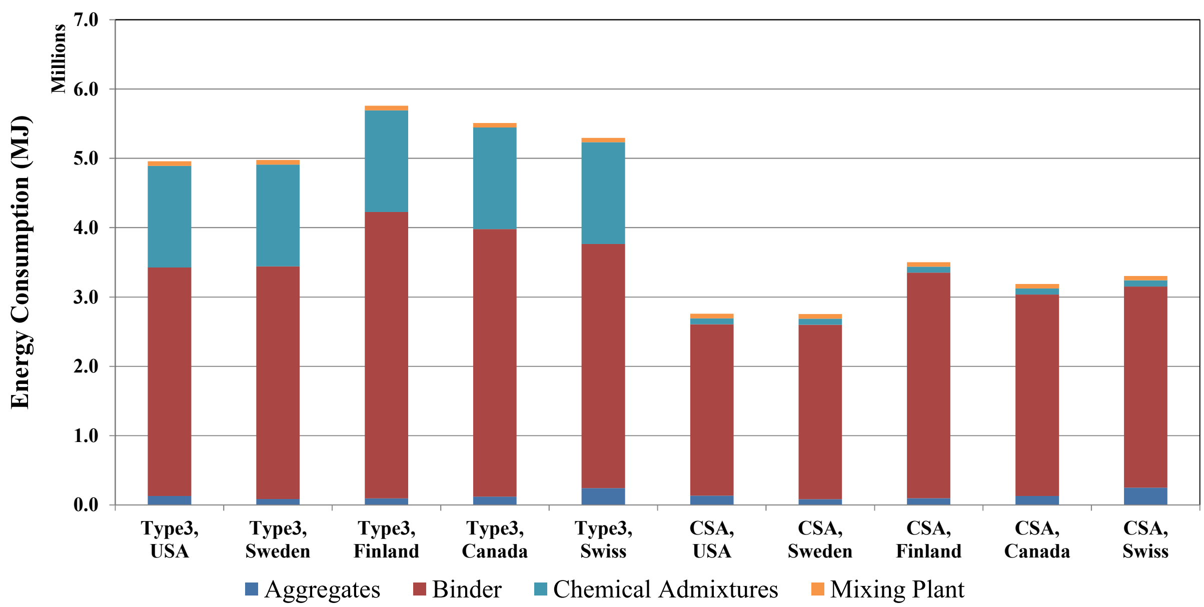


Figure 7.13: LA-5 Details of Material Production Phase: energy consumption for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix.)

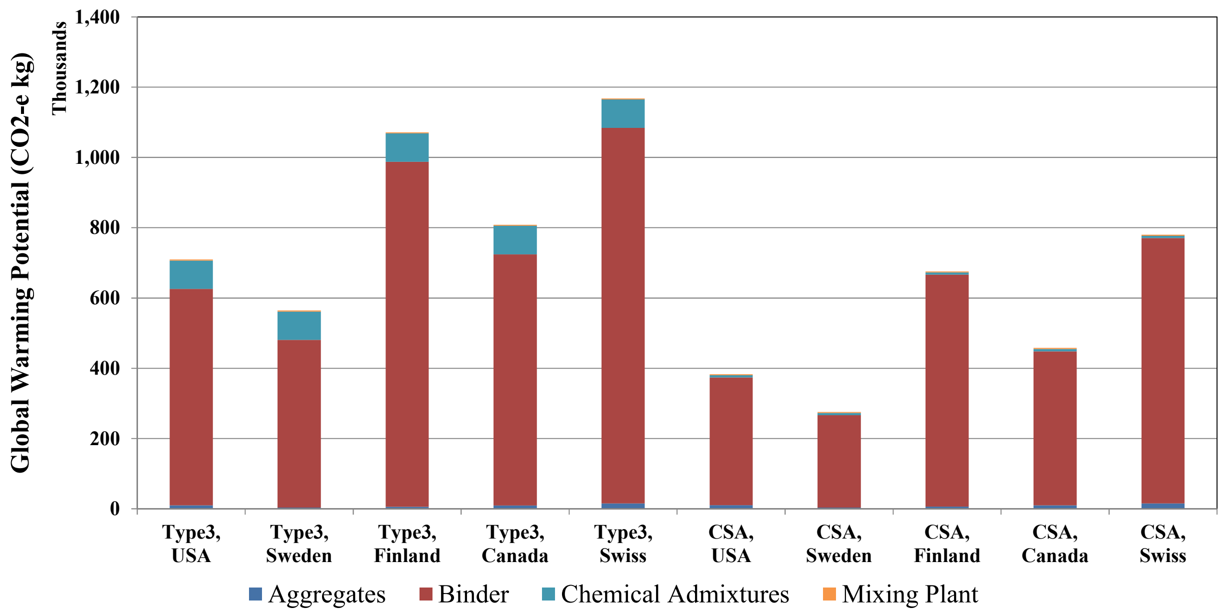


Figure 7.14: LA-5 Details of Material Production Phase: GHG emissions for the functional unit (metric tons). Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

Figure 7.13 and Figure 7.14 show that cement manufacture is the main driver for energy consumption and GHG emissions. As shown in Figure 7.13, the chemical admixture used in the Type III mix has a notable impact on energy consumption. This suggests that, even when used in small quantities, chemical admixtures may substantially increase the energy consumption and GHG emissions associated with concrete mixes. Many of these admixtures are particular to high early strength mixes developed for slab replacements placed during nighttime closures.

7.2.3 Results from the Use Phase

Figure 7.15 and Figure 7.16 show energy consumption in the Use Phase for the HMA overlay on KER-5 and the Type III PCC CPR B on LA-5, compared with several fuel-saving measures, including reducing traffic growth, improving vehicle fuel economy, and applying the pavement preservation across the five- and ten-year respective analysis periods for asphalt and concrete. Other case studies give similar results (shown in the appendices). Zero and three percent annual traffic growth were calculated to show the impact from reducing VMT. The default vehicle fleet fuel economy improvement strategy in *MOVES* is also shown compared with keeping the current fleet fuel economy. An “Equivalent Gasoline” is shown in the figure to relate energy consumed to the equivalent volume of gasoline burned by vehicles (diesel is converted to equivalent gasoline based on lower heating value [LHV]).

The results show that the most significant reduction in fuel use will come from less VMT, especially under the assumption shown that the growth rate is zero from the year after construction. Placing a *Smooth Rehab* can reduce the annual energy consumption by about 2 percent. Because GHG emissions in this phase are completely generated from burning gasoline or diesel by vehicles, GHG emissions have a trend that closely resembles that of fuel consumption in the Use Phase. Another result shown by both the concrete and the asphalt case studies is that, if construction quality is not well controlled during the asphalt paving or concrete grinding in a pavement preservation project—as represented by a greater IRI after construction—then the energy savings of the Use Phase attained by application of the pavement preservation treatment can be very small.

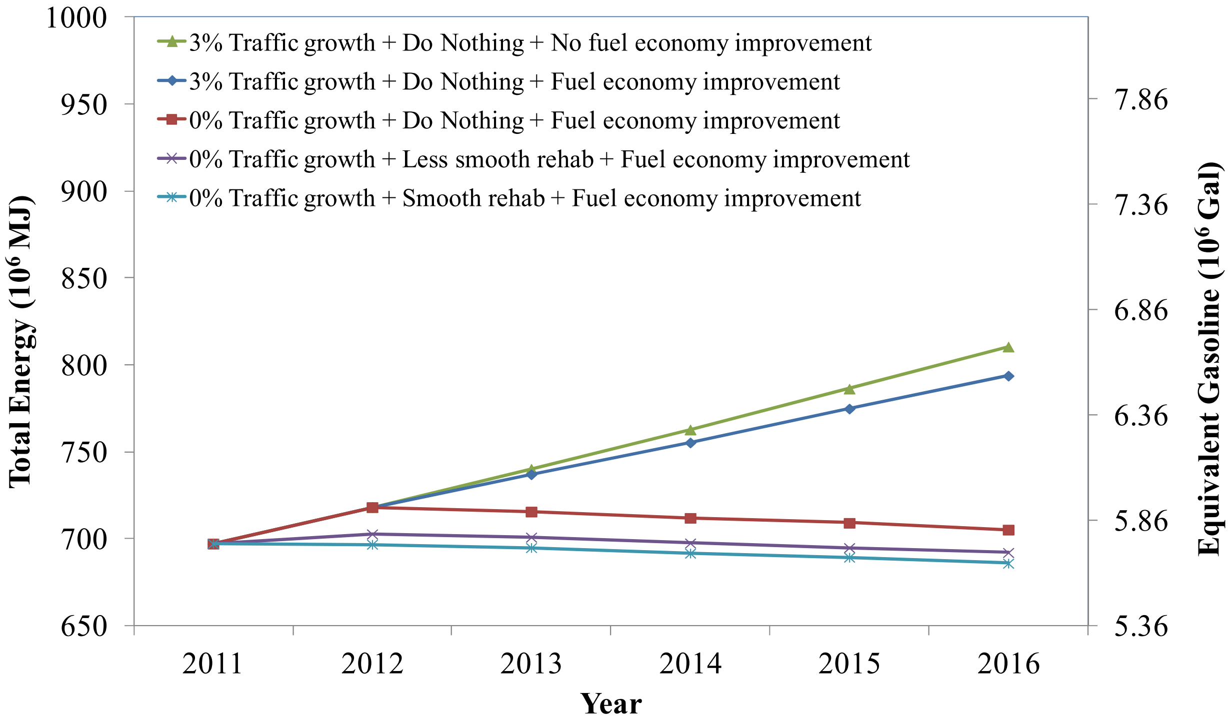


Figure 7.15: Energy consumption in Use Phase with 0 percent and 3 percent traffic growth on KER-5.

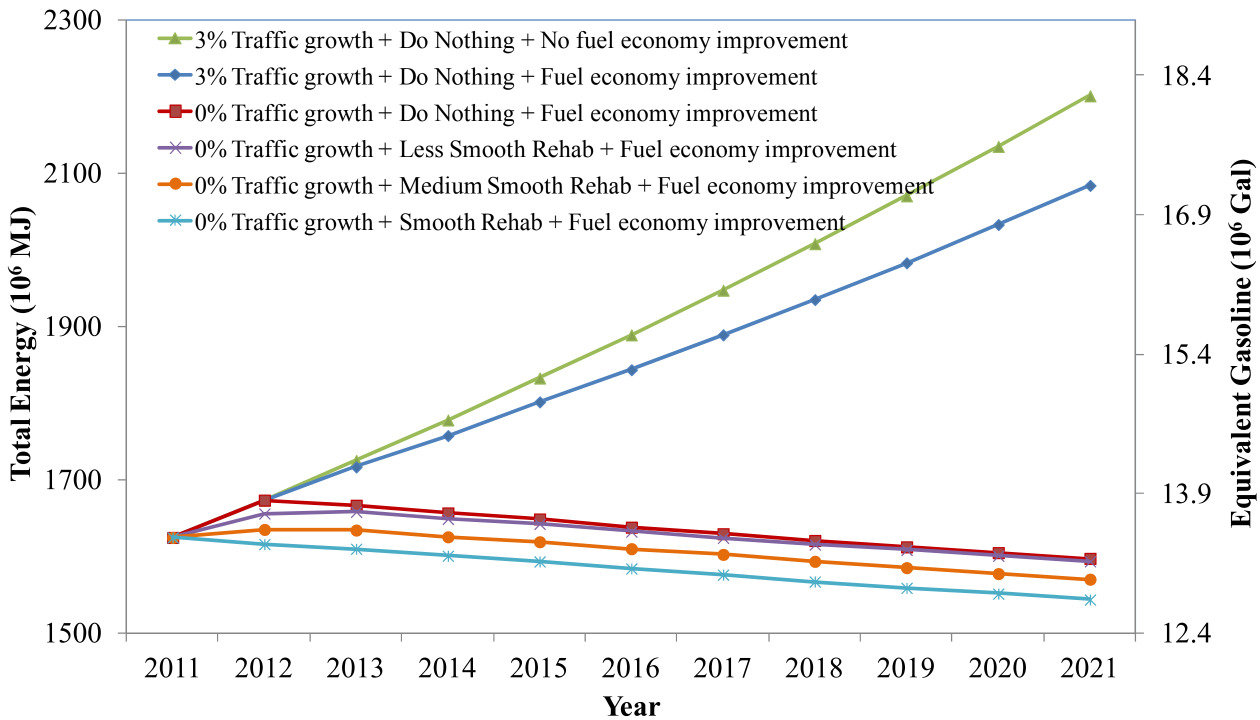


Figure 7.16: Energy consumption in Use Phase with 0 percent and 3 percent traffic growth on LA-5.

7.2.4 Preservation Treatment Life Cycle Results Considering GHG Emissions and Energy Use

The preservation treatment life cycle energy consumption for the HMA scenarios and Type III PCC scenarios in all the case studies are shown in Figure 7.17 (high and low traffic asphalt cases) and Figure 7.18 (high and low traffic concrete cases). It should be remembered that the asphalt and concrete case studies are for different projects and conditions so they cannot be compared to each other.

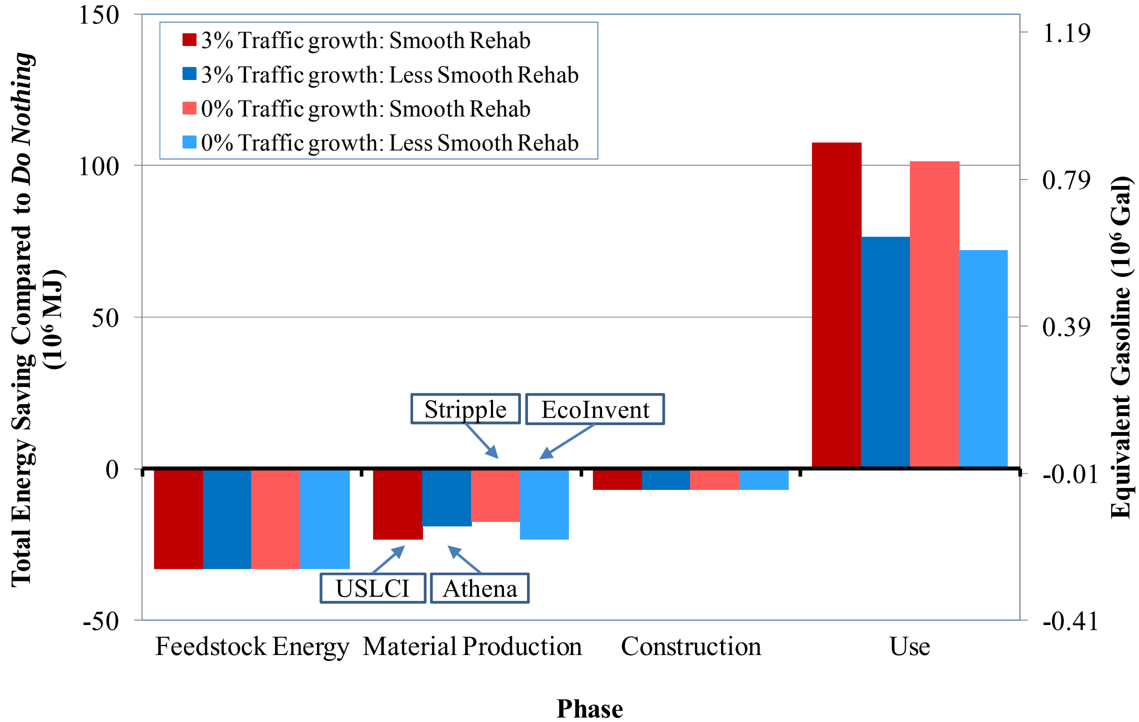
As noted previously, the asphalt cases used a five-year analysis period and the concrete cases a ten-year period. Preservation treatments, such as the CAPM treatments used as examples in this study, are applied to pavements that do not have major structural failure requiring rehabilitation or reconstruction. They tend to be placed several times in succession until eventually a rehabilitation or reconstruction is required and funds are available. For this reason, the analysis period was selected to be the design life, with the assumption that the treatment would be repeated. The analysis periods were specifically selected to be different for the asphalt and concrete treatments and the results were not annualized to avoid direct comparison between them, because that is not the objective of this first study in the research program. It should be remembered as well, that CAPM treatments are used extensively when M&R funding levels are insufficient for longer life treatments that may have lower life cycle costs and potentially lower life cycle environmental impacts.

The RHMA and CSA cement scenarios in these two case studies, included in Appendices A and B, show trends similar to the HMA and PCC studies, respectively. The complete results are summarized in Table 7.10, Table 7.11, Table 7.12, and Table 7.13. All of the numbers shown in the figures and tables are relative to the *Do Nothing* scenario. Therefore a positive result means it is a saving compared to *Do Nothing*, while a negative result indicates greater consumption than *Do Nothing*. In Figure 7.17 and Figure 7.18, different bars in the Material Production Phase indicate the different data sources used for material production in the sensitivity analysis.

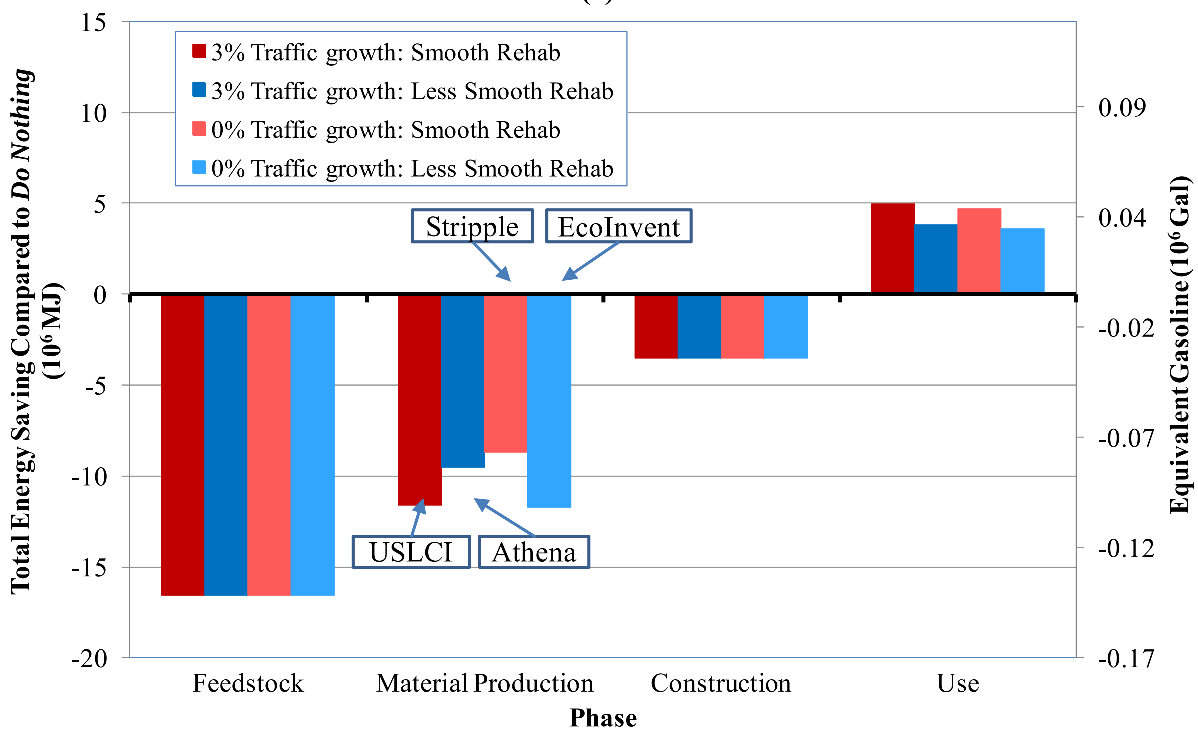
The results show that for the asphalt cases the feedstock energy of materials can be up to three times the energy actually used in the material production. Reporting of feedstock energy for asphalt was the subject of a session at the 2010 Pavement LCA Workshop. Participants in the session agreed to report feedstock energy to maintain compliance with ISO standards, but to do so separately from other primary energy in recognition of the fact that the feedstock energy in asphalt would likely never be used as an energy resource (*66*), unless it is diverted at the refinery into production of products other than asphalt.

Figure 7.17 and Figure 7.18 show that for segments with high traffic volume such as KER-5 or LA-5, using either material, even in the weakest case where *Less Smooth Rehab* is carried out under "0% Traffic growth," the energy savings in the Use Phase are greater than the energy consumed by the sum of the Material Production and Construction phases. However, for segments with low traffic volume such as BUT-70 and IMP-86 (shown in Figure 7.17 and Figure 7.18), the energy consumption and GHG emissions in the upstream phases exceed the savings during the Use Phase. This indicates that applying maintenance to a rough pavement has the capacity to significantly reduce the energy consumption and GHG emissions when a systemwide analysis is considered, but the result is heavily traffic-dependent. They will also be dependent on the assumptions regarding transport of the asphalt and cement to the construction site and the haul distances between the quarry and the construction site, and the construction site and the demolition dump site.

