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Davis, CA 95616

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16. ABSTRACT

This technical memorandum documents the details and assumptions used to develop the University of California Pavement Research Center (UCPRC) life cycle inventory (LCI) database for quantifying the environmental impacts of California pavement projects, as well as some impacts from building heating, cooling, and lighting. The UCPRC LCI database presented in this technical memorandum is mainly the result of three UCPRC life cycle assessment studies: one completed for the California Air Resources Board and the California Department of Transportation (Caltrans) looking at the heat island effects of pavement, and two others for Caltrans that updated LCI for pavement processes. The LCI data presented were intended as background data for those studies and do not include foreground inventories for pavement designs, maintenance schedules, building designs, and vehicle traffic levels and fuel consumption. Further, the data in this technical memorandum do not include background information for any use stage elements other than building energy consumption (e.g., the LCI database presented in this report does not include pavement vehicle interaction, street lighting, carbonation, or albedo effects due to radiative forcing).

The LCIs in the database have been incorporated into the life cycle assessment software application eLCAP (environmental Life Cycle Assessment for Pavement). These inventories will be updated continually as part of the ongoing development of eLCAP. The data for the urban heat island studied were submitted for outside critical review to verify the accuracy and reliability of the data sources, modeling assumptions, and LCI results. A three-member review committee conducted the verification according to ISO 14040 requirements. The other data and models in the database that have not yet been critically reviewed are identified. The main goal of the development of each LCI was to represent the local conditions, technologies, and practices in terms of the electricity grid mix, material production processes, plant energy sources, transportation modes, mix designs, construction specifications (new construction, maintenance, and rehabilitation), and end-of-life practices used in California. These inventories can also be used as a framework for creating regional LCIs for other locations around the world. The main commercial software used to develop these LCIs was GaBi, developed by thinkstep. Other database sources were also used, including ecoinvent and the U.S. Life Cycle Inventory (USLCI) database.

This database presented in this document will be periodically updated and subjected to critical review in the future.

17. KEY WORDS

sustainability, life cycle assessment, U.S. Life Cycle Inventory database, transportation infrastructure, cool pavements, eLCAP

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Authors:
Arash Saboori, Ali Azhar Butt, John Harvey, Maryam Ostovar,
Hui Li, and Ting Wang

Partnered Pavement Research Center (PPRC) Contract Strategic Plan Elements 2.8, 4.54, 4.66 and 4.80: Advanced Pavement Research for Long-Term Future Needs (Cool Pavement) and Strategic Plan Elements 4.54, 4.66, and 4.80: Environmental Life Cycle Assessment Updates and Applications

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The LCIs in the database have been incorporated into the life cycle assessment software application *eLCAP* (*environmental Life Cycle Assessment for Pavement*). These inventories will be updated continually as part of the ongoing development of *eLCAP*. The data for the urban heat island studied were submitted for outside critical review to verify the accuracy and reliability of the data sources, modeling assumptions, and LCI results. A three-member review committee conducted the verification according to ISO 14040 requirements. The other data and models in the database that have not yet been critically reviewed are identified. The main goal of the development of each LCI was to represent the local conditions, technologies, and practices in terms of the electricity grid mix, material production processes, plant energy sources, transportation modes, mix designs, construction specifications (new construction, maintenance, and rehabilitation), and end-of-life practices used in California. These inventories can also be used as a framework for creating regional LCIs for other locations around the world. The main commercial software used to develop these LCIs was *GaBi,* developed by thinkstep. Other database sources were also used, including ecoinvent and the U.S. Life Cycle Inventory (USLCI) database.

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7. PROPOSALS FOR IMPLEMENTATION

It is recommended that the LCIs documented in this technical memorandum be used in the *eLCAP* software.

8. RELATED DOCUMENTS

- Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I., Saboori, A., and Kendall, A. .2016. *Pavement Life Cycle Assessment Framework* (FHWA-HIF-16-014). Washington, DC: Federal Highway Administration.
- Harvey, J., Kendall, A., Lee, I., Santero, N., van Dam, T., and Wang, T. 2010. *Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Davis and Berkeley, CA: University of California Pavement Research Center.
- Wang, T., Lee, I., Harvey, J., Kendall, A., Lee, E.B., and Kim, C. 2012. *UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance* (UCPRC-RR-2012-02). Davis and Berkeley, CA: University of California Pavement Research Center.
- Lea, J., Harvey, J., Saboori, A. and Butt, A.A., 2022. *eLCAP: A Web Application for Environmental Life Cycle Assessment for Pavements* (UCPRC-TM-2018-04), Davis and Berkeley, CA: University of California Pavement Research Center.

9. LABORATORY ACCREDITATION

The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report

AASHTO ACCREDITED

10. SIGNATURES

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LIST OF ABBREVIATIONS

BCOA	Bonded concrete overlay of asphalt
BSFC	Brake-specific fuel consumption
CaO	Calcium oxide
CARB	California Air Resources Board
CCPR	Cold central plant recycling
CED	Cumulative energy demand
CExD	Cumulative exergy demand
CH_4	Methane
CIR	Cold in-place recycling
CMU	Concrete masonry unit
CNCA	California Nevada Cement Association
CO	Carbon monoxide
CO_2	Carbon dioxide
CRM	Crumb rubber modifier
CSA	Calcium sulfoaluminate
DQR	Data quality requirements
EF	Emission factors
EMFAC	EMission FACtor model
EOL	End-of-life
EPD	Environmental product declaration
FDR	Full-depth recycling
FHWA	Federal Highway Administration
GHG	Greenhouse gas emissions
GWP	Global warming potential
HFO	Heavy fuel oil
HHV	High heating value
HMA	Hot mix asphalt
HP	Horsepower
LBNL	Lawrence Berkeley National Laboratory
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

LVH	Low heating value
MSW	Municipal solid waste
MTAG	Maintenance Technical Advisory Guide
NAPA	National Asphalt Pavement Association
N_2O	Nitrous oxide
NO_x	Nitrogen oxide
NREL	National Renewable Energy Lab
OPC	Ordinary portland cement
PC	Portland cement
PCA	Portland Cement Association
PCC	Portland cement concrete
PDR	Partial-depth reclamation
PED	Primary energy demand
PLC	Portland-limestone cement
PM2.5	Particulate matter smaller than 2.5 microns
PM10	Particulate matter smaller than 10 microns
POCP	Photochemical ozone creation potential
PPRC	Partnered Pavement Research Center
RAP	Reclaimed asphalt pavement
RCA	Recycled concrete aggregate
RHMA	Rubberized hot mix asphalt
ROG	Reactive organic gases
SBR	Styrene butadiene rubber
SCM	Supplementary cementitious materials
SO_x	Sulfur oxides
SSC	Sweeper and scrubber combo
T&D	Transmission and distribution
THC	Total hydrocarbons
TOG	Total organic gases
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
UCPRC	University of California Pavement Research Center
US EPA	United States Environmental Protection Agency
USLCI	U.S. Life Cycle Inventory
VMT	Vehicle miles traveled