Multiple data sources were reviewed and used to characterize asphalt and cement production. These data sources represent different manufacturing conditions, technologies, and system boundaries. To increase the accuracy of an LCA, the data source that represents the current state of knowledge for the location of interest (California in this case) should always be used. However, California-specific data was not currently available at the time of this study. Instead, the variability among the different data sources is explicitly shown in the result: USLCI, PCA, Athena, Stripple, and EcoInvent. Different data sources for cement have resulted in a cement LCI with low variability and almost the same answer. The variability of LCI for asphalt may reflect the influence of different types of refineries, e.g. oil refinery or asphalt refinery.



(a)



(b)

Figure 7.17: (a) Analysis period energy saving compared to *Do Nothing* with HMA overlay in KER-5; (b) Analysis period energy saving compared to *Do Nothing* with HMA overlay in BUT-70.

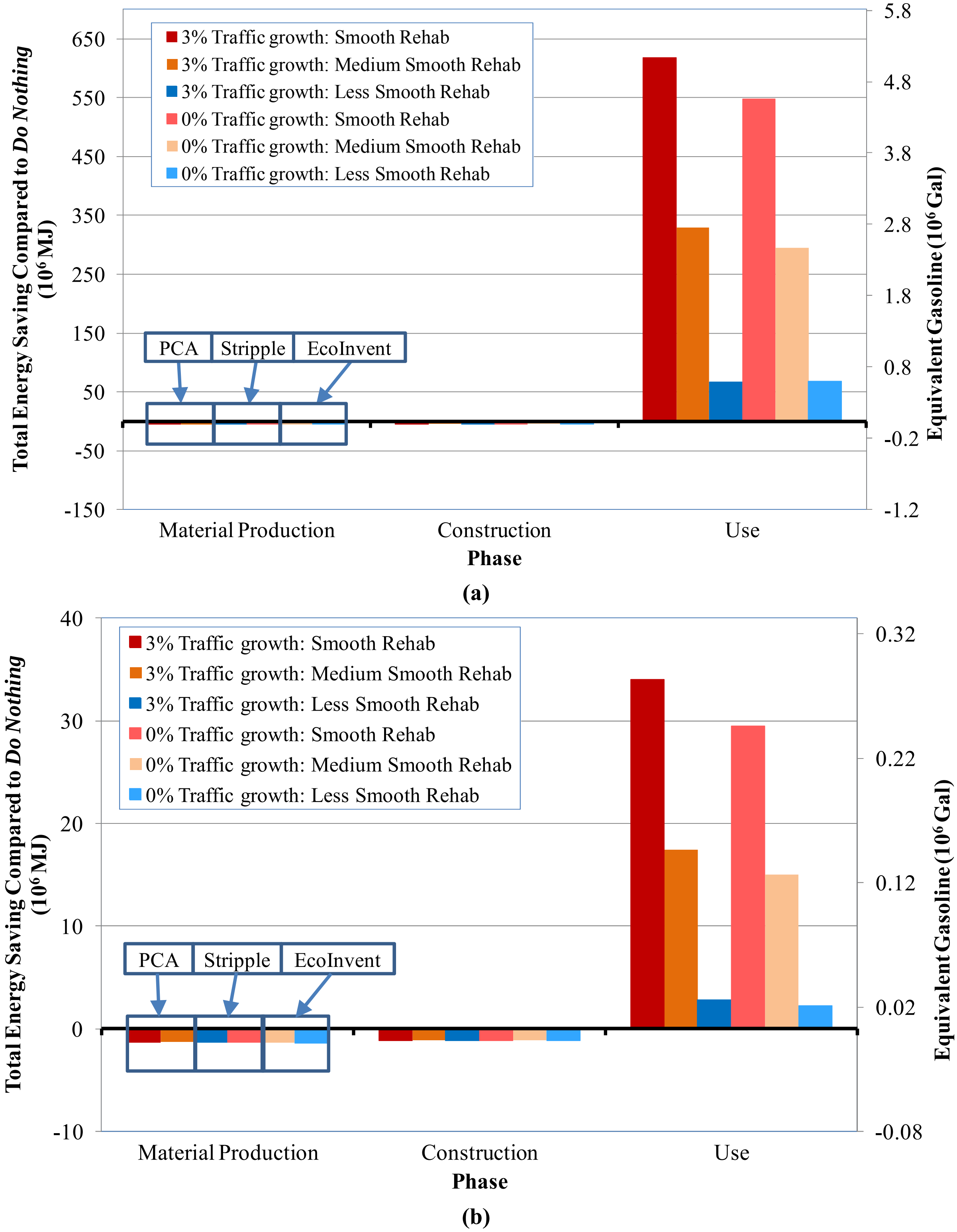


Figure 7.18: (a) Analysis period energy saving compared to *Do Nothing* with Type III PCC in LA-5; (b) Analysis period energy saving compared to *Do Nothing* with Type III PCC in IMP-86.

Nevertheless, in high traffic volume cases (KER-5 and LA-5), because the energy consumption in the Material Production Phase and Construction Phase is very small compared to the Use Phase, the differences between the different data sources do not significantly change the result. However, on low traffic volume roads the differences in the Material Production and Construction phases are more important. In addition, poor construction quality always has an important effect on the net results, such as for the BUT-70 and *Less Smooth Rehab* case shown in Figure 7.18. Under these situations the data source that represents the current state of knowledge for the location of interest (California in this case) should be used.

The effects of construction quality on pavement performance (IRI rate of change) are also important. Better performance models will show more clearly the additional effect of more rapid deterioration of the pavement when there is poor construction quality, either in smoothness or materials quality.

The results of checking the relative contributions of a reduction in IRI and the change in the macrotexture for the high traffic asphalt and concrete cases are shown in Figures A.9 (KER-5, HMA overlay and smooth construction) and A.10 (LA-5, Type III concrete and smooth construction) for the Use Phase. The results indicate that for the HMA overlay the change in MPD from overlay compared to *Do-Nothing* contributed 10 percent of the energy savings, while the change in IRI from the overlay (smooth construction case) contributed 90 percent of the benefits. The results for the CPR B show that the change in MTD from grinding and slab replacement (Type III concrete and smoothest grinding case) contributed 5 percent of the energy savings, while the change in IRI from the treatment contributed 95 percent of the benefits. These results indicate that the primary benefit of the pavement preservation treatments comes from reduction in IRI, and that texture plays a minor role, particularly for the concrete treatment. These results are in agreement with the calibration exercise for the *HDM-4* models described in Section 1.2 of this report, which indicated that IRI has a much more important impact on effective rolling resistance than does texture within normal ranges of these variables.

Table 7.10: Analysis Period Energy and GHG Compared to *Do Nothing* Over 5 Years in KER-5

Material	Annual Traffic Growth	Initial Smoothness	Feedstock Energy (10^6MJ)	Material Production Energy (Average value, 10^6MJ)	Construction Energy (10^6MJ)	Use Phase (10^6 MJ)	Total Energy Saving (10^6 MJ)	Equivalent Gasoline Saving (10^6 Gal)	GHG Reduction (Metric Ton CO_2-e)
HMA	3%	*Smooth*	-33	-21	-7.0	110	80	0.66	5,675
		Less Smooth				76	49	0.40	3,426
	0%	*Smooth*				100	74	0.61	5,232
		Less Smooth				72	44	0.37	3,114
RHMA	3%	*Smooth*	-49	-18	-5.4	110	84	0.69	6,161
		Less Smooth				76	53	0.43	3,912
	0%	*Smooth*				100	78	0.64	5,718
		Less Smooth				72	48	0.40	3,600

Table 7.11: Analysis Period Energy and GHG Compared to *Do Nothing* Over 5 Years in BUT-70

Material	Annual Traffic Growth	Initial Smoothness	Feedstock Energy (10^6MJ)	Material Production Energy (Average value, 10^6MJ)	Construction Energy (10^6MJ)	Use Phase (10^6 MJ)	Total Energy Saving (10^6 MJ)	Equivalent Gasoline Saving (10^6 Gal)	GHG Reduction (Metric Ton CO_2-e)
HMA	3%	*Smooth*	-17	-10	-3.5	5.0	-8.9	-0.07	-700
		Less Smooth				3.8	-910	-0.08	-782
	0%	*Smooth*				4.7	-9.2	-0.08	-721
		Less Smooth				3.6	-10	-0.08	-798
RHMA	3%	*Smooth*	-24	-9.2	-2.7	5.0	-6.9	-0.06	-457
		Less Smooth				3.8	-8.1	-0.07	-539
	0%	*Smooth*				4.7	-7.2	-0.06	-478
		Less Smooth				3.6	-8.3	-0.07	-555

Table 7.12: Analysis Period Energy and GHG Compared to *Do Nothing* Over 10 Years in LA-5

Material	Annual Traffic Growth	Initial Smoothness	Material Production Energy (Average value, 10^6MJ)	Construction Energy (10^6MJ)	Use phase (10^6MJ)	Total Energy Saving (10^6MJ)	Equivalent Gasoline Saving (10^6 Gal)	GHG Reduction (Metric Ton CO_2-e)
Type III cement	3%	*Smooth*	-5.3	-4.4	620	610	5.03	43,682
		Medium smooth			330	320	2.64	22,694
		Less Smooth			66	57	0.47	3,618
	0%	*Smooth*			550	540	4.44	38,507
		Medium smooth			300	290	2.36	20,227
		Less Smooth			68	58	0.48	3,751
CSA cement	3%	*Smooth*	-3.1	-4.4	620	610	5.04	44,018
		Medium smooth			330	320	2.66	23,030
		Less Smooth			66	59	0.48	3,955
	0%	*Smooth*			550	540	4.45	38,844
		Medium smooth			300	290	2.37	20,564
		Less Smooth			68	60	0.50	4,087

Table 7.13: Analysis Period Energy and GHG Compared to *Do Nothing* Over 10 Years in IMP-86

Material	Annual Traffic Growth	Initial Smoothness	Material Production Energy (Average value, 10^6MJ)	Construction Energy (10^6MJ)	Use Phase (10^6MJ)	Total Energy Saving (10^6MJ)	Equivalent Gasoline Saving (10^6 Gal)	GHG Reduction (Metric Ton CO_2-e)
Type III cement	3%	*Smooth*	-1.3	-1.2	34	32	0.26	2,185
		Medium smooth			17	15	0.12	979
		Less Smooth			2.8	0.33	0.003	-87
	0%	*Smooth*			29	27	0.22	1,852
		Medium smooth			15	13	0.10	803
		Less Smooth			2.3	-0.19	-0.002	-125
CSA cement	3%	*Smooth*	-0.78	-1.2	34	32	0.27	2,269
		Medium smooth			17	16	0.13	1,064
		Less Smooth			2.8	0.88	0.007	-3
	0%	*Smooth*			29	28	0.23	1,936
		Medium smooth			15	13	0.11	887
		Less Smooth			2.3	0.35	0.003	-41

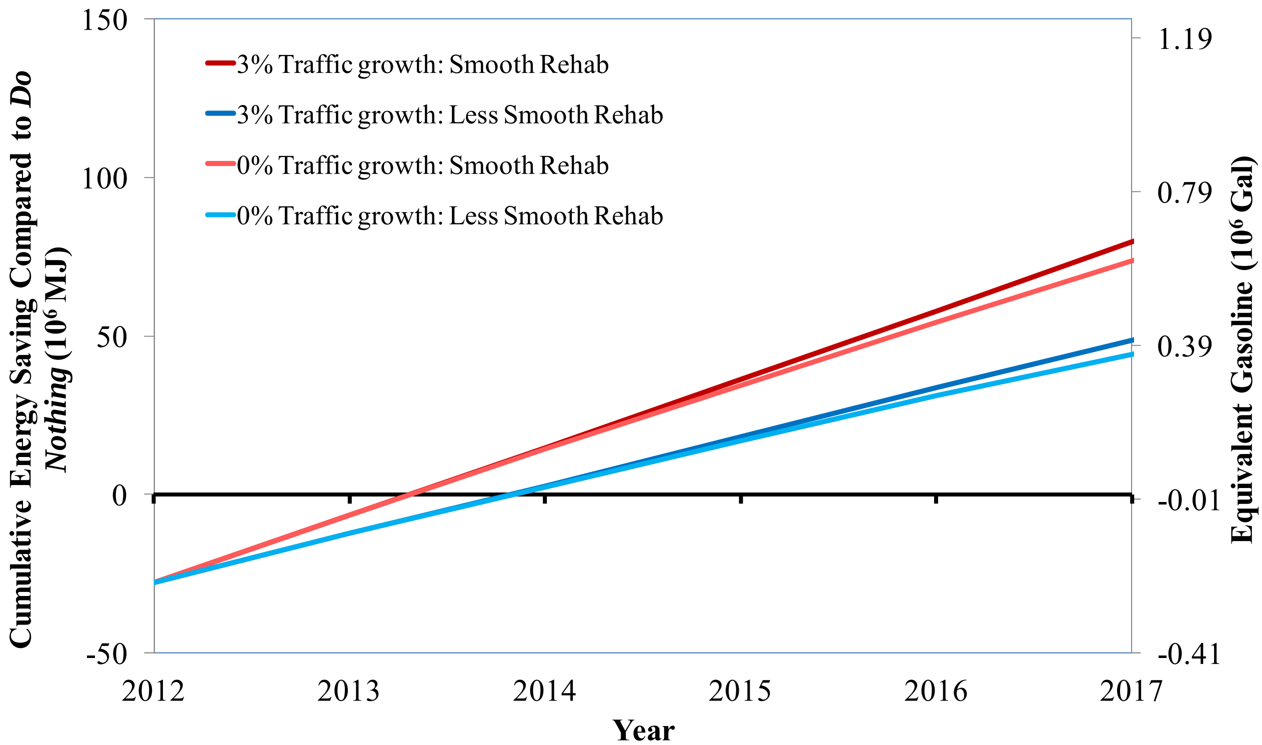
7.2.5 Payback Time Analysis

Material production and construction always produce an initial energy consumption and GHG emissions, which are offset as energy and emissions accumulate during the Use Phase, with the size of the offset depending on the traffic level on that segment. The number of years that it takes to reach zero net energy use or emissions is referred to as the *environmental impact payback time.* To analyze the differences between different scenarios, the payback time in each case was calculated and compared. Figure 7.19 shows examples of the calculation of energy payback time compared to *Do Nothing* for the high traffic asphalt and concrete cases KER-5 and LA-5. It must be remembered that these cases cannot be directly compared to each other because they are for different projects. The complete results for payback time are shown in Appendix B. The GHG emissions have the same trend as energy consumption because nearly all the GHGs emitted in these case studies were from the combustion of fossil fuel. The numbers shown in this figure are also relative to the *Do Nothing* scenario, meaning that a positive result indicates a reduction in fuel use and GHG emissions compared to *Do Nothing,* while a negative result indicates that the energy and emissions savings never pay back the energy use and emissions from the Material Production and Construction phases.

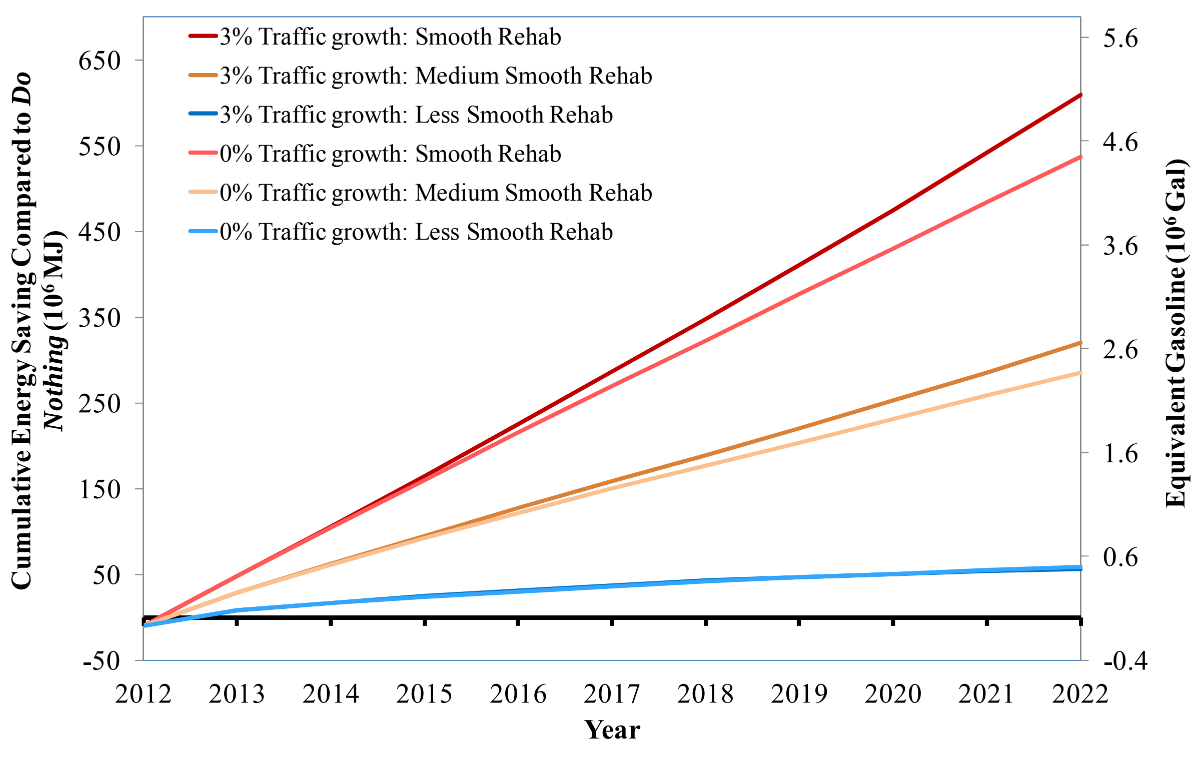
Table 7.14 shows the payback time in each case. The range of numbers indicates the result is dependent on the traffic growth rate.

The results show that the most significant factor in determining payback times is the traffic level, which is reflected in the total traffic volume and truck percentage. For segments with high traffic levels, such as KER-5 and LA-5, the energy consumption because of the initial construction is offset within one to two years of the pavement preservation event, regardless of the material used and smoothness after construction. In the case of BUT-70, with the lowest traffic, the energy consumption is not paid back in the five year life. The second factor affecting the payback time is the construction quality, represented here by the smoothness after construction; a smoother pavement leads to a shorter payback time. There are two reasons for this result: (1) smoother pavement can directly contribute to reduced vehicle fuel consumption during pavement use; and (2) a smooth pavement has slower rate of deterioration compared to a rough pavement, which is reflected in the IRI progression model. For IMP-86, a concrete segment with low traffic volume, the construction quality significantly affected energy savings in the Use Phase, considerably changing the payback time in each smoothness scenario. When this pavement preservation was poorly performed (i.e., the *Less Smooth* case), the energy consumption barely gets paid back within 10 years. This result dropped to one year under a well-performed construction (in *Smooth Rehab).* The third factor shown here is the material used. The inventories and pavement designs for RHMA and CSA cement always have better environmental performance compared to HMA and Type III PCC, respectively. The traffic growth rate does not appear to be significant here because all the comparisons are subject to the same growth rate.

The relative impact of the changes in IRI and macrotexture for the asphalt and concrete treatments for the high traffic cases are shown in Figures B.9 and B.10, respectively. The results show that the changes in texture have a small effect on payback time compared with the changes in IRI.



(a) KER-5 (HMA)



(b) LA-5 (Type III)

Figure 7.19: Cumulative energy saving compared to *Do Nothing* with pavement preservation treatment in KER-5 and LA-5.
Note that the two cases are not directly comparable, and are to illustrate payback time for high traffic cases.

Table 7.14: Payback Time of Energy Consumption for Each Example Case (years)

Case	Material	Asphalt concrete		Case	Material	Cement concrete		
		Smooth	***Less Smooth***			***Smooth***	***Medium Smooth***	***Less Smooth***
KER-5	HMA	1.3	1.7	LA-5	Type III cement	<1	<1	<1
	RHMA	1.1	1.5		CSA cement	<1	<1	<1
BUT-70	HMA	>5	>5	IMP-86	Type III cement	1.1	2.0~2.1	9.5~>10
	RHMA	>5	>5		CSA cement	<1	1.8	8.5~9

8. CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

In this study, an initial life cycle assessment model for pavement preservation was developed and the potential for preservation treatment life cycle energy savings and GHG reductions was assessed through several example case studies representative of some California conditions. Pavement preservation treatments were evaluated under different traffic levels, roughnesses, and materials used in the construction.