LIST OF TEST METHODS AND SPECIFICATIONS USED IN THE REPORT

ASTM A615/A615M (2012)	Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement
ASTM A775/A775M (2007)	Standard Specification for Epoxy-Coated Steel Reinforcing Bars
ISO 14040 (2006)	Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization

SI* (MODERN METRIC) CONVERSION FACTORS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
VOLUME				
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
MASS				
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
TEMPERATURE (exact degrees)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
LENGTH				
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
AREA				
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
VOLUME				
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C + 32	Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

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

PROJECT OBJECTIVES

The goal of this project was to develop a comprehensive life cycle inventory database for the pavement materials, mixtures, surface treatments, materials transportation, and construction activities used by the California Department of Transportation (Caltrans) to build new roads, conduct maintenance and rehabilitation on existing structures, and manage pavements at the end of their service life.

The major achievement of this project was the development of life cycle assessment models that simulate, to the maximum extent possible, the local practices, specifications, technologies, and energy sources used in all life cycle stages, from material production to end-of-life in California.

A third-party critical review process following ISO 14040 requirements was conducted on many of the inventories documented in this technical memorandum to ensure the credibility and reliability of the database developed. The verification team consisted of three independent researchers in the field of pavement life cycle assessment from the Swedish Transport Administration, Michigan Technological University, and Massachusetts Institute of Technology.

1 INTRODUCTION

This technical memorandum documents the details and assumptions used to develop the first-generation University of California Pavement Research Center (UCPRC) life cycle inventory (LCI) database for quantifying the environmental impacts of California pavement projects as well as some impacts from the heating, cooling, and lighting of buildings.

This chapter provides background on the studies used to develop the LCI, their goals and scope statements, a description of the allocation methods used, and a summary of the life cycle impact assessment (LCIA) approach used. Chapter 2 presents the most recent (July 2021) inventory that has been critically reviewed. Chapter 3 reviews the data quality requirements and data validation in the LCI database prior to 2020, and Chapter 4 presents the updates to the metadata and data quality matrix in the current inventory. Appendix A summarizes the critical reviews of the database completed in 2016 and 2021. Appendix B shows the data sources for the modeling done in *GaBi.* Appendix C through Appendix E provide information about details of the data and example calculations.

1.1 Background

The UCPRC LCI database presented here is mainly the product of three earlier UCPRC life cycle assessment (LCA) studies. The first LCI study looked at the heat island effects of pavement, including consideration of "cool" pavement surfaces. In that study, which was completed in 2017, the UCPRC collaborated with the Lawrence Berkeley National Laboratory (LBNL) to perform work for the California Air Resources Board (CARB) and the California Department of Transportation (Caltrans) *(1,2)*. The second study, undertaken for Caltrans between 2017 and 2019 as the UCPRC began developing the web-based LCA tool *eLCAP* (*environmental Life Cycle Assessment for Pavement*) *(3)* for Caltrans, built on work by Wang *(4,5)* and Saboori et al. *(6)* to update the earlier LCI for pavement processes. The third study was performed in 2020, and it updated the earlier LCIs' metadata, data quality assessment, and transportation and construction data and models implemented in *eLCAP* as of July 2021.

The goal and scope of those studies are defined in Sections 1.2.1, 1.2.2, and 1.2.3 to contextualize how the studies used the LCI data and to specify how the data were applied within each study's scope. The LCI data in this technical memorandum were intended to be background LCI data for those studies and do not include foreground inventories for pavement designs, maintenance schedules, building designs, vehicle traffic levels, and fuel consumption. Further, the data provided here do not include background information for any use stage elements other than energy consumption by buildings (e.g., the data do not include pavement vehicle interaction, lighting, carbonation, and albedo effects due to radiative forcing).

The LCIs in this UCPRC LCI database have been incorporated into the LCA software application, *eLCAP*. As part of *eLCAP*'s ongoing development, they will be periodically updated and subjected to outside critical review.

The models and inventories were either developed from scratch or are modified versions of models available in commercial software. Whether the LCI was new or modified, the main goal of the development of each one was to represent California-specific local conditions, technologies, and practices in terms of the electricity grid mix, material production processes, plant energy sources, transportation modes, mix designs, construction specifications (new construction, maintenance, and rehabilitation), and end-of-life (EOL) practices. But these inventories can also be used as a framework for creating regional LCIs in California and for other locations around the world.

Although the main commercial software source used to develop these LCIs was the program *GaBi* (*Ganzheitliche Bilanz*), which was developed by thinkstep (now owned by Sphera) *(7*), the study also used other database sources, including ecoinvent *(8)* and the U.S. Life Cycle Inventory (USLCI) database *(9*). The energy sources and materials for which the LCIs were developed and that were included in the UCPRC LCI database are listed in Table 1.1. Table 1.2 lists the inventories for the pavement surface materials and treatments that are composites (several materials used together, such as portland cement and aggregate used to create portland cement concrete) and the initial transportation modes included in the combined LCI database. Although these LCIs contain the combined results of the first two studies (the CARB/Caltrans/LBNL heat island and cool pavement project and the first Caltrans project), not all the items in the lists were used in both earlier LCIs. For reference, the items included in each earlier study are detailed in Sections 1.2.1 and 1.2.2.

During the CARB/Caltrans/LBNL study on heat island effects and cool pavement *(1,2),* the UCPRC decided that a third-party critical review of the database was needed to verify the accuracy and reliability of the data sources, modeling assumptions, and LCI results. The review was commissioned in early 2016 and the three-member committee reviewed an earlier version of this technical memorandum that included the materials listed in Table 1.1 and Table 1.2. The reviewers, listed in Table 1.3, conducted the review to verify that the methods used to develop the LCI were scientifically and technically valid, that the data used are appropriate and valid with regard to the goal of the studies documented in the LCI document, and that the LCI documentation is transparent and consistent. The summary letter from the 2016 critical review team was sent in August 2016 (Appendix A). The reviewers were not asked to review the draft *eLCAP* software or the results and conclusions of the studies for which most of the inventories were used.

A similar review was conducted in 2021. That critical review panel, also listed in Table 1.3, reviewed the May 14, 2021, and August 5, 2021, draft versions of this technical memorandum and the May 14, 2021, draft version of a technical memorandum about the *eLCAP* tool *(3)*. The scope of the 2021 review included: (1) the model embedded in *eLCAP* compared to LCA expectations and practices, (2) LCI data appropriateness, quality, and documentation, (3) the calculations of life cycle impacts and resource flows, and (4) reporting of results. The materials and processes reviewed by the 2021 critical review panel are shown in Table A.1: Summary of Inventory Elements Critically Reviewed in September 2016 and August 2021 in Appendix A. The cement inventories in Section 2.2.3 of this technical memorandum were not reviewed by the 2021 critical review panel. The 2021 critical review panel's summary letter was sent in October 2021 and is included in Appendix A.[1]

This current version (October 2021) of the inventory includes revisions made in response to the committee's comments as well as other improvements made from 2017 to 2019 as part of the first Caltrans project. In 2019, the method for naming existing default concrete mix designs was changed to better identify the mix type and its intended use, and additional concrete mix design inventories were added for the following items:

- Portland cement Type III
- Calcium sulfoaluminate (CSA) cement
- Default concrete mix designs for state highway lane replacement, local streets, and minor concrete
- Default concrete mix designs for slab replacement with Type III and CSA cement
- Default bonded concrete overlay of asphalt (sometimes referred to as concrete overlay of asphalt [COA]) concrete mix designs from the cool pavement project with three levels of supplementary cementitious materials

As part of the second Caltrans study in 2020, the metadata reporting was improved and the data quality assessment matrix in *eLCAP* was updated using a new approach developed as part of a project working on the Federal Highway Administration (FHWA) LCA *Excel*-based tool, *LCA Pave (10)*. The updated data quality assessment approach is based on the US Environmental Protection Agency (US EPA) pedigree matrix *(11)* with input from a Michigan Technological University/FHWA project *(12,13)* working with the Federal LCA Commons initiative *(14)*. The US EPA pedigree matrix was enhanced for improved specificity for pavement LCA applications aiming to standardize the practice of data quality assessment for the pavement LCA domain. The new data quality matrix is used in abbreviated form in *LCA Pave* tool and is used in full form in *eLCAP*. The matrix was completed for all data elements in *eLCAP*.

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[1] A PDF document with the complete list of critical review panel comments is available to download at: escholarship.org/content/qt8v36909g/supp/LCI_Panel_Review_Comments_UCPRC-TM-2020-01.pdf.

The same project in 2020 built out the data and models in *eLCAP* for material transportation and construction equipment to consider all likely scenarios as well as to make the information changeable by the user. A full range of trucks, rail, and marine transport was added, and fuel use models were developed. Similarly, a full range of construction equipment was added and fuel use models were created, with sets of typical construction equipment assigned to each pavement layer type in *eLCAP*.

Table 1.1: Energy Sources and Materials Included in the Database Reviewed in 2016

Energy Sources	Materials
Electricity Diesel Burned in Equipment Natural Gas Combusted in Industrial Equipment	Aggregate (Crushed) Aggregate (Natural) Bitumen/Virgin Asphalt Binder Bitumen/Asphalt Emulsion Crumb Rubber Modifier (CRM) Dowel Lime Paraffin (Wax) Portland Cement Type I Portland Cement with 19% SCM[a] Portland Cement with 50% SCM Portland Cement Admixtures (Accelerator) Portland Cement Admixtures (Air Entraining) Portland Cement Admixtures (Plasticizer) Portland Cement Admixtures (Retarder) Portland Cement Admixtures (Superplasticizer) Portland Cement Admixtures (Waterproofing) Quicklime Reclaimed Asphalt Pavement (RAP) Reflective Coating (BPA) Reflective Coating (Polyester Styrene) Reflective Coating (Polyurethane) Reflective Coating (Styrene Acrylate) Styrene Butadiene Rubber (SBR) Tie Bar

[a] SCM: supplementary cementitious materials

Table 1.2: Pavement Surface Composite Materials and Treatments and Transportation Mode Inventories Included in the Database Reviewed in 2016

Surface Treatments	Transportation
Bonded Concrete Overlay on Asphalt	Barge Transport
Cape Seal	Heavy Truck (24 tonne)
Chip Seal	Ocean Freighter
Cold in-Place Recycling	
Conventional Asphalt Concrete (Mill-and-Fill)	
Conventional Asphalt Concrete (Overlay)	
Conventional Interlocking Concrete Pavement (Pavers)	
Fog Seal	
Full-Depth Reclamation	
Permeable Asphalt Concrete	
Permeable Portland Cement Concrete	
Portland Cement Concrete	
Portland Cement Concrete with Supplementary Cementitious Materials	
Reflective Coating (BPA)	
Reflective Coating (Polyester Styrene)	
Reflective Coating (Polyurethane)	
Reflective Coating (Styrene Acrylate)	
Rubberized Asphalt Concrete (Mill-and-Fill)	
Rubberized Asphalt Concrete (Overlay)	
Sand Seal	
Slurry Seal	

Table 1.3: The 2016 and 2021 Third-Party Review Committee Members

2016 Reviewer	Position	Institute	Area of Expertise
Robert Karlsson, Ph.D. (Chair of the Review Committee)	Specialist	Swedish Transportation Administration (STA)	Expert in pavement LCA and transportation infrastructure
Amlan Mukherjee, Ph.D., P.E.	Associate Professor, Civil and Environmental Engineering	Michigan Technological University	Expert in pavement LCA and asphalt materials
Jeremy R. Gregory, Ph.D.	Executive Director, Concrete Sustainability Hub	Massachusetts Institute of Technology	Expert in pavement LCA and concrete materials
2021 Reviewer	**Position**	**Institute**	**Area of Expertise**
Arpad Horvath, Ph.D. (Chair of the Review Committee)	Professor, Civil and Environmental Engineering	University of California, Berkeley	Expert in pavement LCA and transportation infrastructure
Amlan Mukherjee, Ph.D., P.E.	Associate Professor, Civil and Environmental Engineering	Michigan Technological University	Expert in pavement LCA and asphalt materials
Jeremy R. Gregory, Ph.D.	Executive Director, Climate & Sustainability Consortium[a]	Massachusetts Institute of Technology	Expert in pavement LCA and concrete materials

[a] At MIT Concrete Sustainability Hub until May 2021.

It should be noted that the impacts calculated using the *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts* (*TRACI*) 2.1 *(15)* were the only impact calculations subjected to critical review.

Metadata regarding the sources of information in the LCIs in *eLCAP* and the updated data quality assessment matrix added in late 2020 can be seen in the program's user interface. That data quality information was the latest available in January 2021, and it is an update from the initial data quality assessment presented in Chapter 4 of this technical memorandum.