The following are indicated by the results:

- Pavement maintenance can result in an important net reduction in GHG emissions and energy use over the analysis period for high-volume routes. The net result is most dependent on the number of vehicles that use the pavement segment. For segments with low traffic volumes, the potential benefits take much longer to accrue, and payback may not occur before the end of the life of the treatment.
- Construction pavement smoothness has an important effect on GHG emissions and energy use in the Use Phase and therefore on the net result. If construction does not result in a smooth pavement, then the benefit of the treatment is greatly reduced.
- Pavement maintenance for a given route with rough surface characteristics can produce energy savings and net GHG emissions reductions of similar size to expected changes in the fleet average fuel economy included in the *MOVES* model. Reductions in the growth rate of vehicle miles traveled on a route have a much larger impact than pavement maintenance or changes in fleet fuel economy.
- The differences in net energy consumption, GHG emissions, and payback time between materials for a given treatment (RHMA and HMA for asphalt overlays, and CSA cement and Type III portland cement for slab replacement) were small compared with the effects of construction smoothness considered in this study. It should be also noted that the analyses in this study assumed that alternative materials have the same performance, which may vary depending on the actual materials and construction quality for a given project. Also, the very low amount of slab replacement used in CPR B (3 percent) made the impact from cement and concrete production insignificant.

Important limitations of this study include the following:

- These initial case studies only represent example sections, which are intended to provide an initial assessment of the relative importance of traffic and other variables in determining whether pavement preservation treatments provided net positive or negative effects on energy use and GHG emissions. The application of this analysis to the network is work that remains.

- The materials datasets for the case studies used data from several sources outside California that were adjusted to California electrical energy supplies. Sensitivity analysis with the different data sets did not change the conclusions.
- All materials mix designs (taken from a series of meetings with the concrete and asphalt industry organizations noted in the acknowledgments) and construction were representative examples. There is a range of mix designs that could have been used for this analysis, and these mix designs were provided by industry with the intention that they be typical.
- The method used to combine pavement characteristics (IRI and texture) and emissions models has not been validated, although the fuel economy models have been validated by Michigan State University.

8.2 Future Work

The case studies presented in this report indicate that the potential impacts of pavement management decisions warrant further evaluation for an entire factorial of cases representing the full network. These are the current plans for the development and implementation of improvements to the models used in this study:

- Implement the variable speed aspects of the vehicle operation model for the Use Phase.
- Develop and implement a work zone traffic delay element for the Construction Phase.
- Develop and implement Material Production and Construction phase LCI models and pavement performance (IRI and macrotexture) models for concrete lane reconstruction (long-life rehabilitation) using Type I/II cement for concrete pavement, and thicker asphalt overlays (rehabilitation) for asphalt pavement.
- Improve Material Production and Construction phase inventories where possible with data more applicable to California material production and construction.

Additional case studies will be performed to assess the net life cycle energy and GHG emissions from preservation treatments for the factorial shown in Table 2.1 (prior to implementation of the energy dissipation model), which is intended to encompass all types of pavement facilities within the state highway network. Within each of the cells in the factorial the following variables will be considered:

- Automobile and truck traffic levels
- Constructed smoothness of the M&R treatment
- Material used for the M&R treatment (type of concrete or asphalt)
- Management strategy/design life (pavement preservation versus rehabilitation versus routine maintenance)

These case studies will be applied to the state highway network to develop preliminary example comparisons of the life cycle impact on energy use and GHG emissions for the pavement management strategies (overlays, CPR, and lane reconstruction). These comparisons will be done for different levels of M&R funding and different strategies for selecting projects for application of the funding. Different levels of construction smoothness will also be evaluated. Recent improvements in the Caltrans PMS database will provide network traffic, IRI and texture (asphalt only) information, and improved models for IRI performance.

As was done for the four case studies presented in this report, the effects of pavement management strategy will also be compared with one prediction of expected change in fleet fuel efficiency versus no change, and with continuation of the historical annual growth in vehicle miles traveled versus no growth, which are two of the strategies being implemented by the California Air Resources Board as part of implementation of AB 32 (as discussed in Chapter 1).

Future work after the environmental impact assessment in all case studies also includes the combination of life cycle cost analysis and use of cost-effectiveness analysis to prioritize different energy and GHG-reduction strategies as mentioned in Chapter 1. In the cost-effectiveness analysis, the environmental benefit (e.g., GHGs reduced) will be analyzed against its life cycle cost (e.g., $/ton GHG reduced). With this analysis, it is possible to evaluate the significance of improving pavement condition compared with other policies to reduce GHG in the transportation sector.

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APPENDIX A: PRESERVATION TREATMENT LIFE CYCLE RESULTS CONSIDERING GHG EMISSIONS AND ENERGY USE FOR EACH CASE STUDY

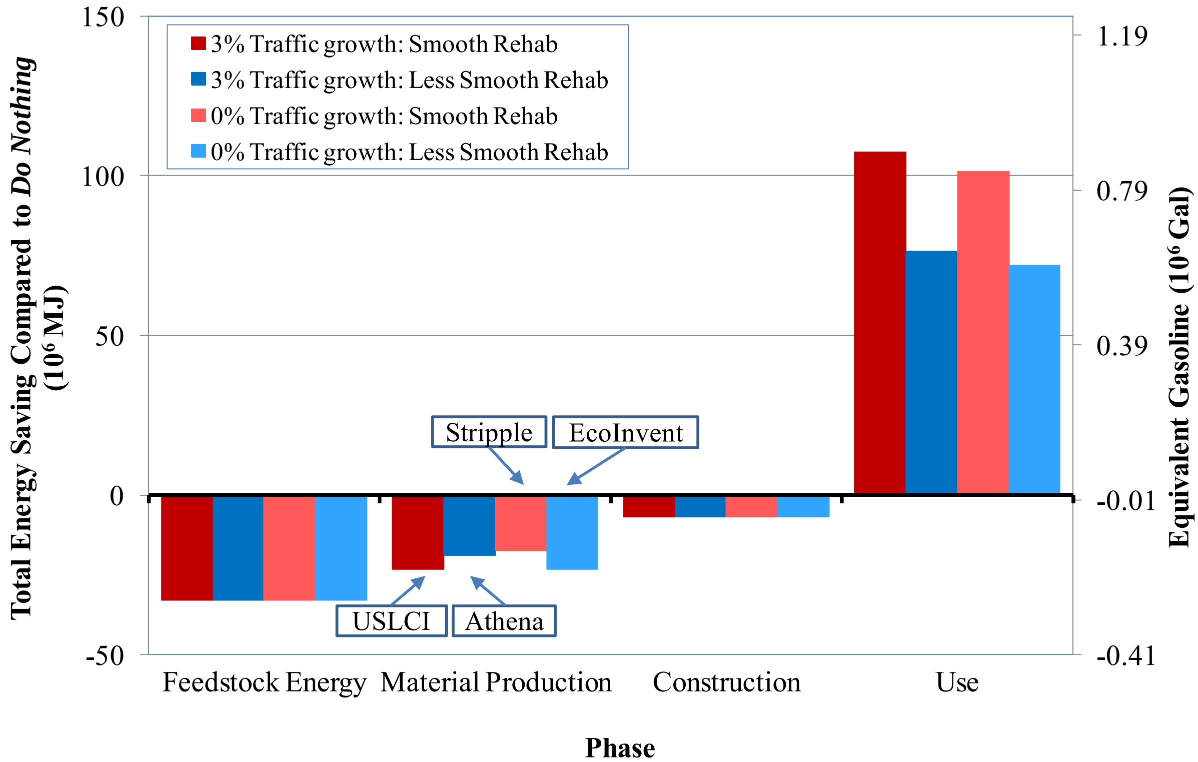

Figure A.1: Analysis period energy saving compared to *Do Nothing* with HMA overlay in KER-5.

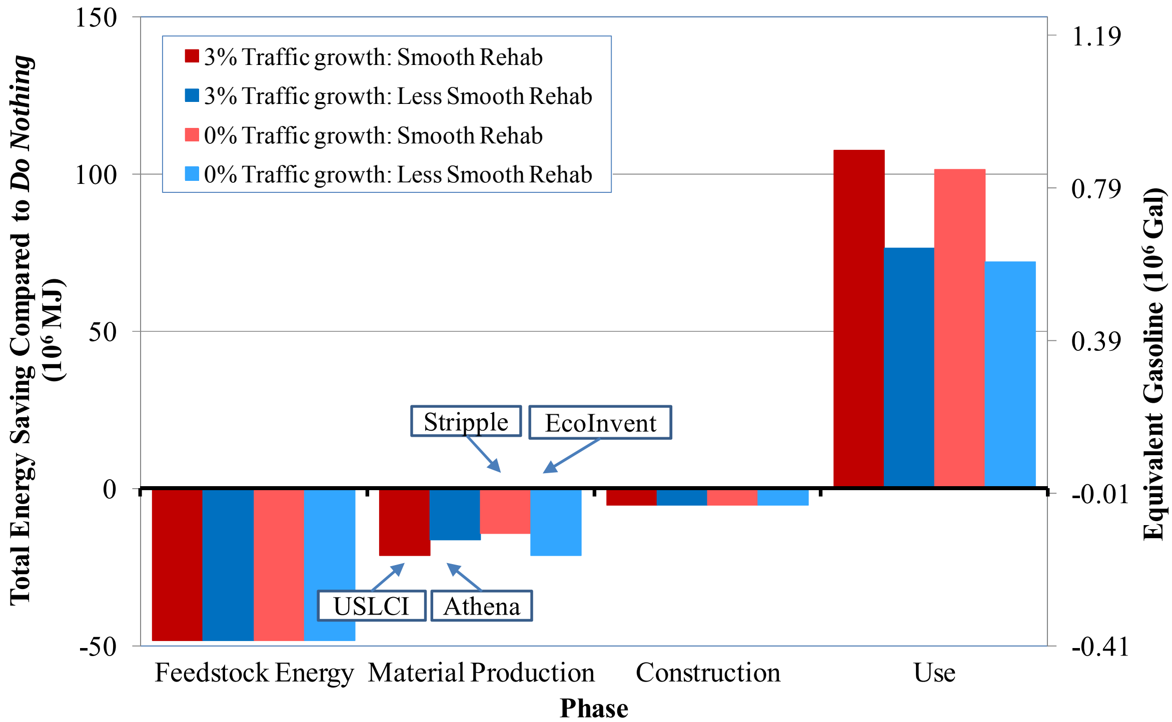

Figure A.2: Analysis period energy saving compared to *Do Nothing* with RHMA overlay in KER-5.

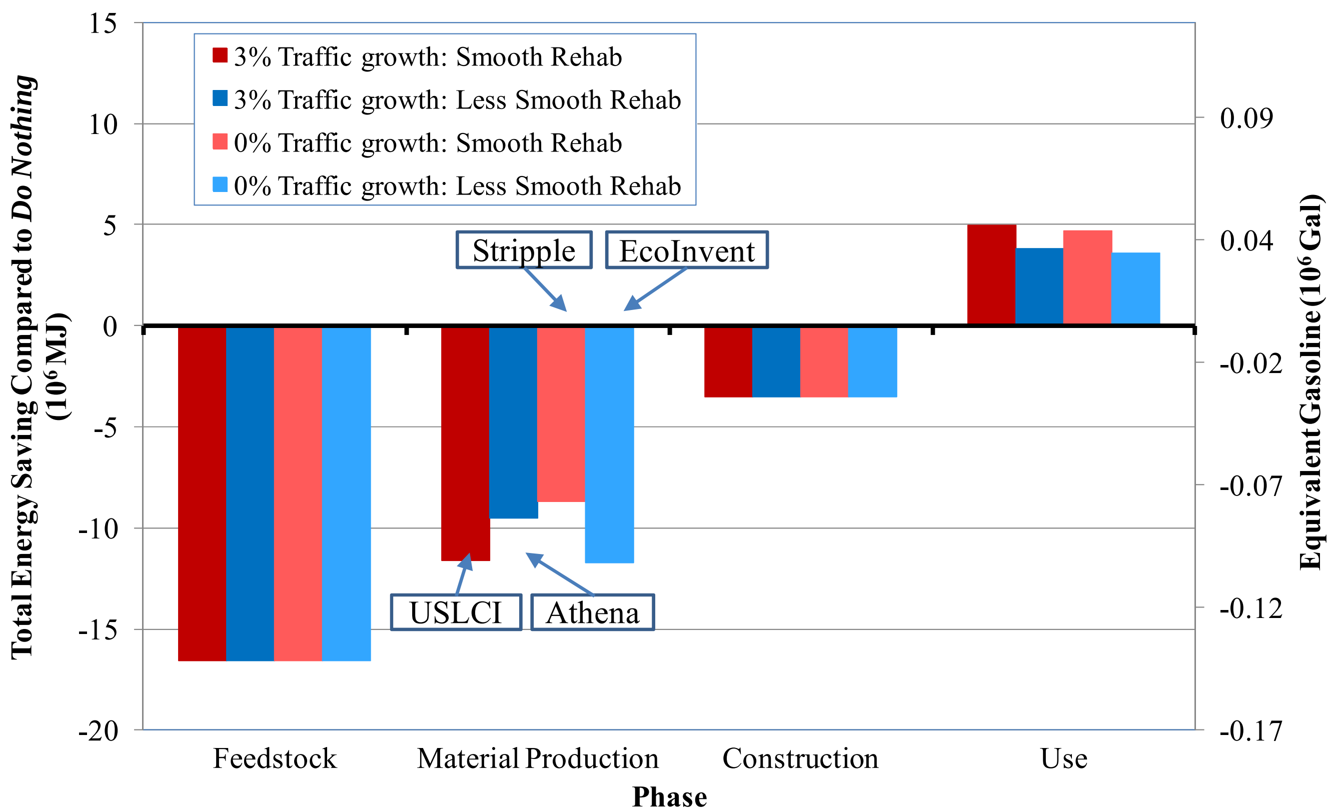

Figure A.3: Analysis period energy saving compared to *Do Nothing* with HMA overlay in BUT-70.

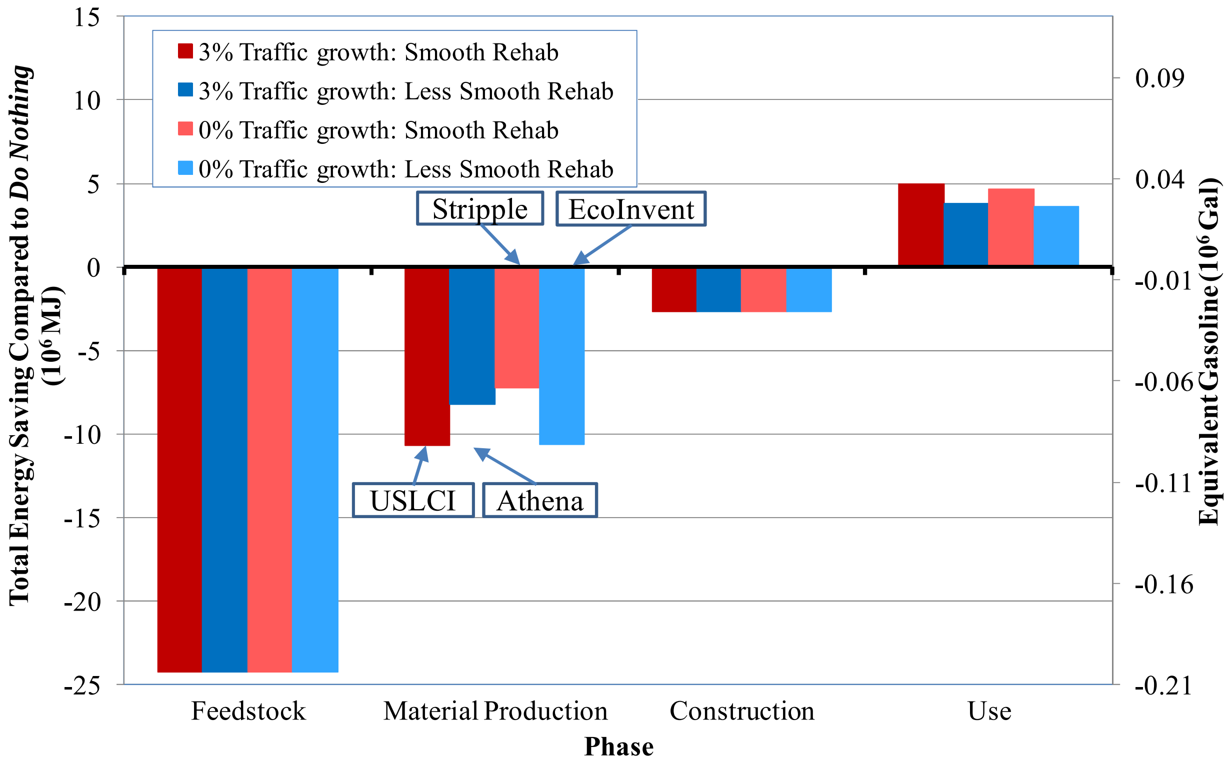

Figure A.4: Analysis period energy saving compared to *Do Nothing* with RHMA overlay in BUT-70.

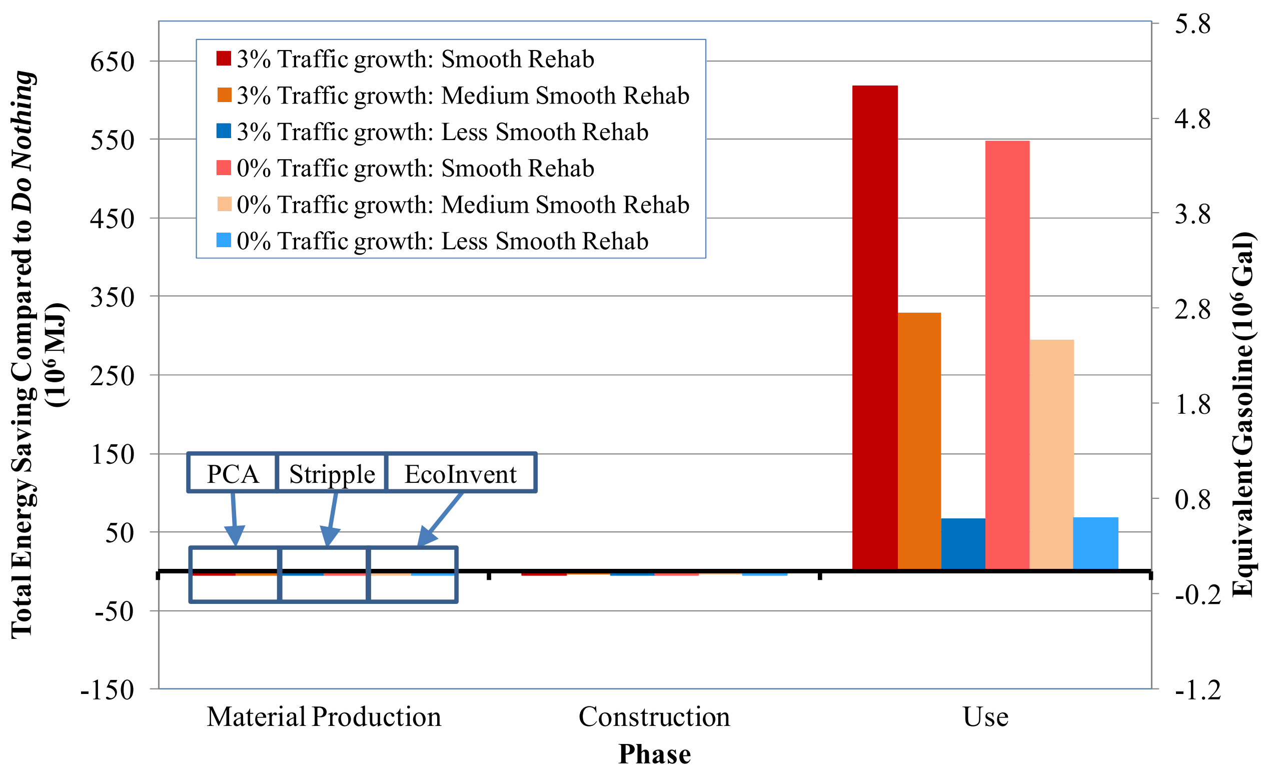

Figure A.5: Analysis period energy saving compared to *Do Nothing* with Type III cement in LA-5.