In general, the system boundary of the LCIs developed in the CARB/Caltrans/LBNL study on heat island effects and cool pavement and the first Caltrans study that began development of *eLCAP* included: (1) extraction of raw material from the ground, (2) transportation of raw materials to the plant, and (3) processes conducted at the plant to prepare the final product for shipping to the construction site. An LCI that includes this system boundary is referred to as a "cradle-to-gate LCI." Delivery of the product to the construction site and the impacts associated with its transportation are not included in a cradle-to-gate LCI. Instead, transportation has been included as a separate item in the LCIs, with the different inventories for each transportation mode shown in Table 1.2. Each section in Chapter 2 describes the specific system boundary for each item in more detail. It should be noted that the transportation modes shown in Table 1.2 were updated extensively in late 2020 and the details of that update are provided in Section 2.6.

1.2 Goal and Scope of Three Studies Used to Develop the Inventories

1.2.1 First Study: Goal and Scope of the CARB/Caltrans/LBNL Heat Island Study

This project was a collaborative effort between the Lawrence Berkeley National Laboratory as lead, the UCPRC, the University of Southern California, and thinkstep, and it was jointly funded by CARB and Caltrans. The study's goal was to produce a tool that enables decision-makers to compare the environmental life cycle impacts of conventional pavements and cool pavements in urban areas (the tools are summarized in Levinson et al. *[1]*, and the study's results are summarized in Gilbert et al. *[2]*). Urban areas generally have higher temperatures than the undeveloped land around them, as they are covered with pavement and buildings that absorb heat from solar irradiance and warmed by many other heat sources—including building heating and cooling systems and motor vehicles. This localized warming phenomenon is referred to as an "urban heat island."

Cool pavements have generally been defined as those that have higher albedo (reflectivity) than conventional pavements and that can, as a result, contribute to reducing urban heat island effects by reflecting more solar irradiance than conventional pavements. Less commonly, cool pavements have also been defined as those that have lower greenhouse gas emissions (GHG) during their life cycle. The two definitions have sometimes been used interchangeably without clarification.

The objective of the study was to conduct a full life cycle analysis of the greenhouse gas emissions of pavements that are more reflective, and therefore physically cooler, to determine whether they also lowered life cycle emissions by reducing heat island effects and the need to cool buildings. This was done by accounting for the materials, construction, transportation, and end-of-life stages for the pavements, and year-round building energy use. Unlike earlier LBNL studies that had focused on urban heat island reduction and observation of urban heat island impacts from use stage summertime building energy consumption, this study adopted this comprehensive system boundary to evaluate the environmental impacts of the full life cycle. For the various surface treatments compared in the study, the analysis period was defined as 50 years.

The project considered a comprehensive list of conventional and alternative surface treatment approaches that could potentially be applied to public urban pavements. For example, it considered an approach where pavement surfaces are covered with reflective coatings instead of conventional asphalt-based slurry seals, even though reflective coatings were not generally market-available at the time of the study. The study's geographic scope was limited to California, and its temporal scope was assumed to be begin between 2012 (using then-current electrical energy production data) and 2020 (under the California Renewables Portfolio Standard).

In the study, the material stage included extraction of raw materials from the ground, their transportation to processing plants, and the processing conducted in the plants. Transportation of the materials from the plant to the site and then from the site to the landfill or recycling plant at the EOL was also included for each case. On-site construction activity processes were modeled for each surface treatment according to Caltrans specifications and information received from local contractors. When the study quantified use stage building energy consumption, it considered (1) urban temperature changes, based on the applied surface treatment's albedo (calculated using the University of Southern California's Weather Research and Forecasting Model), (2) the percentage of the urban public pavements treated, and (3) albedo changes expected over time. Radiative forcing from the reflection of solar energy off the pavement into the atmosphere was outside the system boundary but was considered separately in a journal article describing the total study, which included a summary of the LCA *(2)*. The study's intended audience included local governments, pavement researchers and practitioners, and construction contractors. The study's selected functional unit was 1 lane-mile of pavement surface. To enable investigation of the impact of the cleaner electricity grid mix mandated by the California Renewable Portfolio Standard, the LCI for the study was developed under two assumptions, one based on the year 2012 California electricity grid mix and one based on the California grid mix anticipated for the year 2020.

The tool developed was named *pLCA* (*pavement LCA*), and Figure 1.1 shows the system boundary defined for this project and the resulting tool.

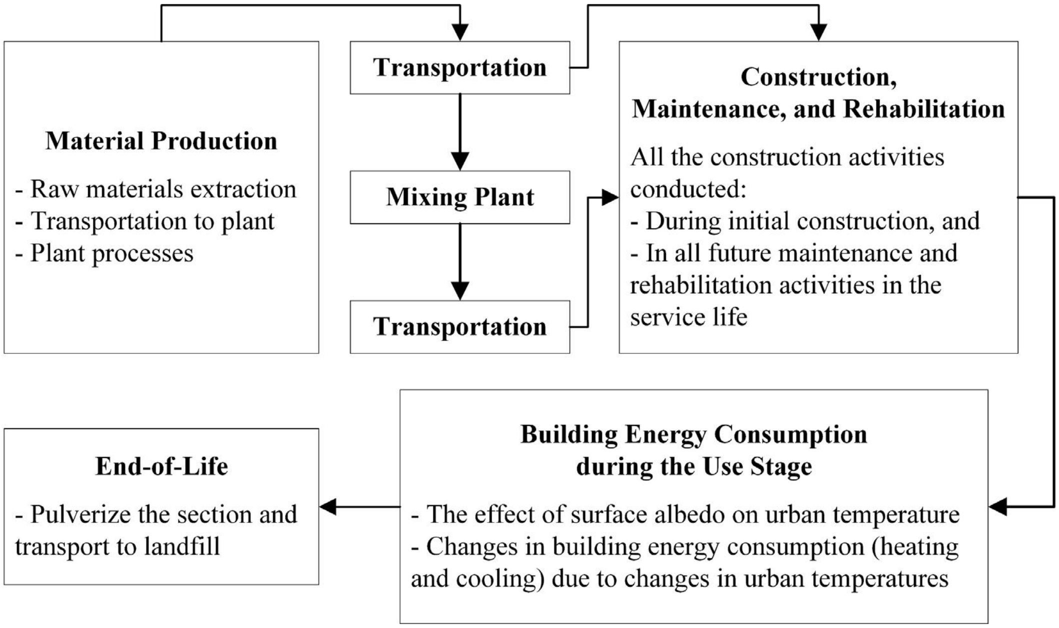
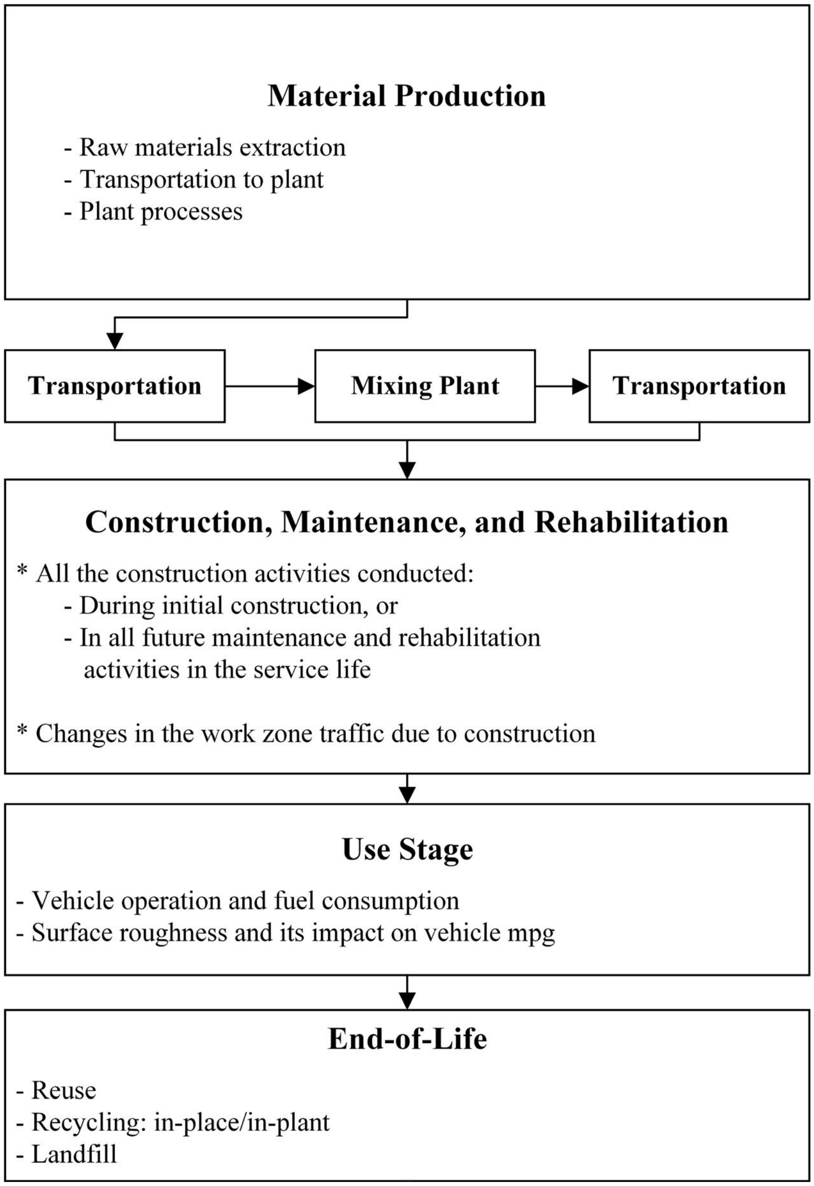


Figure 1.1: Scope of the CARB/Caltrans/LBNL heat island and cool pavement study and resulting *pLCA* tool.

1.2.2 Second Study: First Version of eLCAP for Caltrans

The UCPRC developed *eLCAP,* a web-based LCA tool, to allow pavement designers and policymakers to quantify the environmental impacts of their pavement design and policy decisions, both at the planning and project design stages of project development and when evaluating policies for materials, designs, construction, and maintenance and rehabilitation *(3)*. Caltrans provided the primary funding for the project, and the UCPRC provided supplementary academic recovery funding for a period when Caltrans funding was unavailable. *eLCAP* includes the inventories developed in the CARB/Caltrans/LBNL heat island and cool pavement project as well as complementary items needed to quantify all the impacts across the full life cycle of pavements under the management of public agencies. Currently, the inventories in *eLCAP* focus on California. Figure 1.2 shows the scope of the first version of *eLCAP*.



Note: The scope of the processes included in the *eLCAP* software includes those developed as part of the CARB/Caltrans/LBNL heat island and cool pavement project and additional processes.

Source: Lea et al. (2022) *(3)*.

Figure 1.2: Scope of the *eLCAP* software.

1.2.3 Third Study: Updates to Data Quality Assessment and Transportation and Construction Inventories for Caltrans

In a Caltrans-funded third study conducted in 2019 and 2020, the UCPRC undertook four important tasks to update the LCIs. The results were implemented in *eLCAP* in late 2020. The four tasks were the following:

1. Update the definitions of the metadata fields.
2. Adapt and enhance the data quality assessment approach and data quality matrix.

3. Develop fuel consumption and emissions data and models for additional material transportation vehicles beyond those shown in Table 1.2. Assign default transportation vehicles to each type of layer but make changes in the program to allow users to modify them.
4. Develop fuel and emission rates for all types of construction equipment used in pavement. Develop a matrix of the default equipment assigned to construction of each type of pavement layer, and make changes in the program that allow users to modify them.

The list of impact indicators and flows reported by *eLCAP* was also updated as part of this work to better reflect the indicators recommended in the FHWA pavement LCA framework *(16)*.

1.3 Allocation

Allocation is used to proportionately distribute the total impacts of a single process among multiple products that the process generates. Allocation is required when such a process cannot be subdivided into individual physical subprocesses that are responsible for generating each product. Two pavement material inventories in this study required allocation: (1) bitumen (referred to as virgin asphalt binder), one of oil refining's many coproducts, and (2) reclaimed asphalt pavement (RAP), whose inventory includes the processes in the original asphalt pavement's creation and the additional EOL ones required to recycle the material into a new material. Details of the allocation assumptions and the corresponding results can be found in the respective sections for these products in Chapter 2. The applicable allocation methods considered are shown in Table 1.4.

Table 1.4: Possible Allocation Methods to Be Used for Selected Pavement Materials in the Database

Item	Applicable Allocation Methods
Virgin asphalt binder	Mass-based, energy-based, and value-based (economic)
Reclaimed asphalt pavement (RAP)	Cutoff and 50/50

As the table shows, for virgin asphalt binder, three allocation methods apply. *Mass-based* means that the impacts are allocated based on the mass of each coproduct from the process. *Energy-based* means that the allocation uses the energy content of each coproduct per unit of mass or volume. *Value-based* uses the market value of each coproduct per unit of mass or volume.

1.4 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) results are also presented in this technical memorandum as a validation check of the LCI results. *TRACI* 2.1 *(15)* was used as the main methodology for converting the LCI results into impact assessment indicators. The following were the impact indicators used for the LBNL heat island and cool pavement study:

- Global warming potential (GWP).
- Photochemical ozone creation (smog) potential (POCP). Smog emissions, unlike global warming, are a local issue, and, therefore, the location of the emissions matters. However, this study did not specify the location or timing of the emission of these ozone precursors. Instead, the study measured the total POCP over the full life cycle of the surface treatment regardless of where it occurred.
- Particulates smaller than 2.5 µm (PM2.5). As with smog potential, particulate emissions occur on a local scale and are emitted at various locations as part of the different stages of a pavement section's life cycle, from raw material extraction to EOL. This study did not consider the timing and location of emissions for this category.
- Primary energy used as fuel from renewable and non-renewable resources (net calorific value excluding feedstock energy).
- Primary energy used as a material from non-renewable resources (feedstock energy).