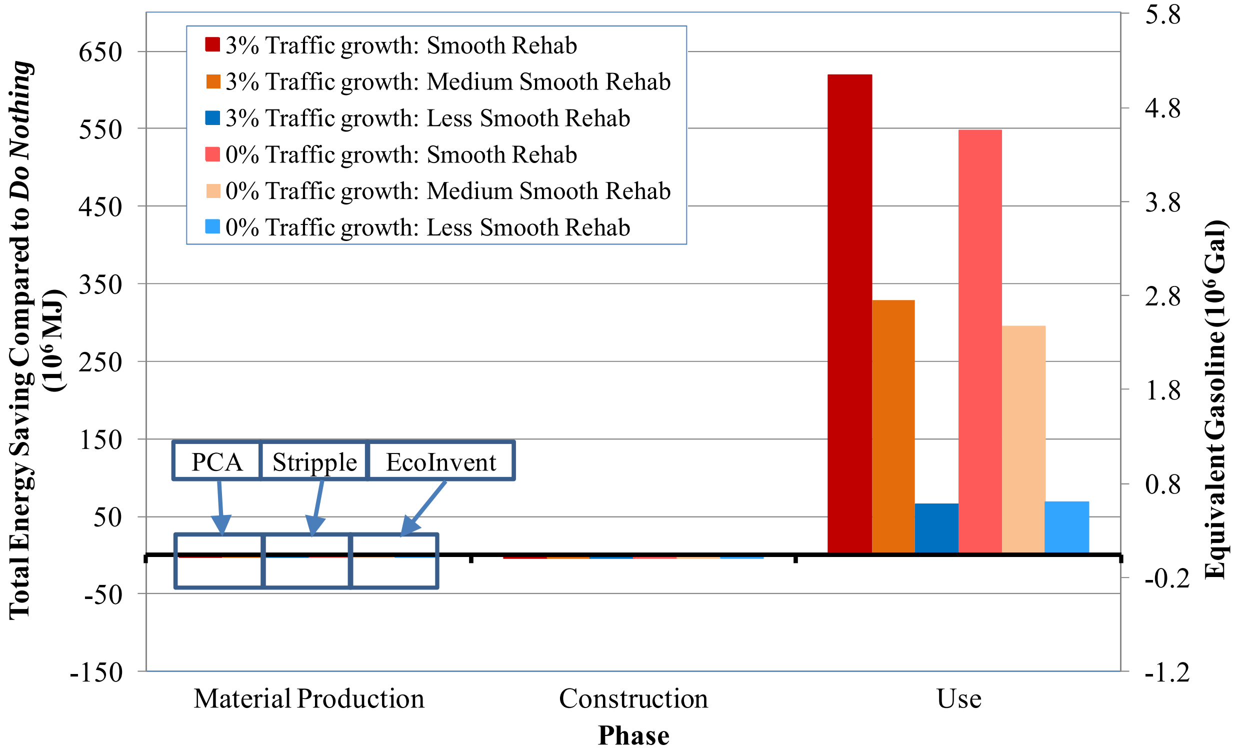

Figure A.6: Analysis period energy saving compared to *Do Nothing* with CSA cement in LA-5.

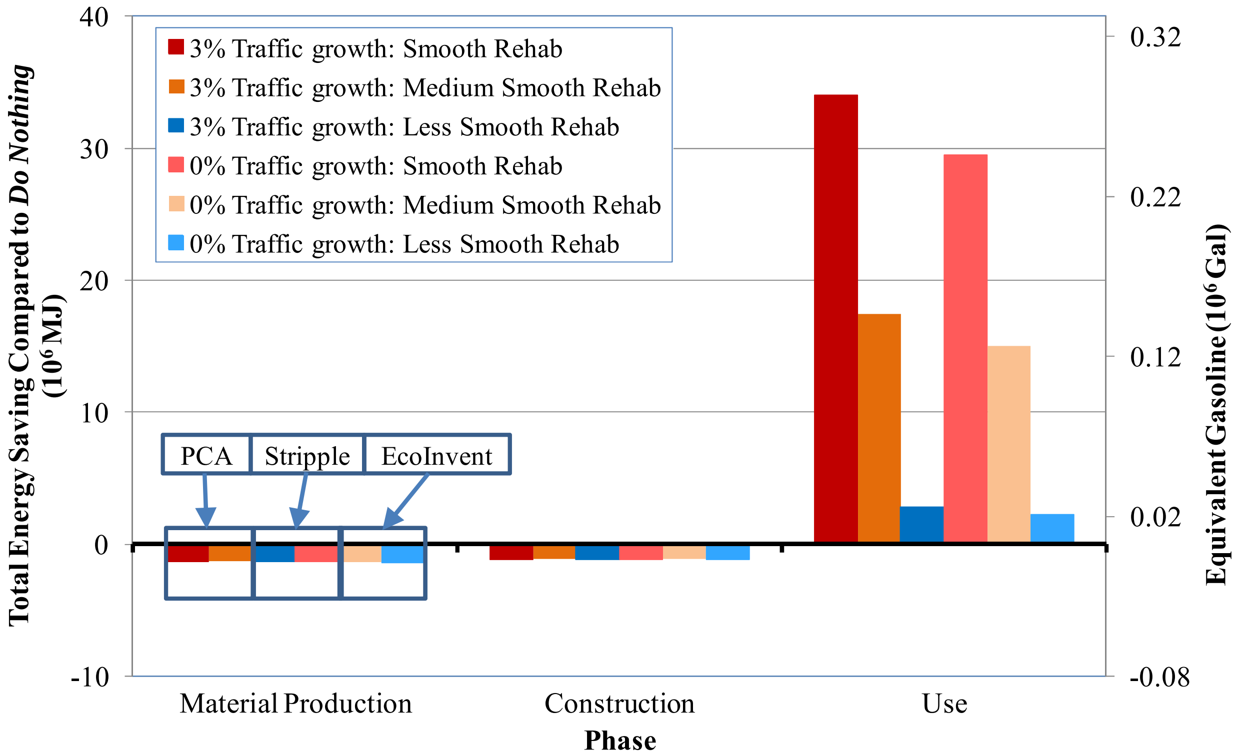

Figure A.7: Analysis period energy saving compared to *Do Nothing* with Type III cement overlay in IMP-86.

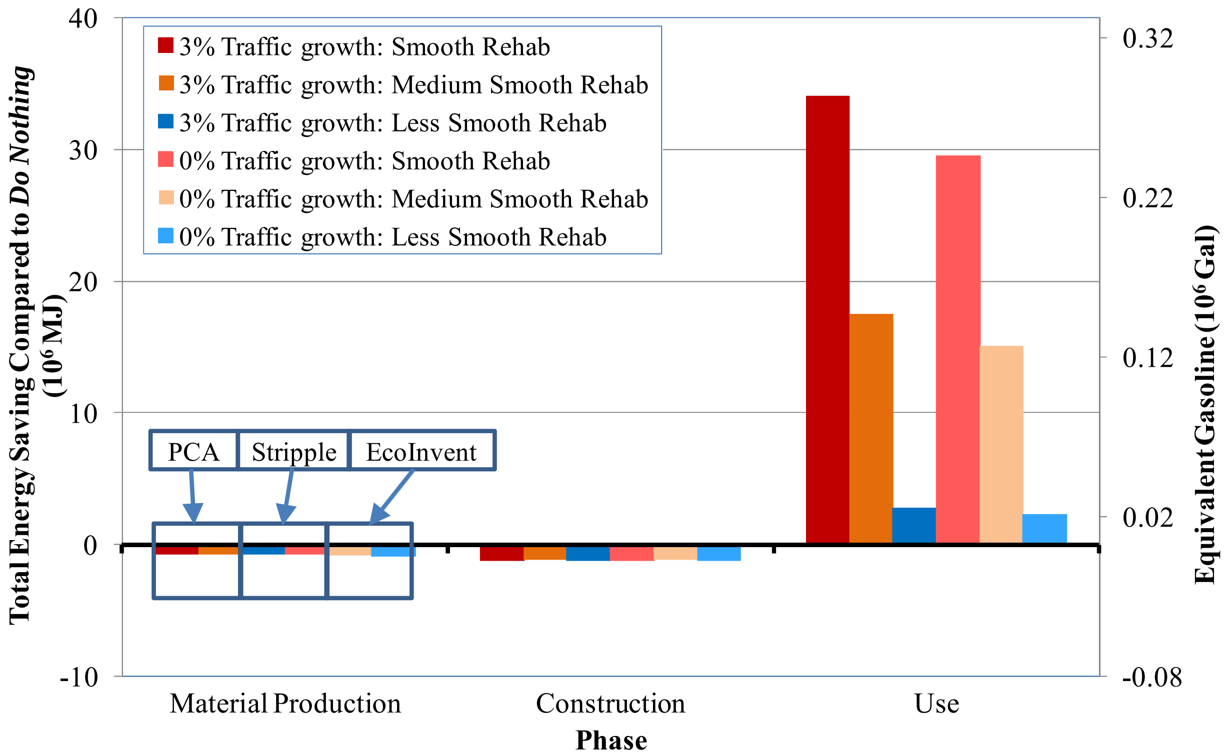

Figure A.8: Analysis period energy saving compared to *Do Nothing* with CSA cement in IMP-86.

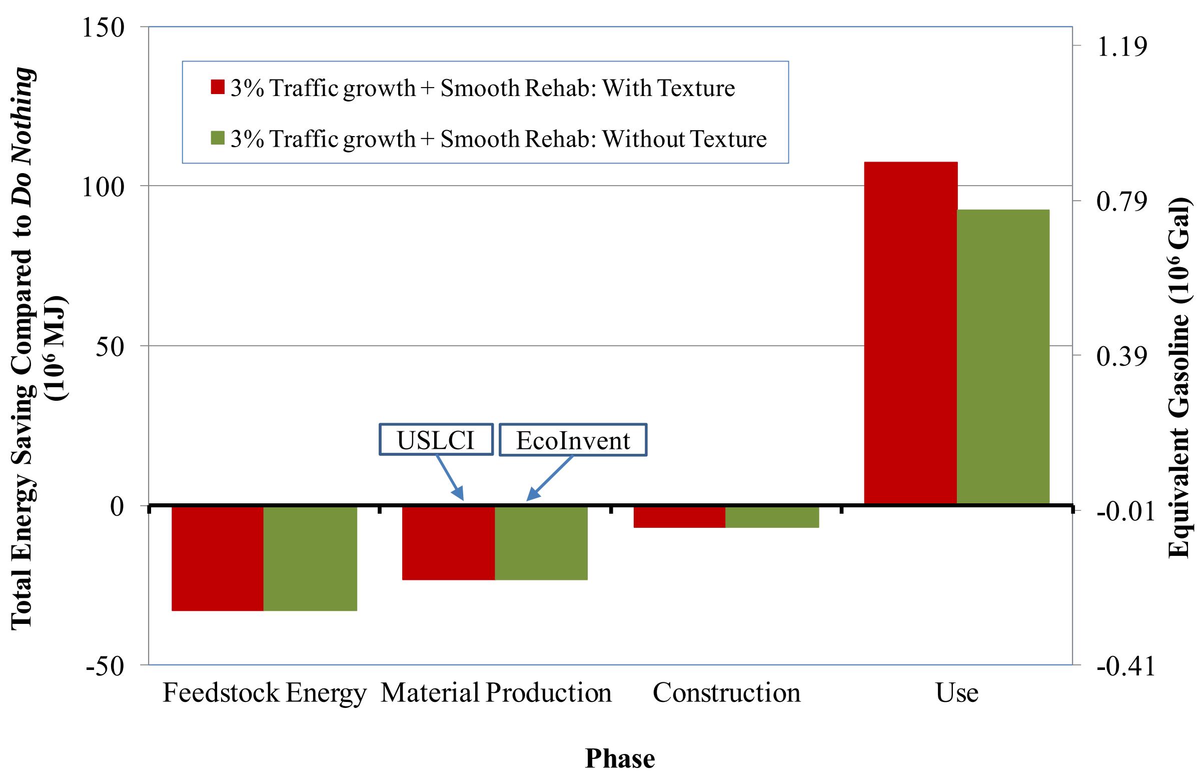

Figure A.9: Sensitivity analysis for macrotexture of analysis period energy saving compared to *Do Nothing* with HMA overlay in KER-5.

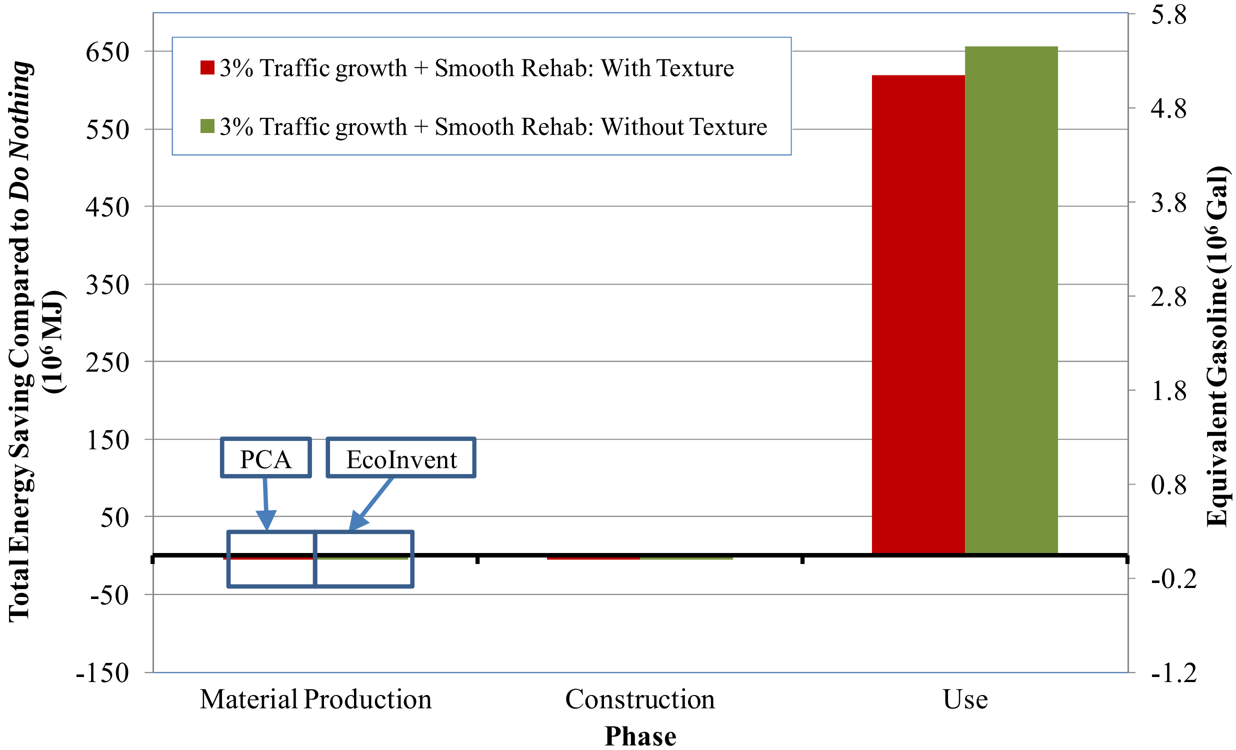

Figure A.10: Sensitivity analysis for macrotexture of analysis period energy saving compared to *Do Nothing* with Type III cement in LA-5.

APPENDIX B: PAYBACK TIME RESULT IN EACH CASE STUDY

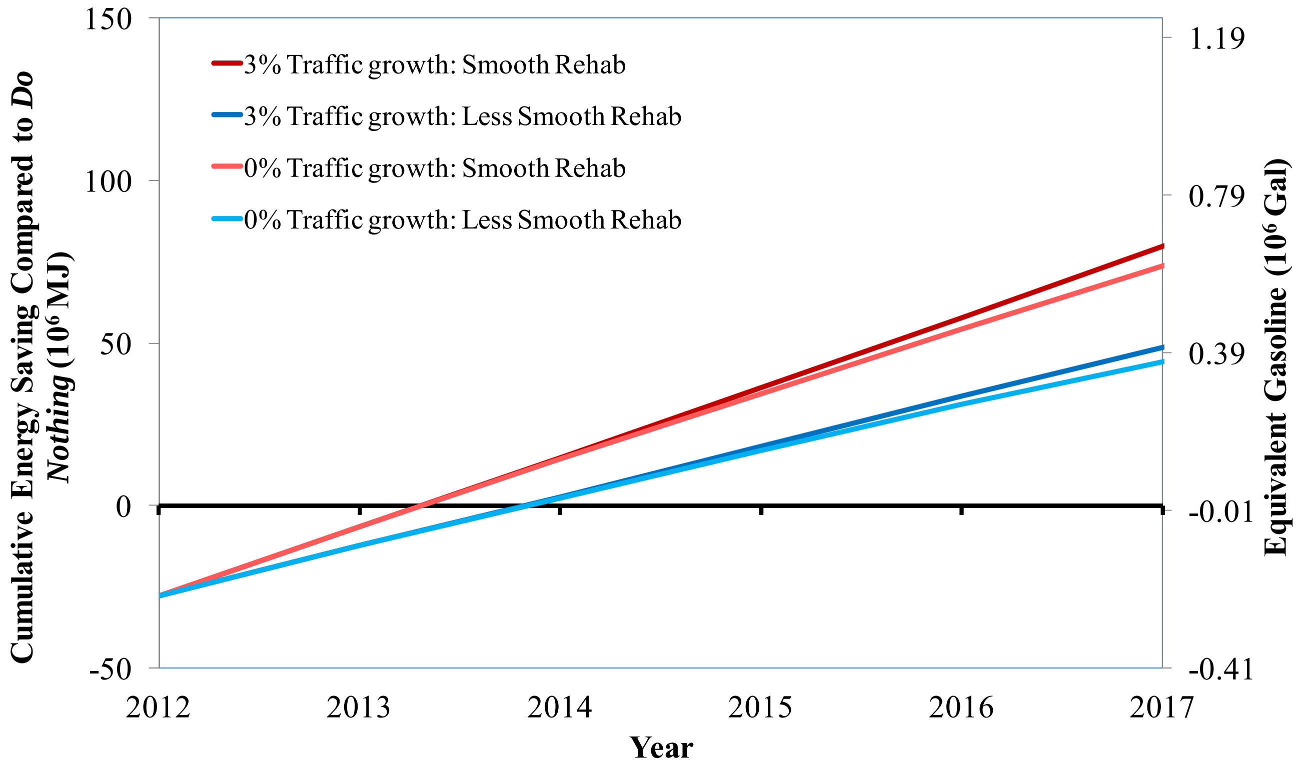

Figure B.1: Cumulative energy saving compared to *Do Nothing* with HMA overlay in KER-5.

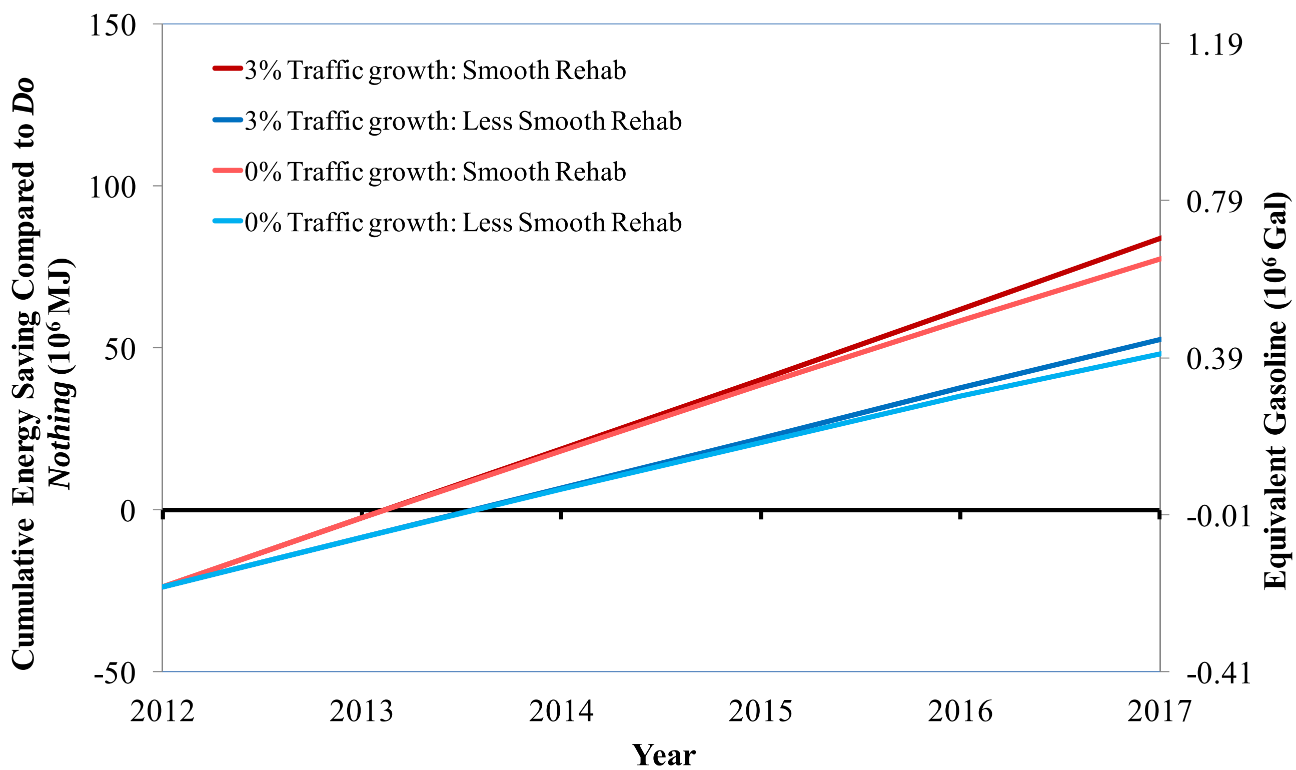

Figure B.2: Cumulative energy saving compared to *Do Nothing* with RHMA overlay in KER-5.

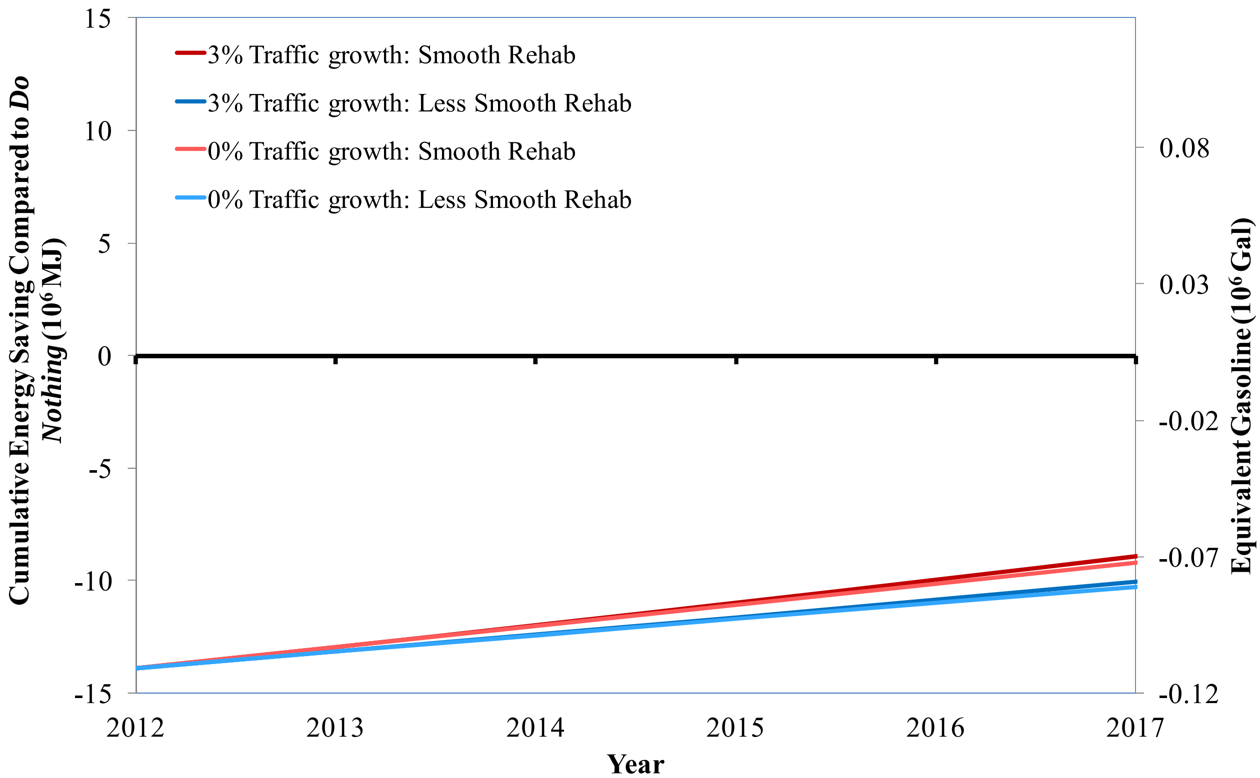

Figure B.3: Cumulative energy saving compared to *Do Nothing* with HMA overlay in BUT-70.

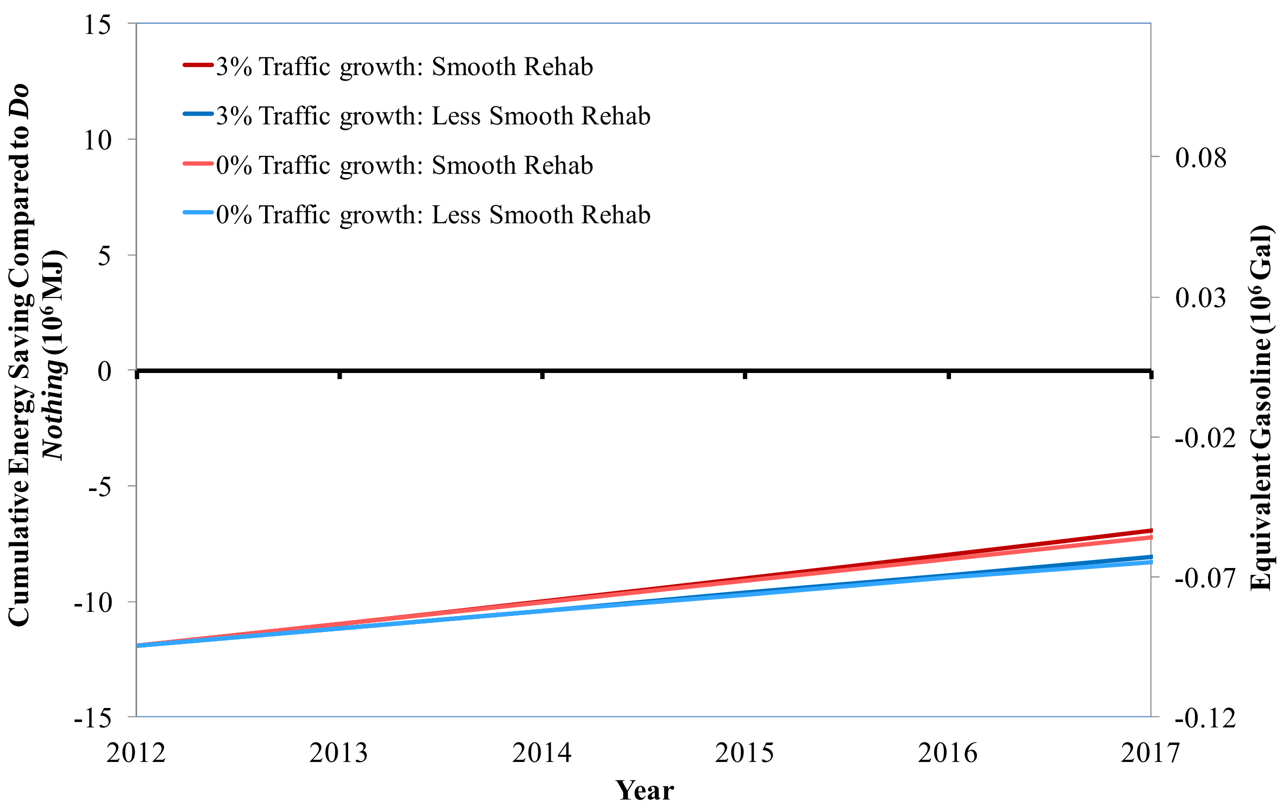

Figure B.4: Cumulative energy saving compared to *Do Nothing* with RHMA overlay in BUT-70.

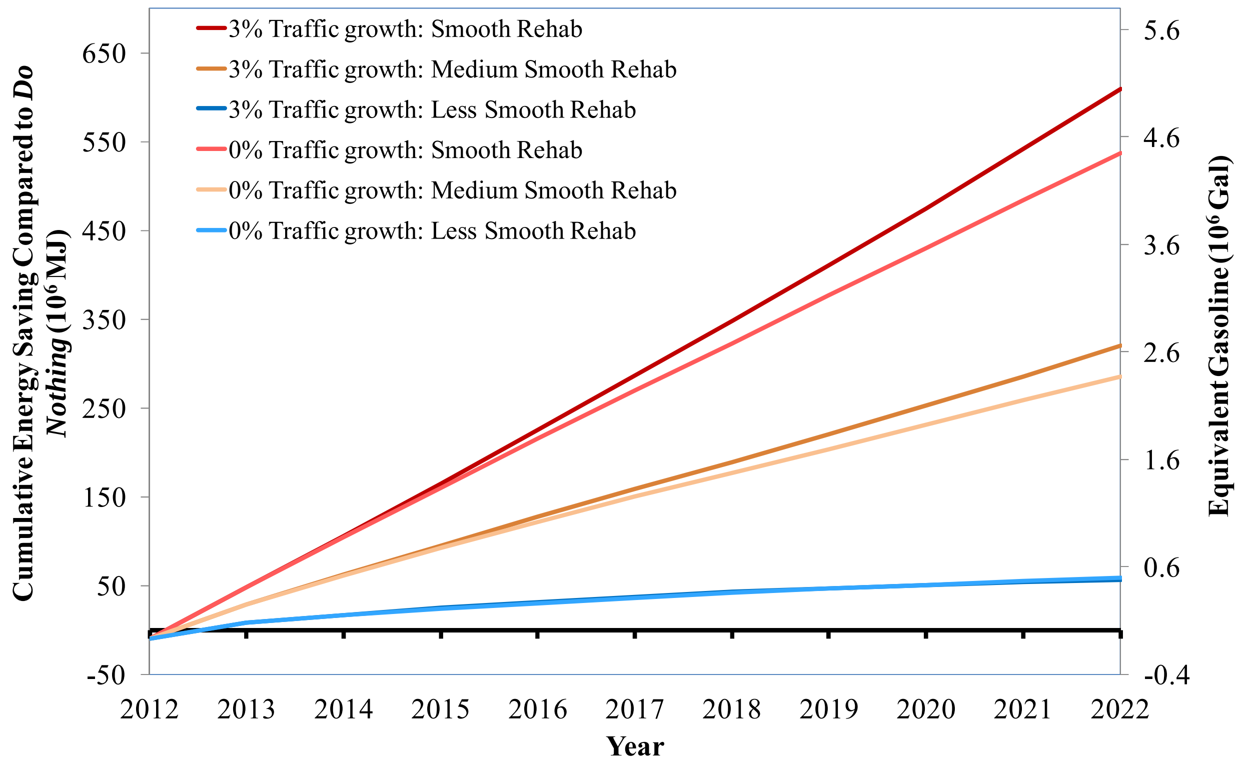

Figure B.5: Cumulative energy saving compared to *Do Nothing* with Type III cement in LA-5.

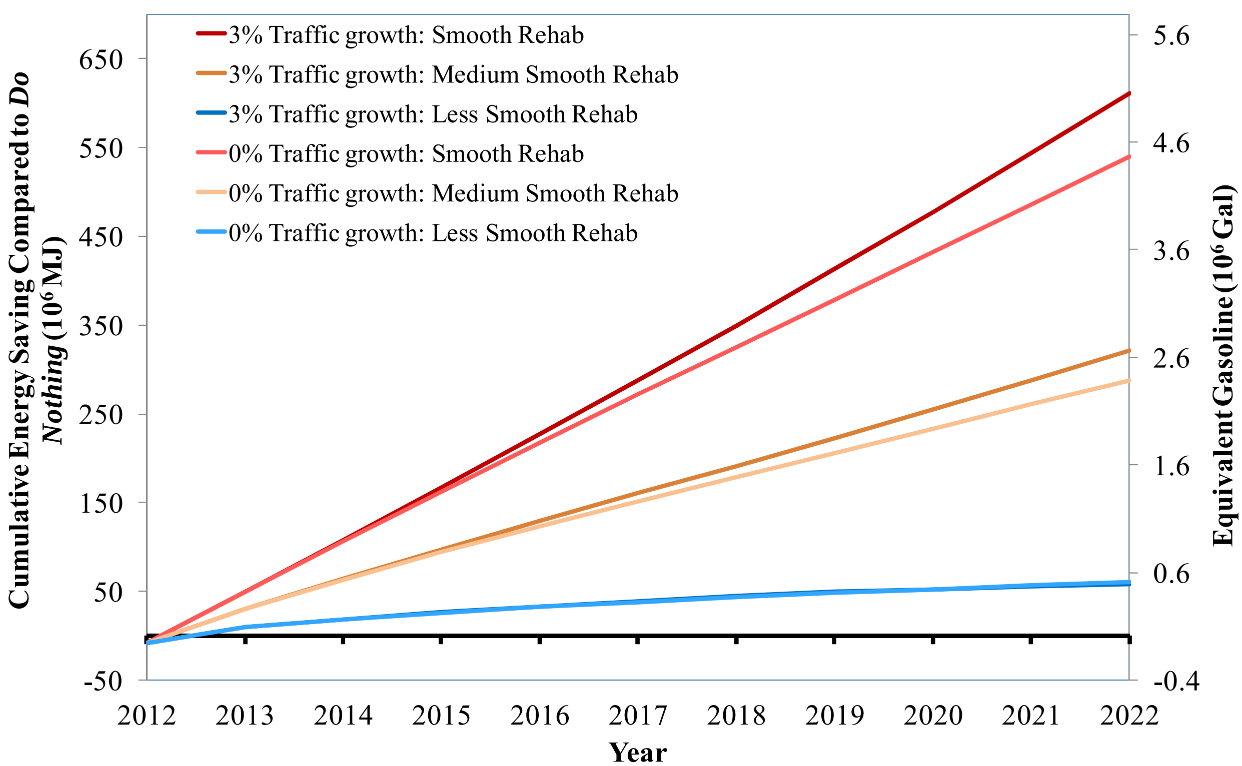

Figure B.6: Cumulative energy saving compared to *Do Nothing* with CSA cement in LA-5.

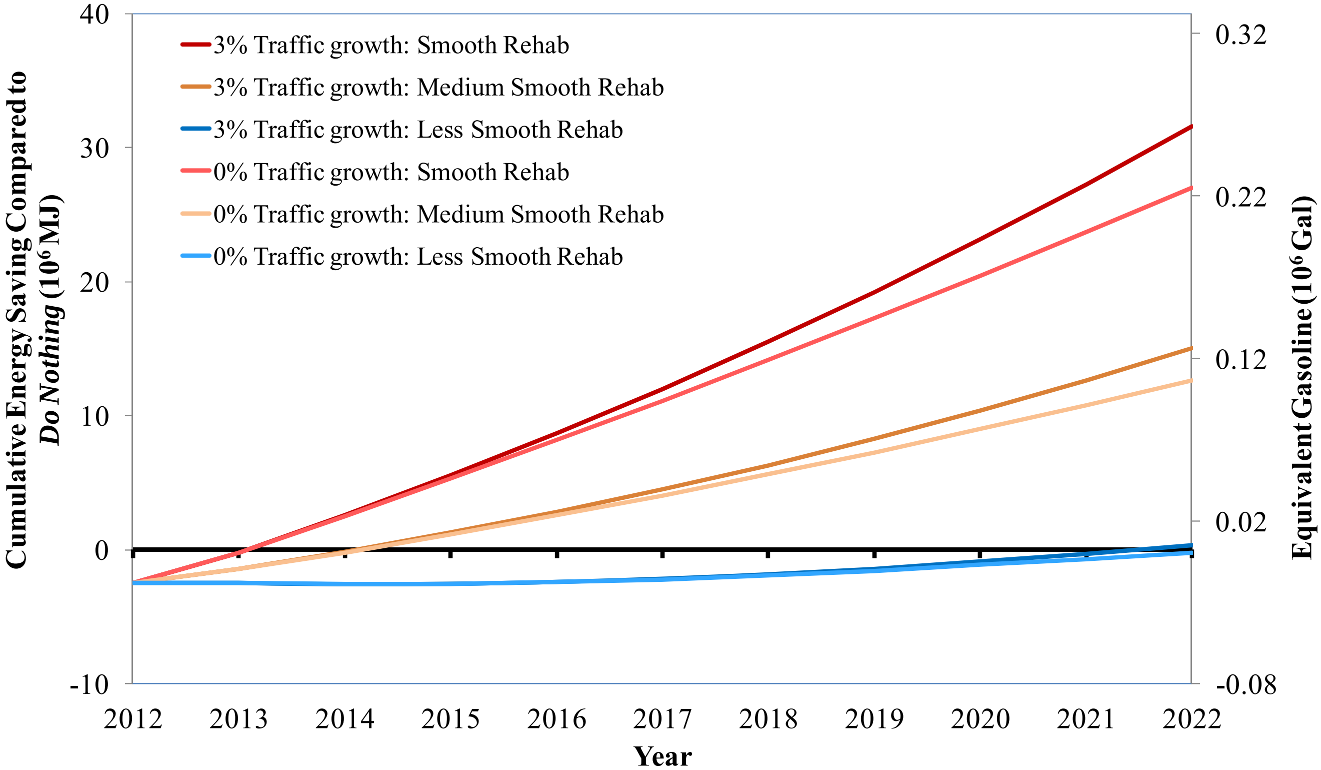

Figure B.7: Cumulative energy saving compared to *Do Nothing* with Type III cement overlay in IMP-86.

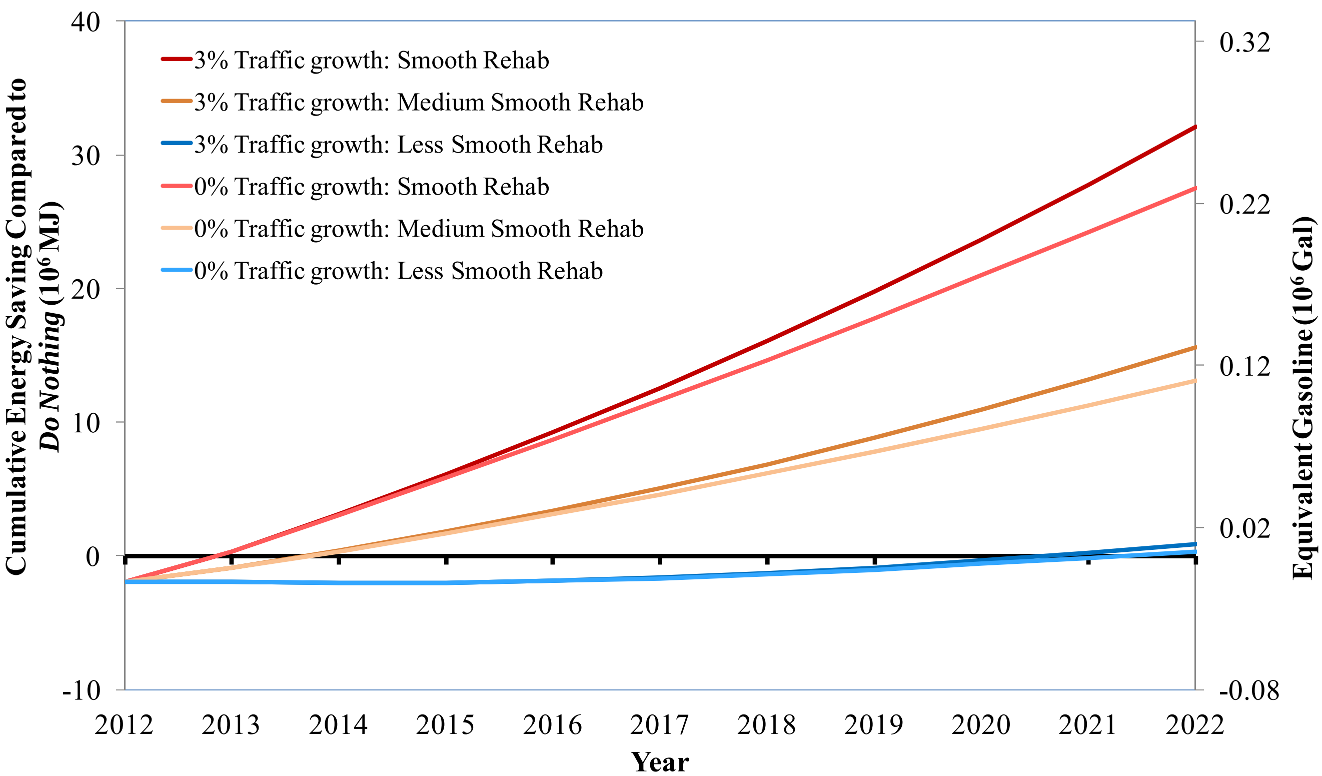

Figure B.8: Cumulative energy saving compared to *Do Nothing* with CSA cement in IMP-86.