In addition to several external databases (including ecoinvent, ReCiPe, IPCC AR5, Impact 2002+, and USLCI), *GaBi* has its own extensive database that can be used to model processes and calculate economic, social, and environmental impacts. Primary energy consumption in *GaBi* is modeled as the sum of the last six energy impact indicators presented in Table 1.5. *GaBi* documentation states that "primary energy demand (PED) is the quantity of energy directly withdrawn from the hydrosphere, atmosphere or geosphere or energy source without any anthropogenic changes. For fossil fuels and uranium, PED would be the amount of resources withdrawn expressed in their energy equivalents (i.e., the energy content of the raw material). For renewable resources, the energy characterized by the amount of biomass consumed would be described. PED for hydropower would be based on the amount of energy that is gained from the change in the potential energy of the water (i.e., from the height difference)" *(17)*. SimaPro, another popular and commonly used LCA tool, uses cumulative energy demand (CED) and cumulative exergy demand (CExD) instead of PED. The exergy of a system is defined in thermodynamics as the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, reaching maximum entropy *(18)*. It therefore identifies the energy quality rather than the energy content of an energy resource, and exergy rather than energy could also be used to model energy flows in LCA.

The initial LCA study conducted for Caltrans *(4,5)* primarily focused on GWP, PED used as fuel (renewable and non-renewable), and primary energy used as a material from non-renewable resources (feedstock energy) while also considering pavement vehicle interaction. More recent studies, such as the benchmarking of EOL practices *(6)*, also include smog and particulate matter. The *eLCAP* updates completed in 2019 and 2020 included the addition of more indicators to better match those recommended in the FHWA pavement LCA framework *(16)* and are shown in Table 1.5.

Table 1.5: Impact Categories in eLCAP as of July 2021

Impact Indicator or Flow	Units
Acidification	kg SO2-e[a]
Ecotoxicity	CTU-e
Eutrophication	kg N-e
Global warming air, excl. biogenic carbon	kg CO2-e
Global warming air, incl. biogenic carbon	kg CO2-e
Human health particulate	kg PM2.5-e
Human toxicity cancer	CTUh[b]
Human toxicity non-cancer	CTUh
Ozone depletion	kg CFC 11-e
Resources, fossil fuels	MJ surplus energy
Smog air	kg O3-e
Primary energy demand used as raw materials (feedstock energy)	MJ
Primary energy demand from renewable (renewable) and non-renewable resources (gross calorific value[c])	MJ
Primary energy demand from renewable and non-renewable resources (net caloric value[d])	MJ
Primary energy from non-renewable resources (gross calorific value)	MJ
Primary energy from non-renewable resources (net calorific value)	MJ
Primary energy from renewable resources (gross calorific value)	MJ
Primary energy from renewable resources (net calorific value)	MJ

Note: Subscripts are not used consistently across all sources. For example, CO2 can also appear as CO_2.

[a] e: equivalent (note that in some tables may also appear as -eq).

[b] h: hours.

[c] Gross calorific value or the high heating value (HHV) is where all the products of combustion (condensing water vapor produced) are returned to the pre-combustion temperature.

[d] Net calorific value or the low heating value (LHV) is the HHV minus the heat of vaporization of water.

2 UCPRC LIFE CYCLE INVENTORY AS OF JULY 2021

The data sources used to model each item in the life cycle inventory (LCI) are described in this chapter. They were chosen after the available options were examined to see which were the most up to date and representative of regional conditions in California. It should also be noted that a few of the models built using the USLCI database contain dummy flows that have zero upstream impacts; use of dummy flows was unavoidable at this time as no better datasets were available.

Appendix B provides more details for the main processes taken directly from *GaBi* that were used to build the UCPRC models. Importantly, *GaBi* input and output flows for each item, material, and process are not presented in this report. This is because of the license agreement between thinkstep and the University of California, Davis. Only the results (LCIAs of cradle-to-gate and cradle-to-lay) are presented in this report. *GaBi* process names are used where applicable to make it easy for users to identify and reproduce results in *GaBi* based on the information and assumptions provided for the processes in this report. It should also be noted that *GaBi* results change as thinkstep updates its databases.

2.1 Energy Sources

2.1.1 Electricity

The electricity grid mix for California was taken from the California Energy Almanac website *(19),* and the table for 2012 is reproduced in Table 2.1. Figure 2.1 shows the model developed using the *GaBi* software program. The average Western US grid process (based on the EPA's Emissions & Generation Resource Integrated Database [eGRID]) included in *GaBi* was used in the model to account for the unspecified portion of the grid mix. The electricity LCI was developed under two different grid mix scenarios, one based on the year 2012 and one based on the year 2019 for California. The grid mix for 2020 that was anticipated in 2016 is also shown for comparison with the actual grid mix in 2019 (Table 2.2). The anticipated 2020 renewables portfolio was specifically requested by CARB, assuming that implementation of cool pavement strategies would happen after 2020. The 2016 projection for 2020 slightly underestimated the use of renewables that was already occurring in 2019.

The electricity transmission and distribution (T&D) losses are assumed to be 8.0 % for 2012 grid mix. Based on the US Energy Information Administration 2019 California electricity data, T&D losses were calculated to be 5.1%.[2]

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[2] T&D losses as a percentage = estimated losses divided by the result of total disposition minus direct use: eia.gov/tools/faqs/faq.php?id=105&t=3.

Table 2.1: Electricity Grid Mix in California in Year 2012

Fuel Type	Percent in CA Grid Mix[a] (%)
Total Renewables	**15.40**
Biomass	2.30
Landfill Gas	0.00
Geothermal	4.40
Small Hydro	1.50
Solar	0.90
Wind	6.30
Total Non-Renewables	**84.60**
Hard Coal	7.50
Hydro Large	8.30
Natural Gas	43.40
Nuclear	9.00
Unspecified	16.40
Total	**100.00**

Source: California Energy Almanac website *(79)*.

[a] Year 2012 California grid mix includes in-state electricity generation as well as electricity imports from Northwest and Southwest regions.