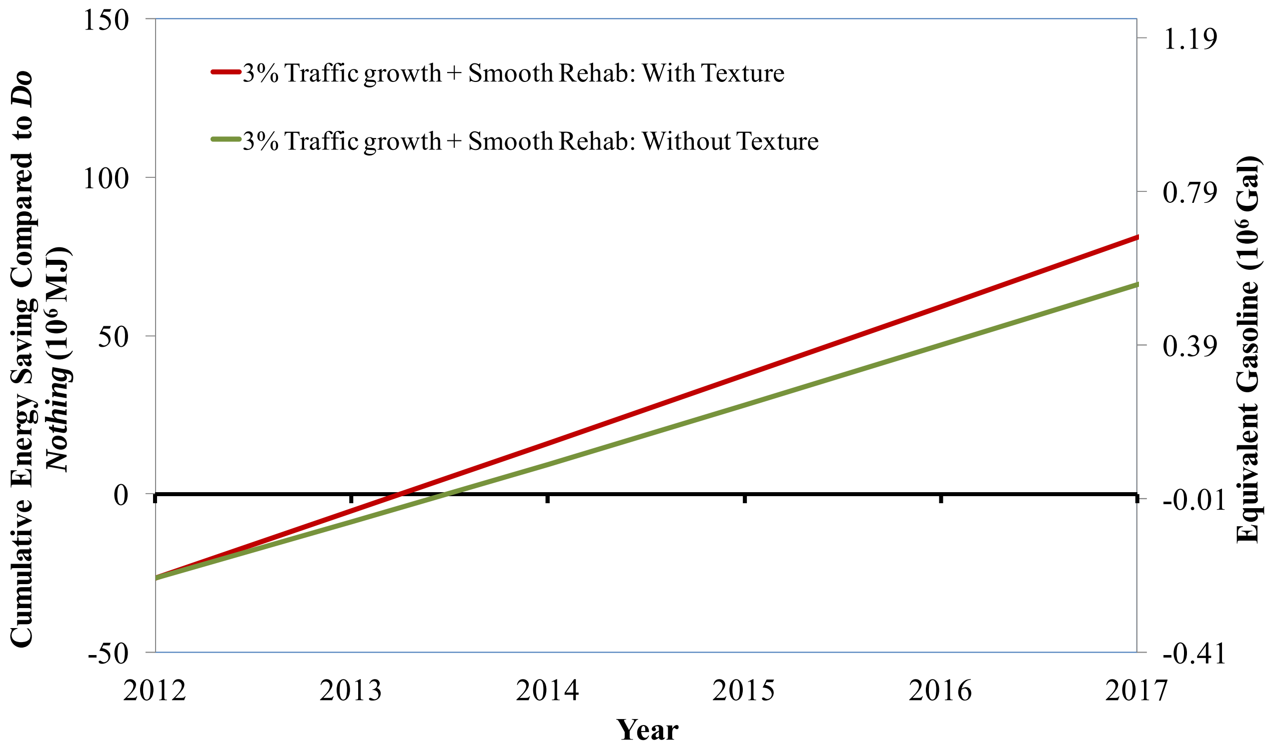

Figure B.9: Sensitivity of payback analysis with and without macrotexture of cumulative energy saving compared to *Do Nothing* with HMA overlay in KER-5.

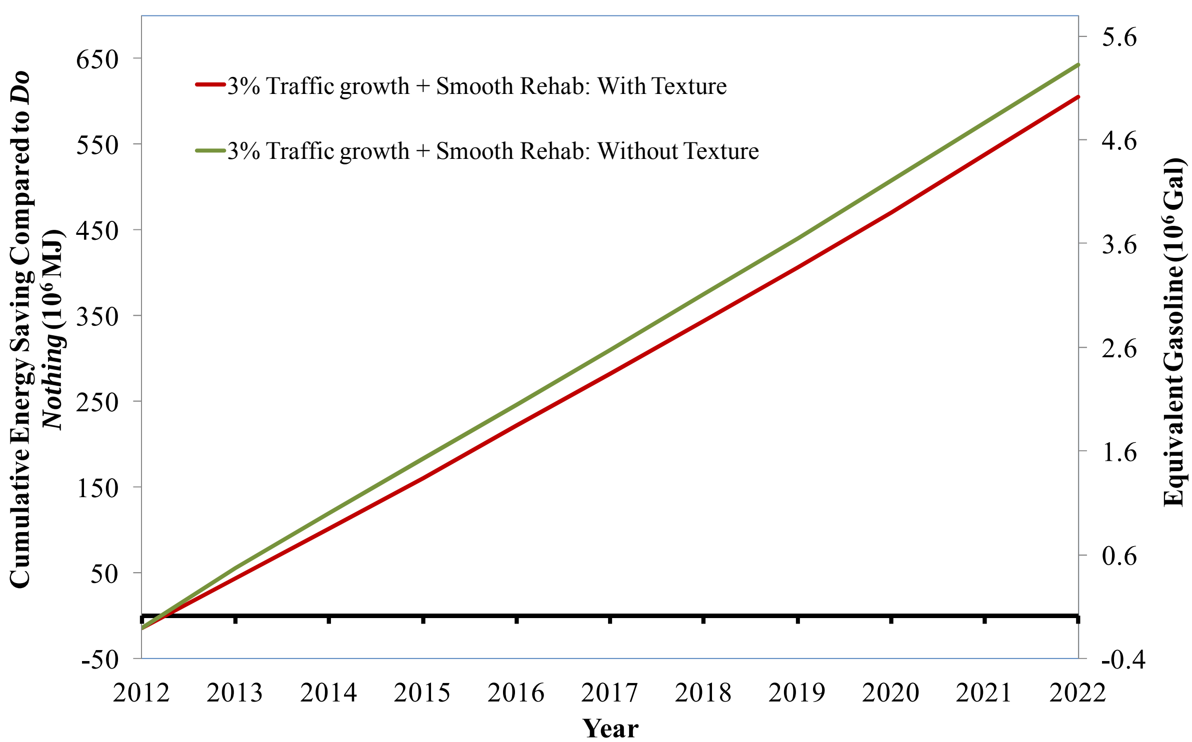

Figure B.10: Sensitivity of payback analysis with and without macrotexture of cumulative energy saving compared to *Do Nothing* with Type III cement in LA-5.

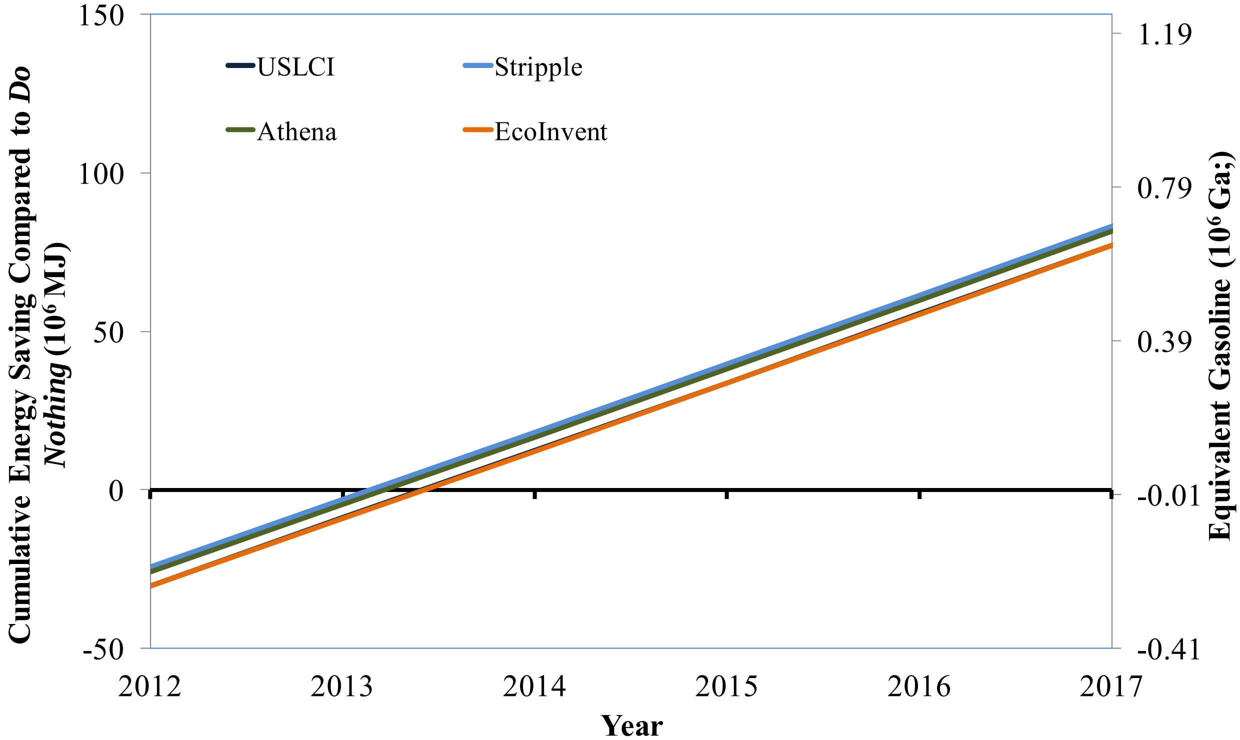

Figure B.11: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with HMA overlay using *Smooth Rehab* under 3% traffic growth rate in KER-5.

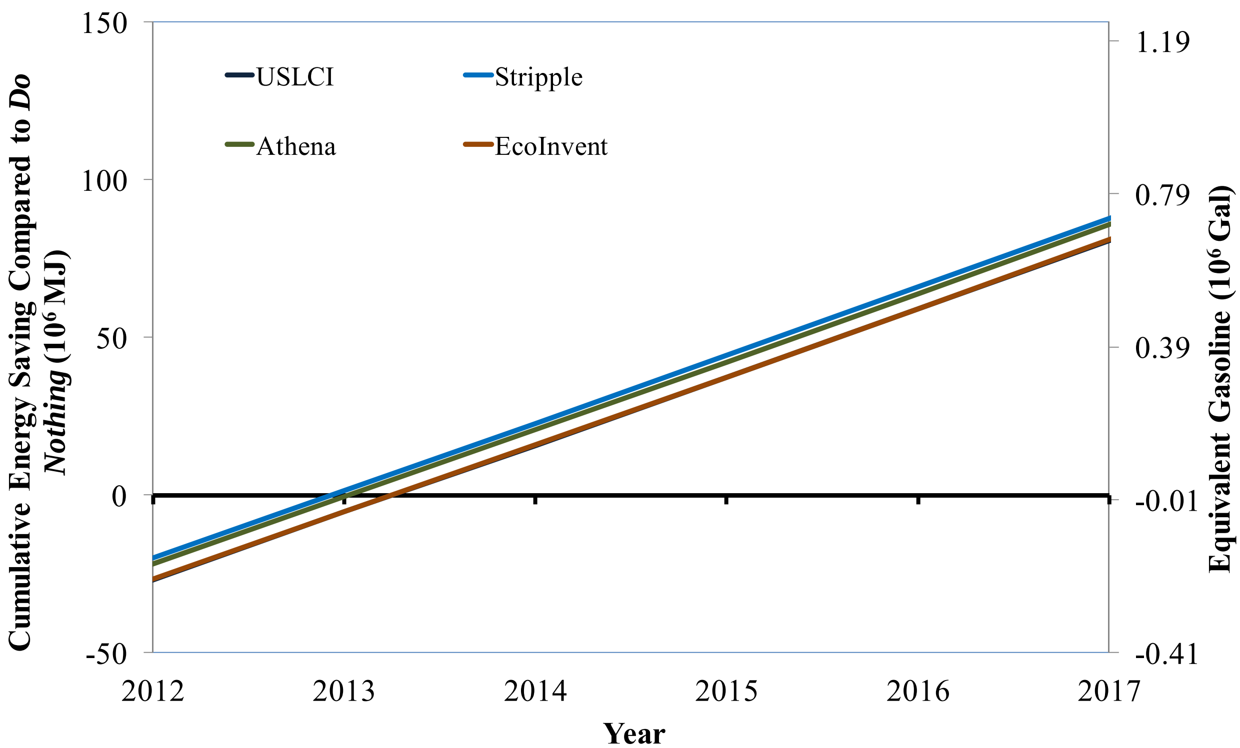

Figure B.12: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with RHMA overlay using *Smooth Rehab* under 3% traffic growth rate in KER-5.

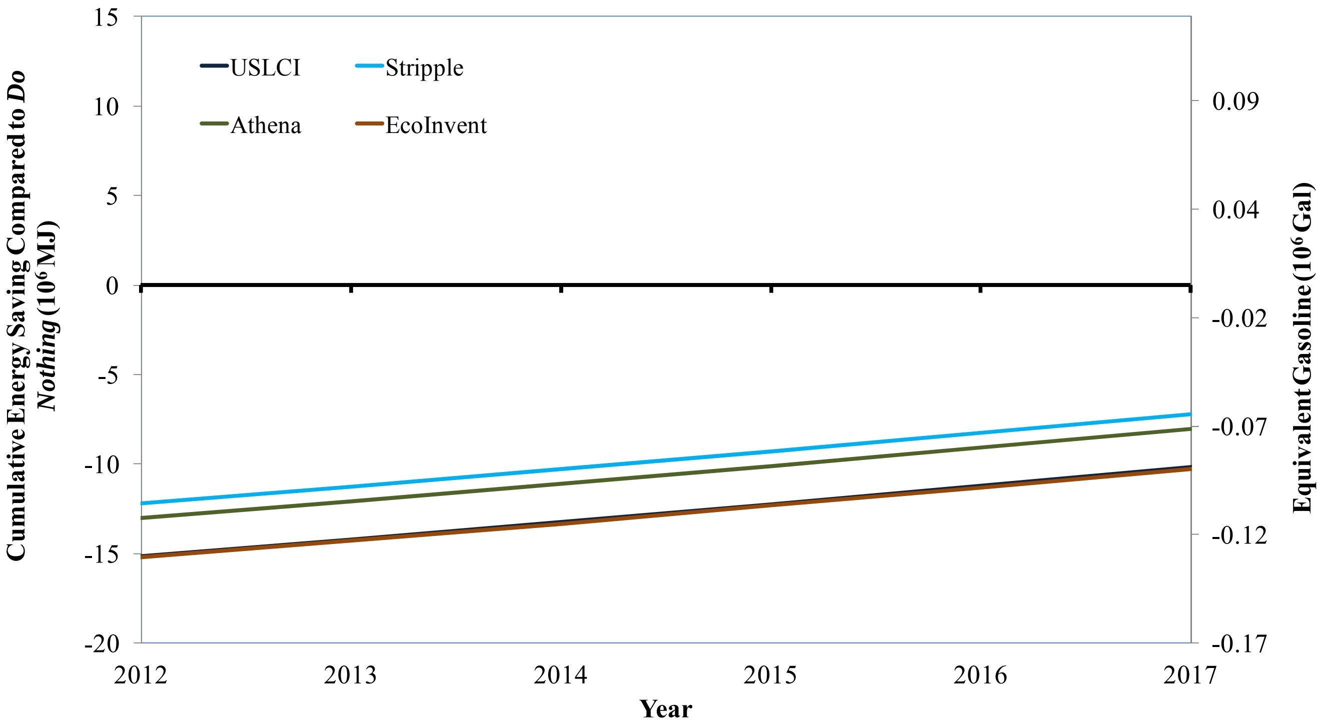

Figure B.13: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with HMA overlay using *Smooth Rehab* under 3% traffic growth rate in BUT-70.

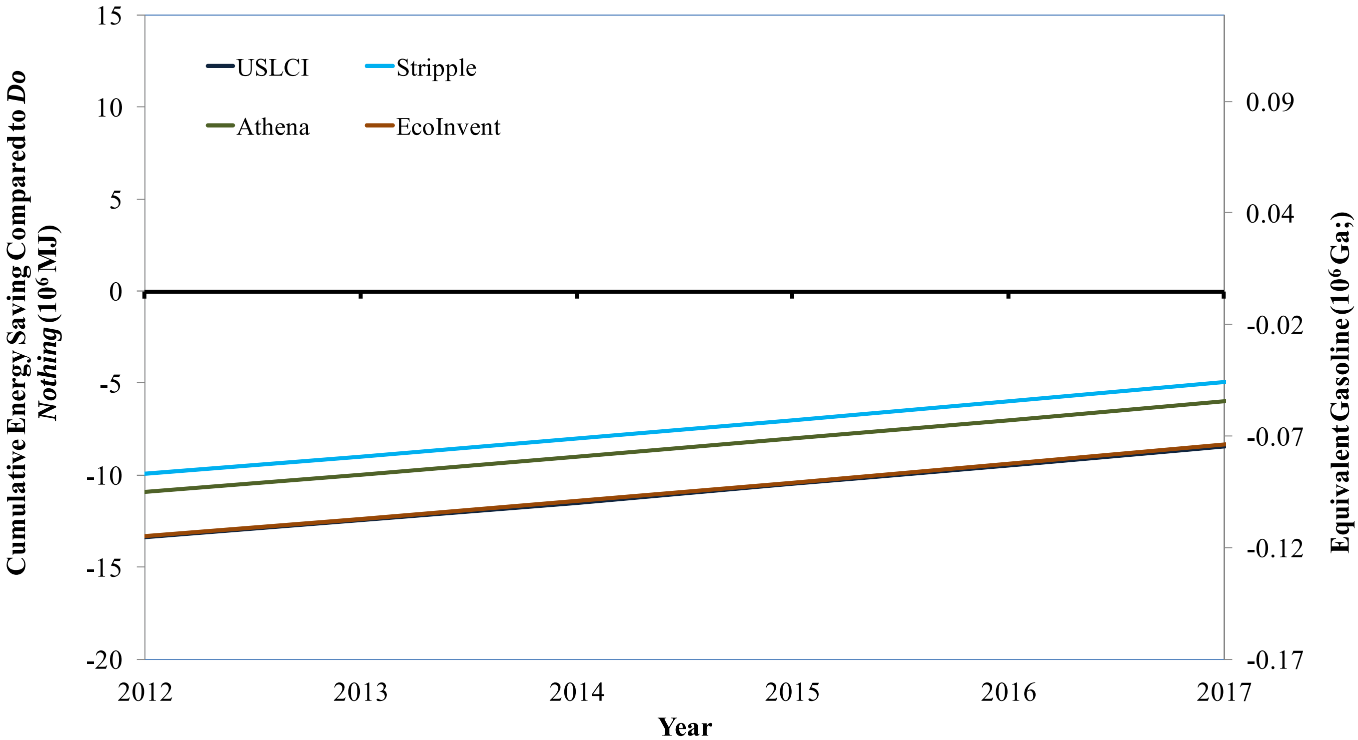

Figure B.14: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with RHMA overlay using *Smooth Rehab* under 3% traffic growth rate in BUT-70.

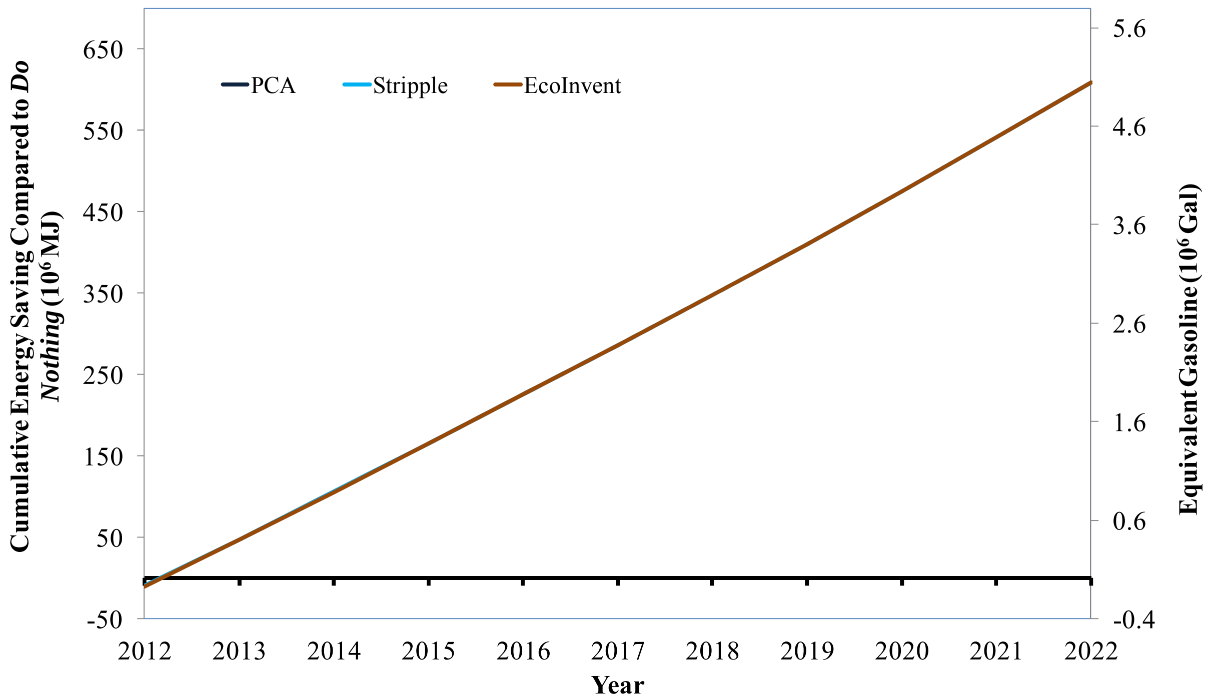

Figure B.15: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with Type III cement using *Smooth Rehab* under 3% traffic growth rate in LA-5.

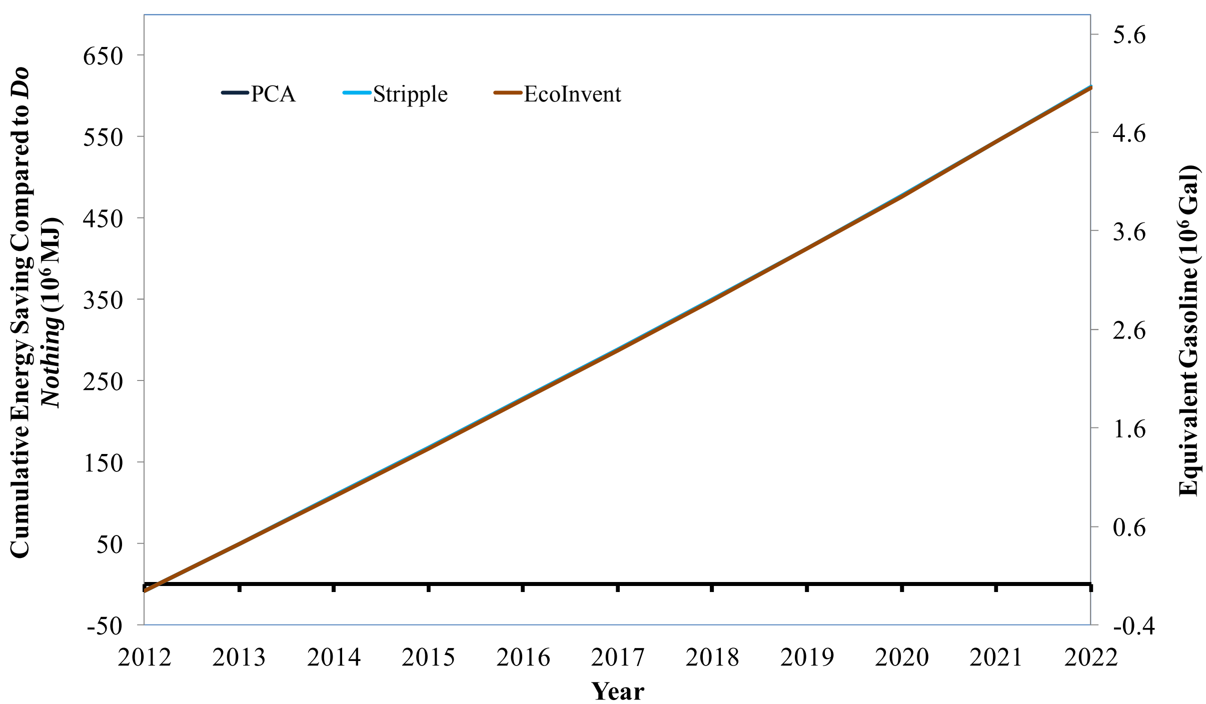

Figure B.16: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with CSA cement overlay using *Smooth Rehab* under 3% traffic growth rate in LA-5.

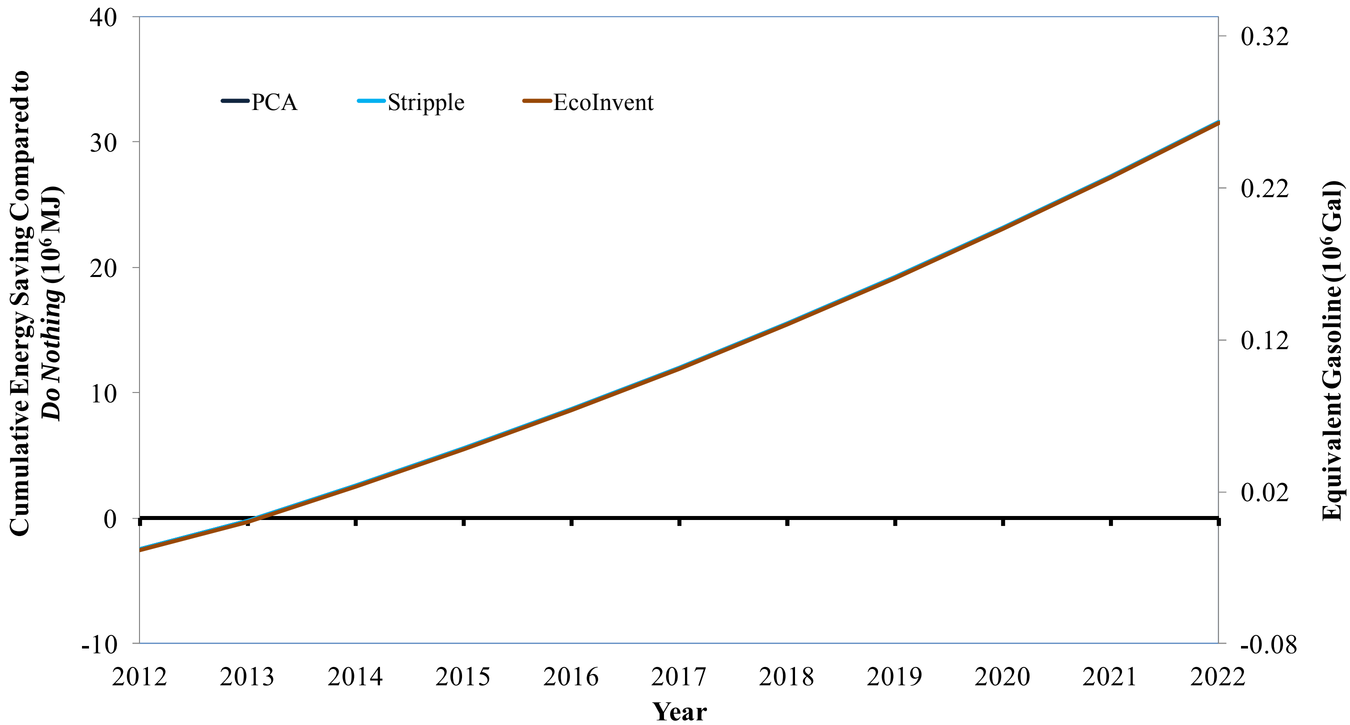

Figure B.17: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with Type III cement using Smooth Rehab under 3% traffic growth rate in IMP-86.

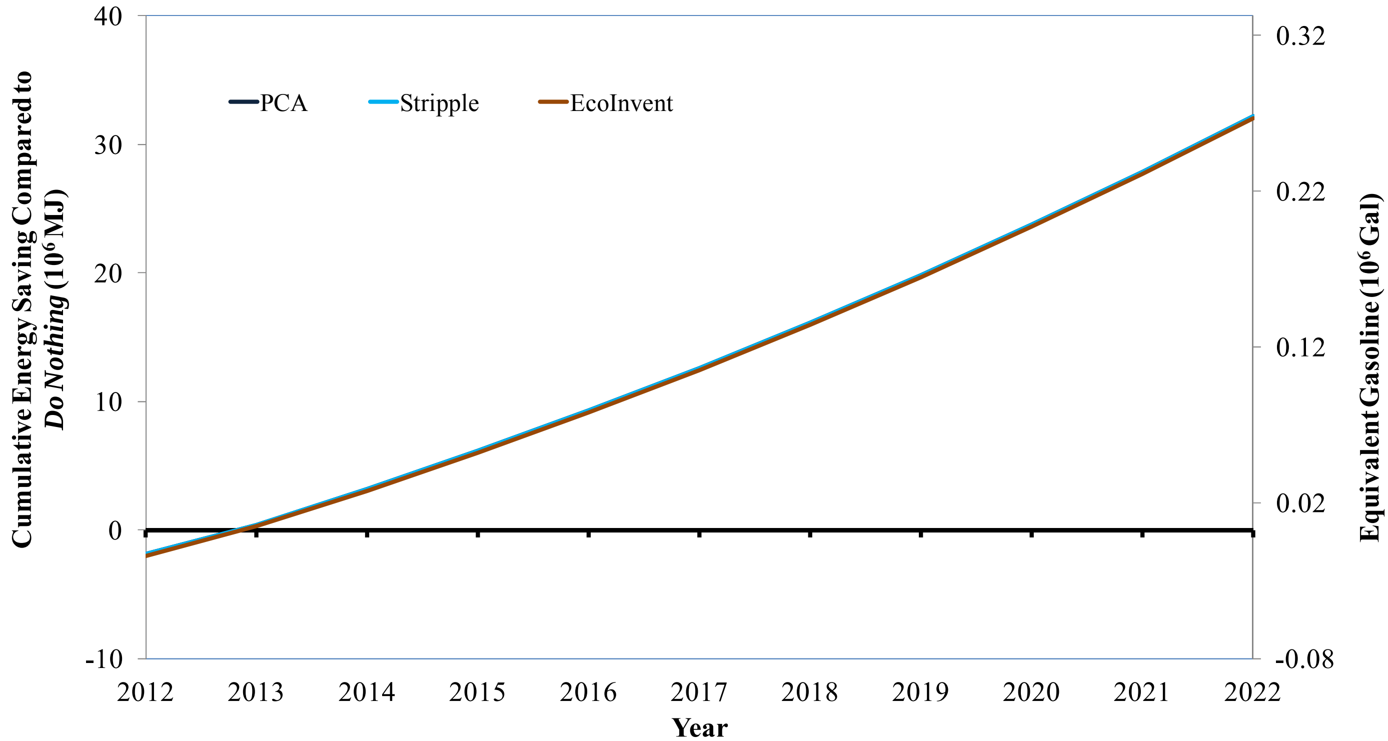

Figure B.18: Sensitivity analysis for data source of cumulative energy saving compared to *Do Nothing* with CSA cement overlay using *Smooth Rehab* under 3% traffic growth rate in IMP-86.

APPENDIX C: ENERGY CONSUMPTION AND GHG EMISSIONS IN THE MATERIAL PRODUCTION AND CONSTRUCTION PHASES FOR BUT-70 AND IMP-86

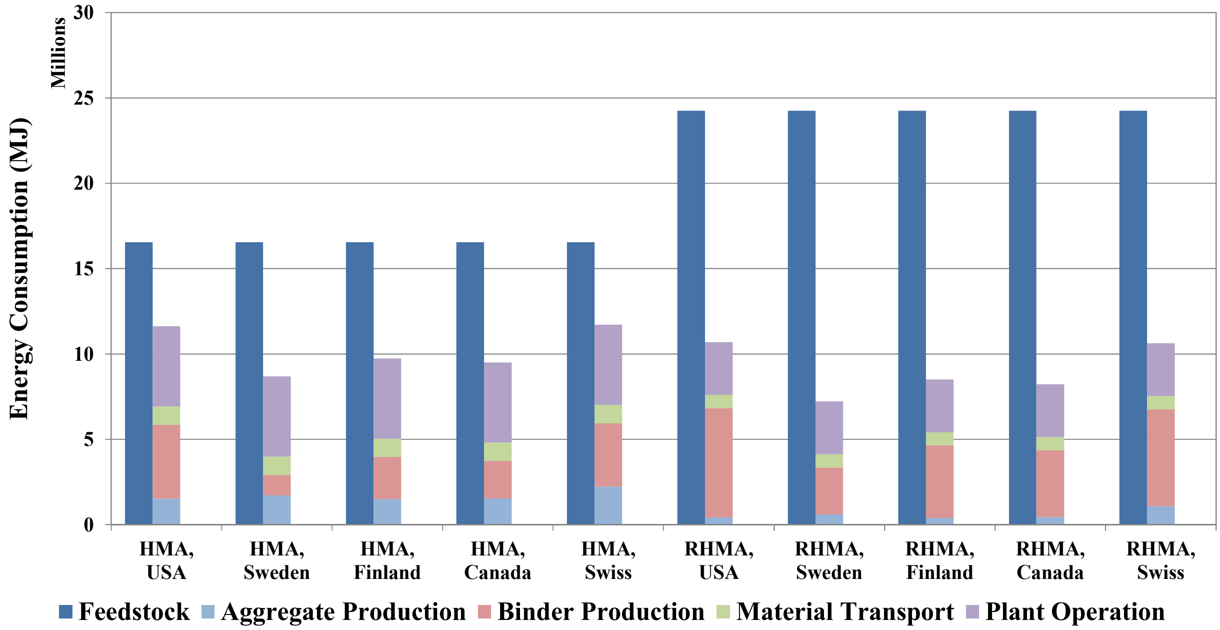

Figure C.1: BUT-70 Material Production Phase: energy consumption for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

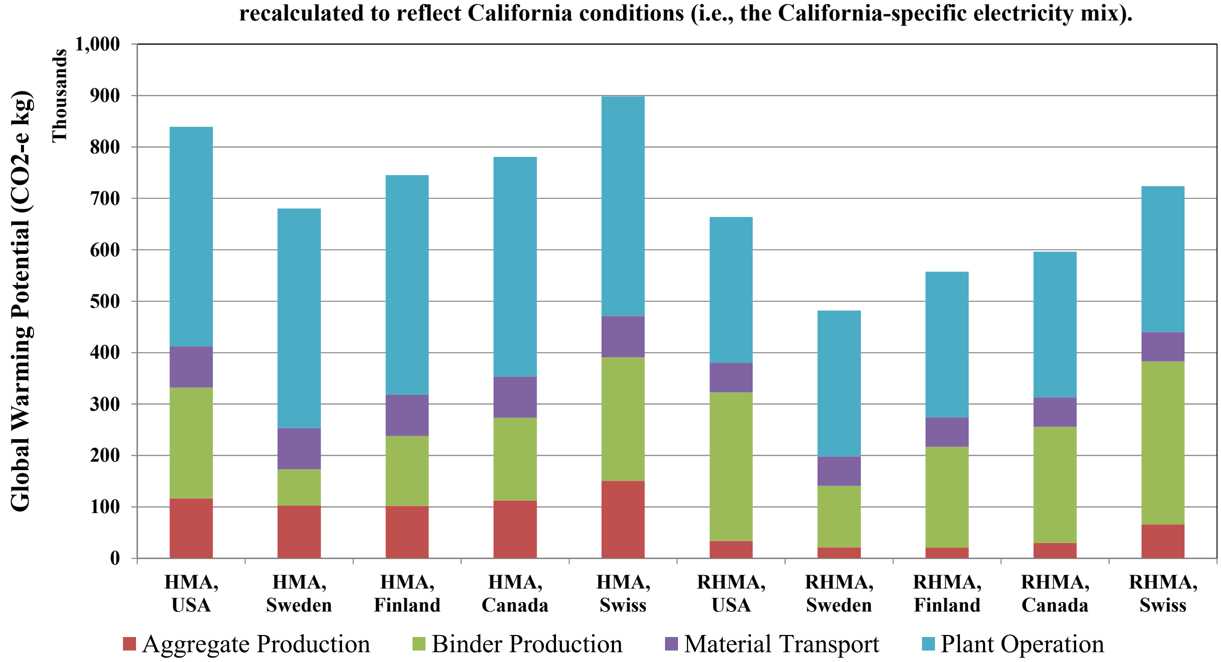

Figure C.2: BUT-70 Material Production Phase: GHG emissions for the functional unit (metric tons).
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

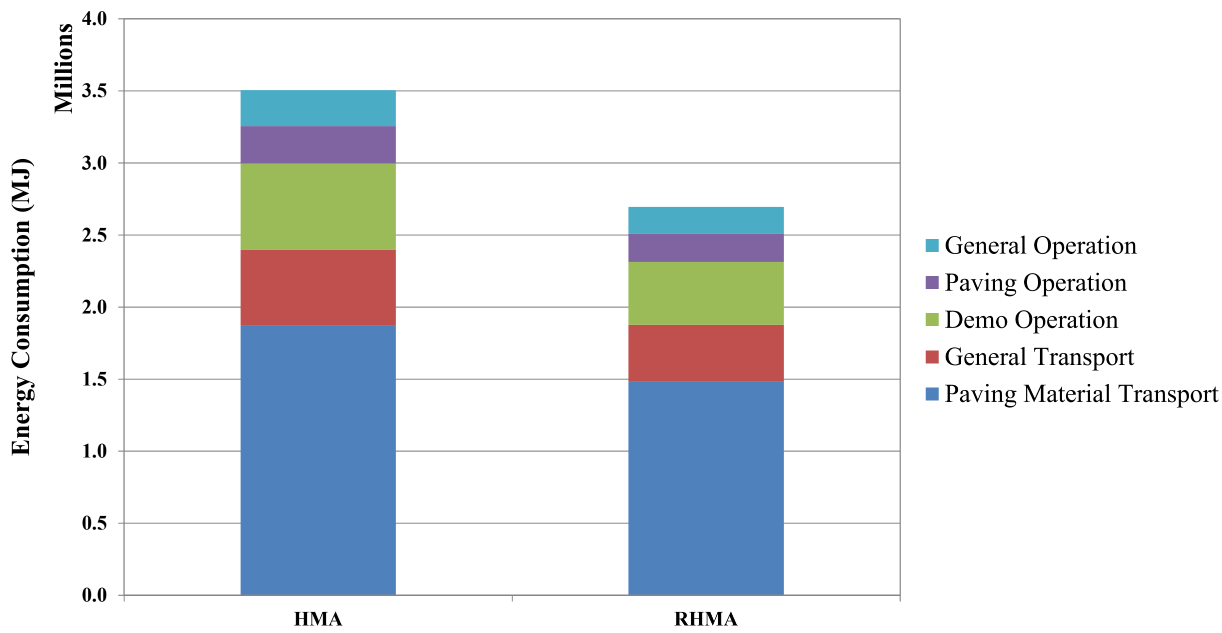

Figure C.3: BUT-70 Construction Phase: energy consumption for the functional unit.

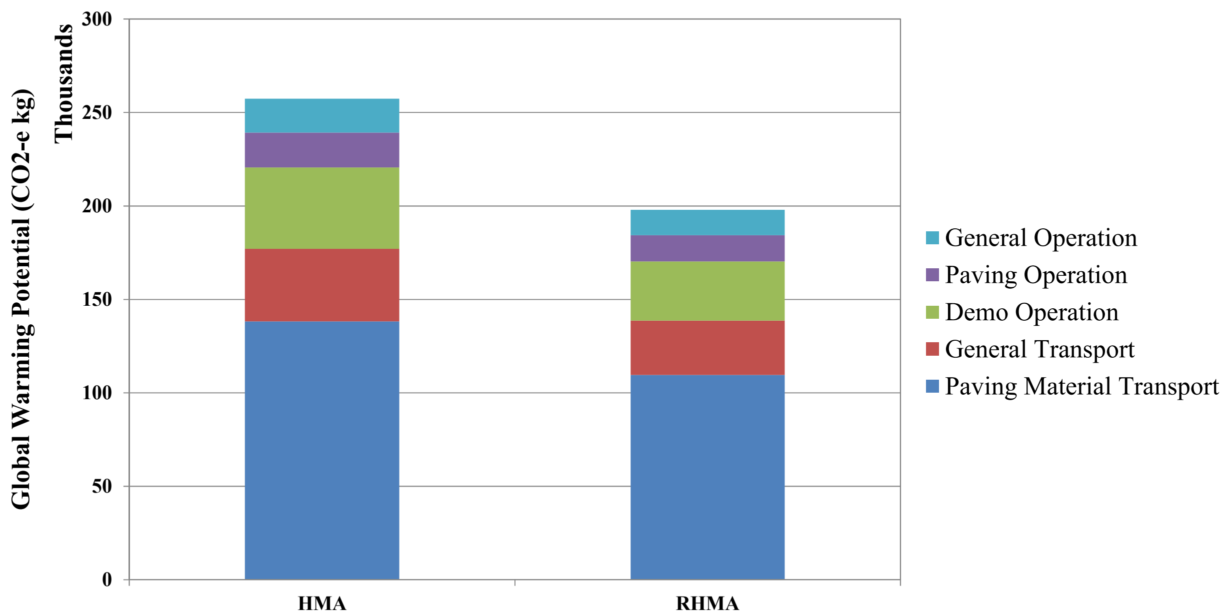

Figure C.4: BUT-70 Construction Phase: GHG emissions for the functional unit (metric tons).