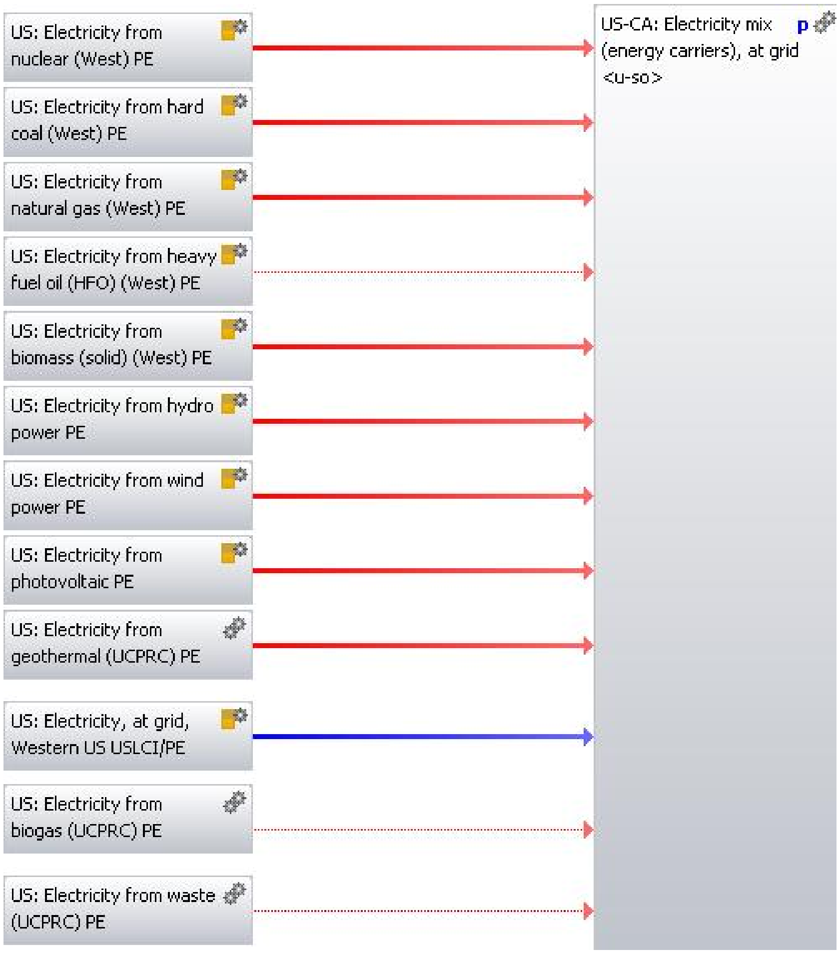
Table 2.2: Electricity Grid Mix in California in Year 2012 in Year 2019 and Anticipated Year 2020 as Forecast in Year 2016

Fuel Type	Year 2020 CA Grid Mix (as anticipated in 2016) (%)	Actual Year 2019 CA Grid Mix[a] (%)
Total Renewables	**28.20**	**31.70**
Biomass	1.20	2.44
Landfill Gas	0.30	—
Geothermal	2.90	4.77
Small Hydro	1.60	2.03
Solar PV	10.90	12.28[b]
Solar Thermal	2.30	
Wind	9.00	10.17
Total Non-Renewables	**71.80**	**68.30**
Hard Coal	6.40	2.96
Hydro Large	7.00	14.62
Natural Gas	36.80	34.23
Nuclear	7.60	8.98
Unspecified	13.90	7.34
Oil	—	0.01
Other (Waste Heat/Petroleum Coke)	—	0.15
Total	**100.00**	**100.00**

Source: Year 2012 in Year 2019, California Energy Commission *(20)*; anticipate Year 2020 as forecast in Year 2016, California Renewables Portfolio Standard Program *(21)*.

[a] Year 2019 California grid mix includes in-state electricity generation as well as electricity imports from Northwest and Southwest regions.

[b] 12.28% is total solar (solar PV + solar thermal).

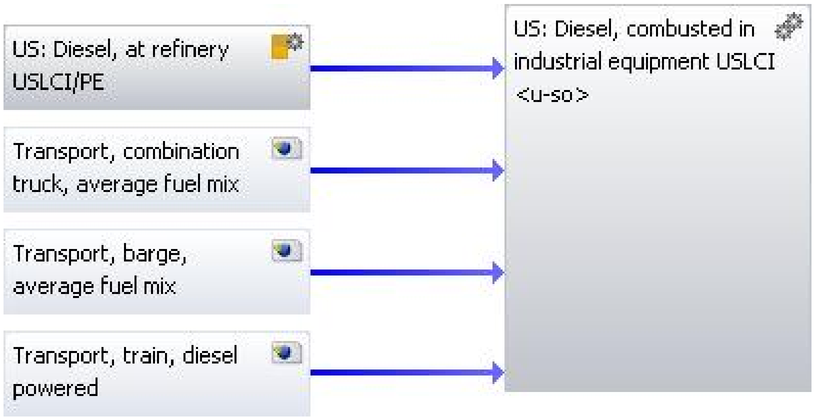


Note: Model developed in *GaBi*.

Figure 2.1: The model UCPRC developed for the California electricity grid mix.

2.1.2 Diesel Combusted in Industrial Equipment

The data for diesel combusted in industrial equipment were directly taken from the *GaBi* database, which uses USLCI data. Figure 2.2 shows the diesel model (agg), which is developed in *GaBi.*

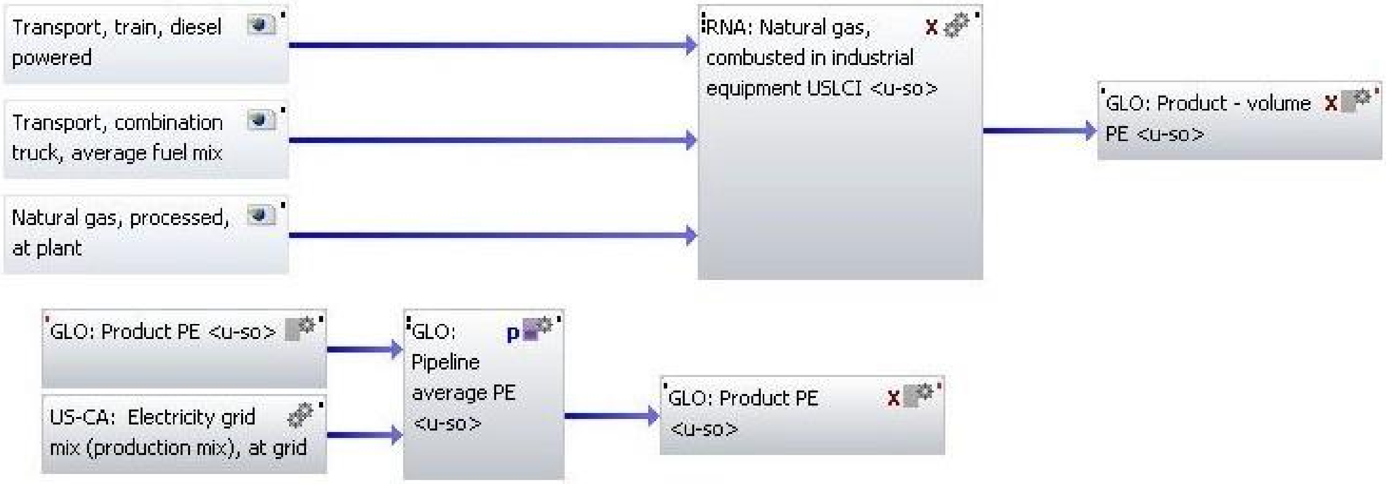


Note: GaBi model using data from USLCI.