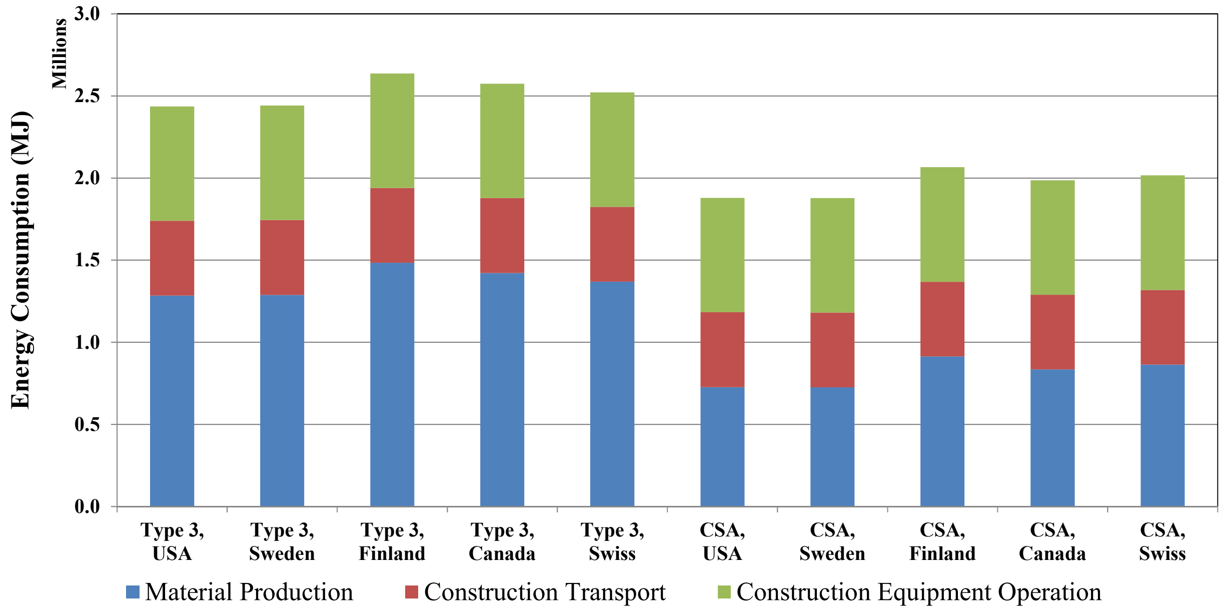

Figure C.5: IMP-86 Material Production Phase and Construction Phase: energy consumption for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

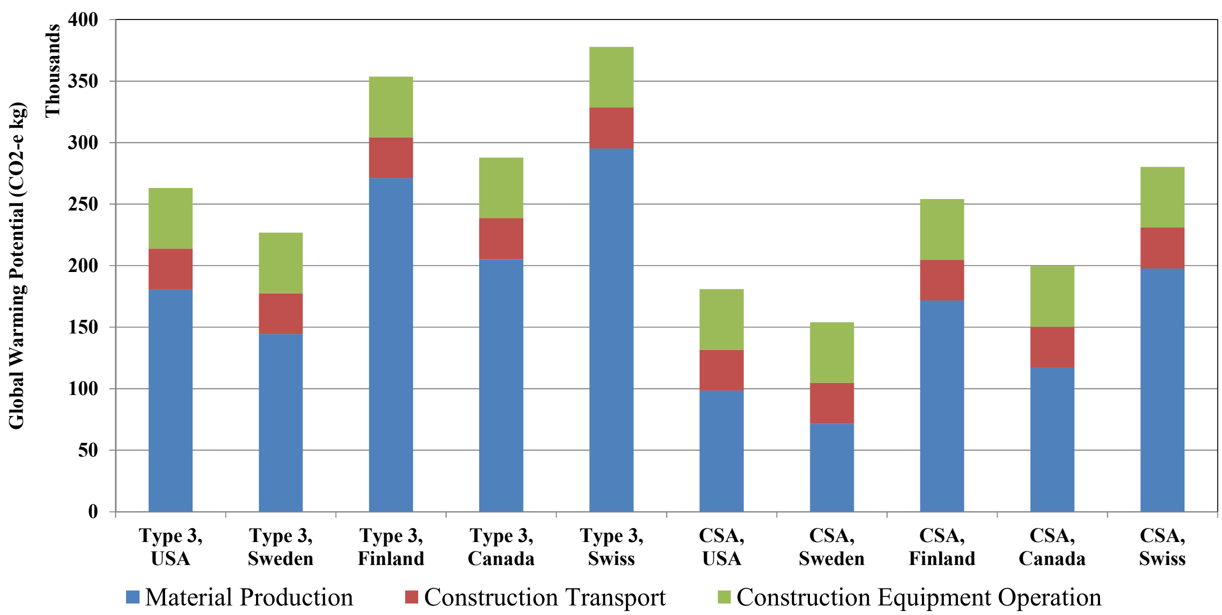

Figure C.6: LA-5 Material Production Phase and Construction Phase: GHG emissions for the functional unit (metric tons).
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

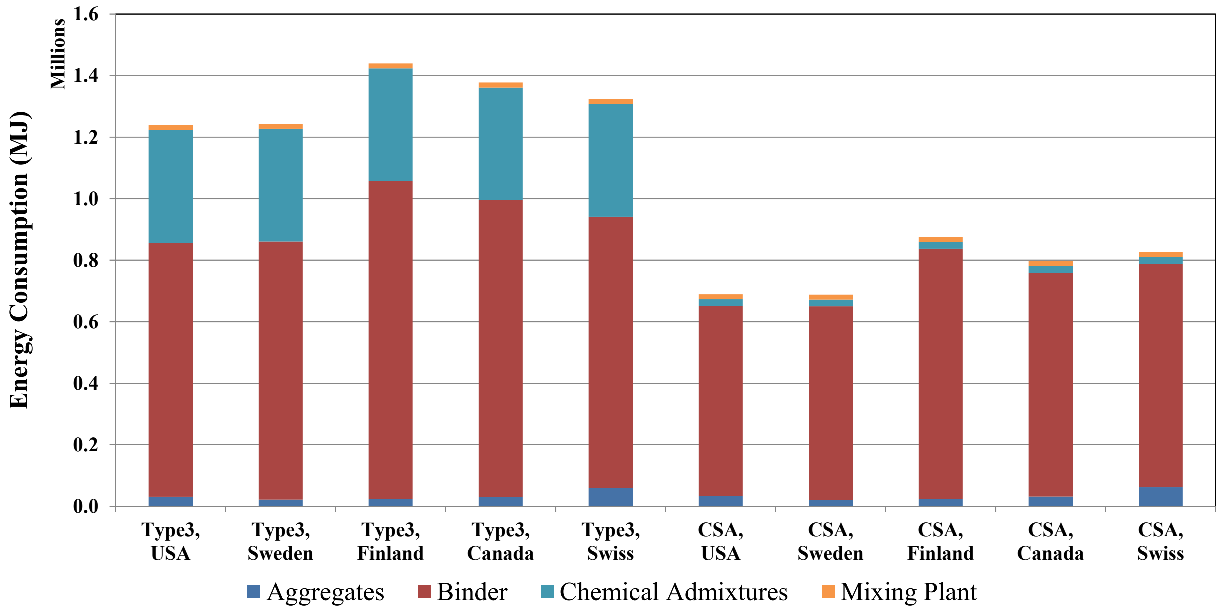

Figure C.7: IMP-86 details of Material Production Phase: energy consumption for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

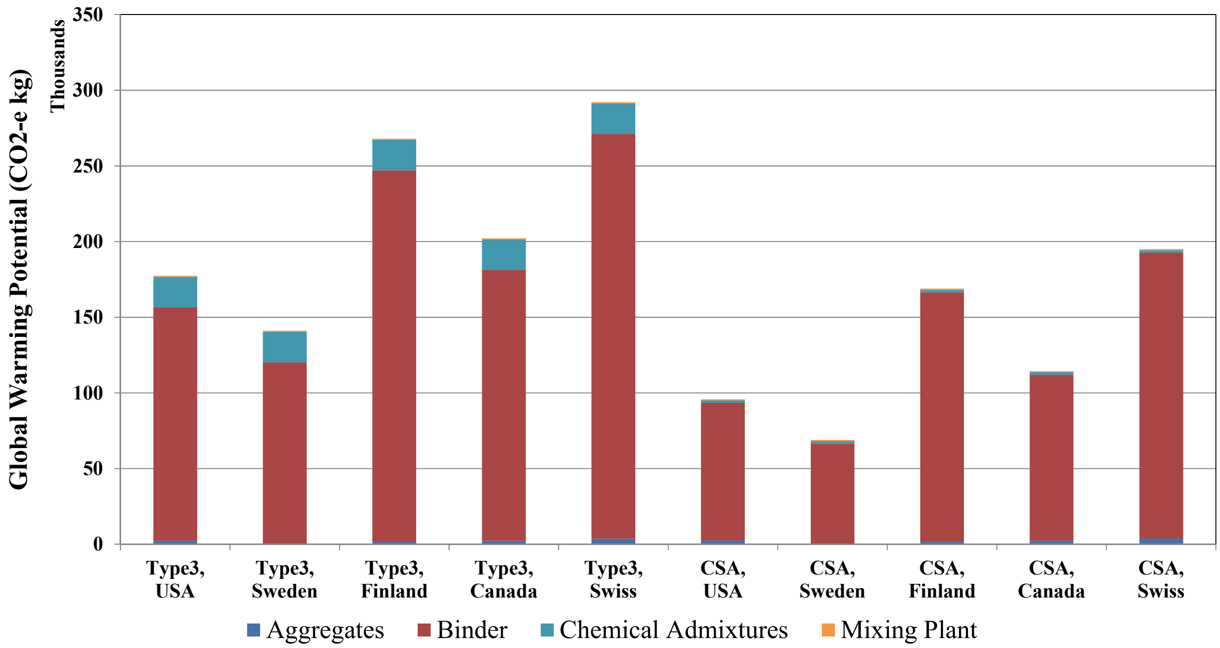

Figure C.8: IMP-86 details of Material Production Phase: GHG emissions (metric tons) for the functional unit.
Note: These are based on LCIs from five different regions. However, each LCI was updated and recalculated to reflect California conditions (i.e., the California-specific electricity mix).

APPENDIX D: LCI DATA TABLES FOR ALL FOUR CASE STUDIES

Table D.1: Primary Energy Consumption per Mass of Each Material or Process (MJ/kg)

Material \ Source	Stripple	Athena	EcoInvent	USLCI	PCA	Other
Crushed aggregate	0.0786	0.0576	0.14	0.056		
Natural aggregate	0.00767	0.0360	0.059	0.0397		
Asphalt: Feedstock	40.2	40.2	40.2	40.2		
Asphalt: Manufacturing	2.89	5.32	9.0	10.5		
Crumb rubber modifier: Feedstock						34.9
Crumb rubber modifier: Manufacturing						4.27
Extended oil: Feedstock			41.5			
Extended oil: Manufacturing			54.1			
Asphalt mixing plant: Hot mix asphalt (with reclaimed asphalt pavement)[1]	0.551	0.531				
Asphalt mixing plant: Rubberized hot mix asphalt[1]	0.404	0.375				
Type I cement	4.34	4.97	4.48		4.25	
Type III cement (high early strength portland cement)	4.38	5.04	4.60		4.31	
Calcium sulpho-aluminate cement	4.00	4.62	4.62		3.93	
Accelerator						23
Retarder						16
Superplasticizers (high range water reducer)						18
Dowel bar						10
Concrete mixing plant[2]			220		41	

Notes:
1: Athena data is used for this process because it represents North American conditions.
2: PCA data is used for this process because it presents U.S. conditions.

Table D.2: Material Production GHG and Energy from Different Data Sources in KER-5

		US LCI	Athena	Stripple	Ecoinvent
HMA	Energy (MJ)	2.3E7	1.9E7	1.7E7	2.3E7
	GWP (metric ton CO_2-e)	1678.7	1561.4	1360.6	1796.5
RHMA	Energy (MJ)	2.1E7	1.6E7	1.4E7	2.1E7
	GWP (metric ton CO_2-e)	1,327	1,193	963	1,447

Table D.3: Material Production GHG and Energy from Different Data Sources in BUT-70

		US LCI	Athena	Stripple	Ecoinvent
HMA	Energy (MJ)	1.16E7	9.51E6	8.68E6	1.17E7
	GWP (metric ton CO_2-e)	839	791	680	898
RHMA	Energy (MJ)	1.1E7	8.2E6	7.2E6	1.1E7
	GWP (metric ton CO_2-e)	664	596	482	724

Table D.4: Material Production GHG and Energy from Different Data Sources in LA-5

		PCA	Stripple	EcoInvent
Type III	Energy (MJ)	5.14E6	5.16E6	5.48E6
	GWP (metric ton CO_2-e)	722	577	1,181
CSA	Energy (MJ)	2.91E6	2.90E6	3.46E6
	GWP (metric ton CO_2-e)	394	286	791

Table D.5: Material Production GHG and Energy from Different Data Sources in IMP-86

		PCA	Stripple	EcoInvent
Type III	Energy (MJ)	1.28E6	1.29E6	1.37E6
	GWP (metric ton CO_2-e)	181	144	295
CSA	Energy (MJ)	7.27E5	7.26E5	8.64E5
	GWP (metric ton CO_2-e)	98	72	198

APPENDIX E: DETAILS OF LCIS FOR CASE STUDIES

Table E.1: Table related to Figure 7.7: KER-5 Material Production Phase: Energy Consumption for the Functional Unit

	HMA, USA	HMA, Sweden	HMA, Finland	HMA, Canada	HMA, Swiss	RHMA, USA	RHMA, Sweden	RHMA, Finland	RHMA, Canada	RHMA, Swiss
Feedstock	3.31E+07	3.31E+07	3.31E+07	3.31E+07	3.31E+07	4.85E+07	4.85E+07	4.85E+07	4.85E+07	4.85E+07
Aggregate Production	3.06E+06	3.44E+06	2.99E+06	3.09E+06	4.47E+06	8.56E+05	1.20E+06	7.94E+05	8.80E+05	2.15E+06
Binder Production	8.65E+06	2.38E+06	4.94E+06	4.38E+06	7.41E+06	1.28E+07	5.51E+06	8.49E+06	7.83E+06	1.14E+07
Material Transport	2.16E+06	2.16E+06	2.16E+06	2.16E+06	2.16E+06	1.55E+06	1.55E+06	1.55E+06	1.55E+06	1.55E+06
Plant Operation	9.39E+06	9.39E+06	9.39E+06	9.39E+06	9.39E+06	6.19E+06	6.19E+06	6.19E+06	6.19E+06	6.19E+06

Table E.2: Table Related to Figure 7.8: KER-5 Material Production Phase: GHG Emissions for the Functional Unit (metric tons)

	HMA, USA	HMA, Sweden	HMA, Finland	HMA, Canada	HMA, Swiss	RHMA, USA	RHMA, Sweden	RHMA, Finland	RHMA, Canada	RHMA, Swiss
Feedstock	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aggregate Production	2.33E+05	2.05E+05	2.04E+05	2.25E+05	3.02E+05	6.81E+04	4.27E+04	4.13E+04	6.03E+04	1.31E+05
Binder Production	4.31E+05	1.41E+05	2.72E+05	3.22E+05	4.80E+05	5.78E+05	2.39E+05	3.92E+05	4.51E+05	6.35E+05
Material Transport	1.61E+05	1.61E+05	1.61E+05	1.61E+05	1.61E+05	1.15E+05	1.15E+05	1.15E+05	1.15E+05	1.15E+05
Plant Operation	8.54E+05	8.54E+05	8.54E+05	8.54E+05	8.54E+05	5.66E+05	5.66E+05	5.66E+05	5.66E+05	5.66E+05

Table E.3: Table Related to Figure 7.9: Construction Phase: Energy Consumption for the Functional Unit

	HMA	RHMA
Paving Material Transport	3.74E+06	2.97E+06
General Transport	1.05E+06	7.87E+05
Demo Operation	1.20E+06	8.73E+05
Paving Operation	5.18E+05	3.88E+05
General Operation	5.00E+05	3.75E+05

Table E.4: Table Related to Figure 7.10: KER-5 Construction Phase: GHG Emissions (metric tons)

	HMA	RHMA
Paving Material Transport	2.77E+05	2.19E+05
General Transport	7.76E+04	5.82E+04
Demo Operation	8.71E+04	6.33E+04
Paving Operation	3.74E+04	2.80E+04
General Operation	3.62E+04	2.71E+04

Table E.5: Table Related to Figure 7.11: LA-5 Material Production Phase and Construction Phase: Energy Consumption for the Functional Unit

	Type 3, USA	Type 3, Sweden	Type 3, Finland	Type 3, Canada	Type 3, Swiss	CSA, USA	CSA, Sweden	CSA, Finland	CSA, Canada	CSA, Swiss
Material Production	5.14E+06	5.16E+06	5.94E+06	5.69E+06	5.48E+06	2.91E+06	2.90E+06	3.65E+06	3.34E+06	3.46E+06
Construction Transport	1.82E+06	1.82E+06	1.82E+06	1.82E+06	1.82E+06	1.82E+06	1.82E+06	1.82E+06	1.82E+06	1.82E+06
Construction Equipment Operation	2.79E+06	2.79E+06	2.79E+06	2.79E+06	2.79E+06	2.79E+06	2.79E+06	2.79E+06	2.79E+06	2.79E+06

Table E.6: Table Related to Figure 7.12: LA-5 Material Production Phase and Construction Phase: GHG emissions (metric tons) for the Functional Unit

	Type 3, USA	Type 3, Sweden	Type 3, Finland	Type 3, Canada	Type 3, Swiss	CSA, USA	CSA, Sweden	CSA, Finland	CSA, Canada	CSA, Swiss
Material Production	7.22E+05	5.77E+05	1.08E+06	8.21E+05	1.18E+06	3.94E+05	2.86E+05	6.86E+05	4.68E+05	7.91E+05
Construction Transport	1.33E+05	1.33E+05	1.33E+05	1.33E+05	1.33E+05	1.33E+05	1.33E+05	1.33E+05	1.33E+05	1.33E+05
Construction Equipment Operation	1.97E+05	1.97E+05	1.97E+05	1.97E+05	1.97E+05	1.97E+05	1.97E+05	1.97E+05	1.97E+05	1.97E+05

TableE.7: Table Related to Figure 7.13: LA-5 Details of Material Production Phase: Energy Consumption for the Functional Unit

	Type 3, USA	Type 3, Sweden	Type 3, Finland	Type 3, Canada	Type 3, Swiss	CSA, USA	CSA, Sweden	CSA, Finland	CSA, Canada	CSA, Swiss
Aggregates	1.26E+05	8.61E+04	9.28E+04	1.21E+05	2.40E+05	1.33E+05	8.39E+04	9.60E+04	1.27E+05	2.47E+05
Binder	3.30E+06	3.36E+06	4.13E+06	3.86E+06	3.53E+06	2.47E+06	2.52E+06	3.25E+06	2.91E+06	2.91E+06
Chemical Admixtures	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	8.64E+04	8.64E+04	8.64E+04	8.64E+04	8.64E+04
Mixing Plant	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04	6.58E+04

Table E.8: Table Related to Figure 7.14: LA-5 Details of Material Production Phase: GHG Emissions for the Functional Unit (metric tons)

	Type 3, USA	Type 3, Sweden	Type 3, Finland	Type 3, Canada	Type 3, Swiss	CSA, USA	CSA, Sweden	CSA, Finland	CSA, Canada	CSA, Swiss
Aggregates	9.90E+03	3.26E+03	5.76E+03	9.17E+03	1.49E+04	1.04E+04	3.21E+03	6.05E+03	9.69E+03	1.54E+04
Binder	6.16E+05	4.77E+05	9.82E+05	7.15E+05	1.07E+06	3.63E+05	2.63E+05	6.60E+05	4.39E+05	7.55E+05
Chemical Admixtures	8.10E+04	8.10E+04	8.10E+04	8.10E+04	8.10E+04	6.56E+03	6.56E+03	6.56E+03	6.56E+03	6.56E+03
Mixing Plant	2.85E+03	2.85E+03	2.85E+03	2.85E+03	2.85E+03	2.85E+03	2.85E+03	2.85E+03	2.85E+03	2.85E+03