Figure 2.2: Diesel combusted in industrial equipment.

2.1.3 Natural Gas Combusted in Industrial Equipment

The data for natural gas combusted in industrial equipment were directly taken from the *GaBi* database, which uses USLCI data. Figure 2.3 shows the model (agg).



Note: GaBi model using data from USLCI database.

Figure 2.3: Natural gas combusted in industrial equipment.

2.1.4 Summary of Energy Sources

Table 2.3 shows a summary of selected LCI and LCIA results for the energy sources studied.

Table 2.3: Cradle-To-Grave Impacts for Different Energy Sources

Item	Functional Unit	GWP[a] [kg CO2-e]	POCP[b] [kg O3-e]	PM2.5[c] [kg]	PED (Total)[d] [MJ]	PED (Non-Renewable)[e] [MJ]	FE[f] [MJ]
Electricity (2012 grid mix; agg)	1 MJ	0.127	4.16E-03	2.51E-05	2.92E+00	2.23E+00	0.00E+00
Electricity (2019 grid mix; agg)	1 MJ	0.080	2.42E-03	1.38E-05	3.31E+00	1.53E+00	0.00E+00
US: Diesel, at Refinery (agg) + US Diesel, combusted in Industrial Equipment (u-so)	1 gal.	1.19E+01	5.27E+00	9.37E-03	1.65E+02	1.65E+02	0.00E+00
US: Natural gas, processed, at plant (agg) + Natural gas, combusted in industrial equipment (u-so)	1 m^3	2.41E+00	5.30E-02	1.19E-03	3.84E+01	3.84E+01	0.00E+00

[a] GWP: Global warming potential.

[b] POCP: Photochemical ozone creation potential (smog formation potential).

[c] PM2.5: Particulate matter smaller than 2.5 μm, which cause respiratory damages and asthma.

[d] PED (Total): Total primary energy demand excluding the feedstock energy, where feedstock energy data were available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[e] PED (Non-Renewable): Total primary energy demand from non-renewable resources. The same note as PED (Total) applies to this category as well. PED from non-renewable resources (net calorific value).

[f] FE: Feedstock energy. Also called PED (non-fuel), it is the energy stored in the construction materials (such as asphalt) that is not consumed and can be recovered later.

2.2 Material Production Stage for Conventional Materials

2.2.1 Aggregates

Aggregate (Crushed)

The data shown in Table 10 in Marceaus et al. *(22)* were used to model plant production of crushed aggregate. That table is reproduced here as Table 2.4. Figure 2.4 shows the model developed in *GaBi* to calculate the LCI and the LCIA results.

Before the data from Marceau et al. *(22)* could be modeled with *GaBi,* it was necessary to convert the units from kJ/metric ton of aggregate to kg/kg of aggregate (for coal) or m^3/kg of aggregate (for the rest of the energy sources). This conversion was done using the conversion factors in Table 2.5. (Note: Modeling of electricity did not require this conversion.)

Table 2.4: Aggregate—Crushed Production in Plant

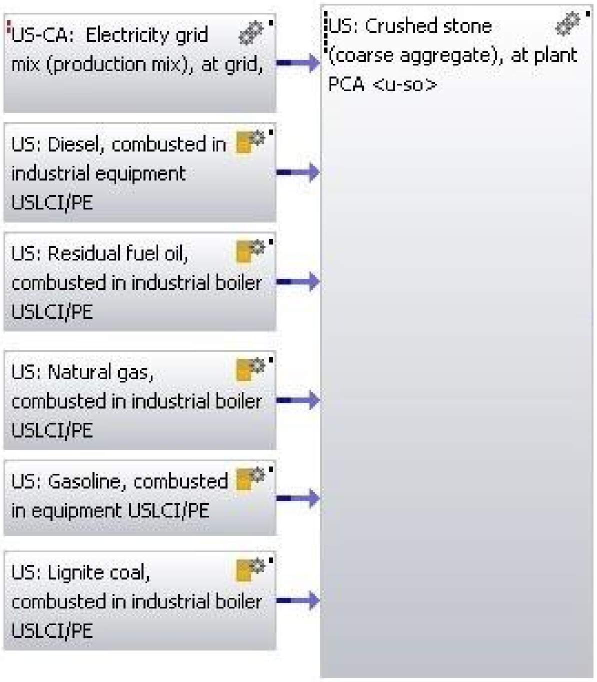
Item	Energy/ton Aggregate		
	Amount/ton	**Btu/ton**	**kJ/metric ton**
Coal, ton	2.75E-05	577	670
Distillate (light) grade nos. 1, 2, 4, and light diesel fuel, gal.	9.32E-02	12,920	15,030
Residual (heavy) grade nos. 5 and 6 and heavy diesel fuel, gal.	1.45E-02	2,167	2,520
Natural gas, 1000 cu ft.	3.45E-03	3,543	4,120
Gasoline used as fuel, gal.	9.39E-03	1,174	1,370
Electricity, 1000 kWh	2.96E-03	10,088	11,730
Total	—	**30,470**	**35,440**

Source: Reproduction of Table 10, Marceau et al. *(22)*.

Table 2.5: Conversion Factors for Items in Table 2.4 and Table 2.6 to Adjust Their Units

Energy Source	kJ/ton of Agg[a]	Energy Content	Unit	Value Used in *GaBi*	Unit
Coal	670	4.10E-05	kJ/kg	2.75E-05	kg/kg of agg[1]
Distillate (light) grades 1, 2, 4, and light diesel fuel	15,030	2.65E-08	kJ/m^3	3.98E-07	m^3/kg of agg
Residual (heavy) grades 5, 6, and heavy diesel fuel	2,520	2.40E-08	kJ/m^3	6.05E-08	m^3/kg of agg
Natural gas	4,120	2.62E-05	kJ/m^3	1.08E-04	m^3/kg of agg
Gasoline used as fuel, gal.	1,370	2.86E-08	kJ/m^3	3.92E-08	m^3/kg of agg

[a] Agg: aggregate.



Note: Model developed in *GaBi* using information from Marceau et al. *(22)*.

Figure 2.4: Model developed for crushed aggregate production.

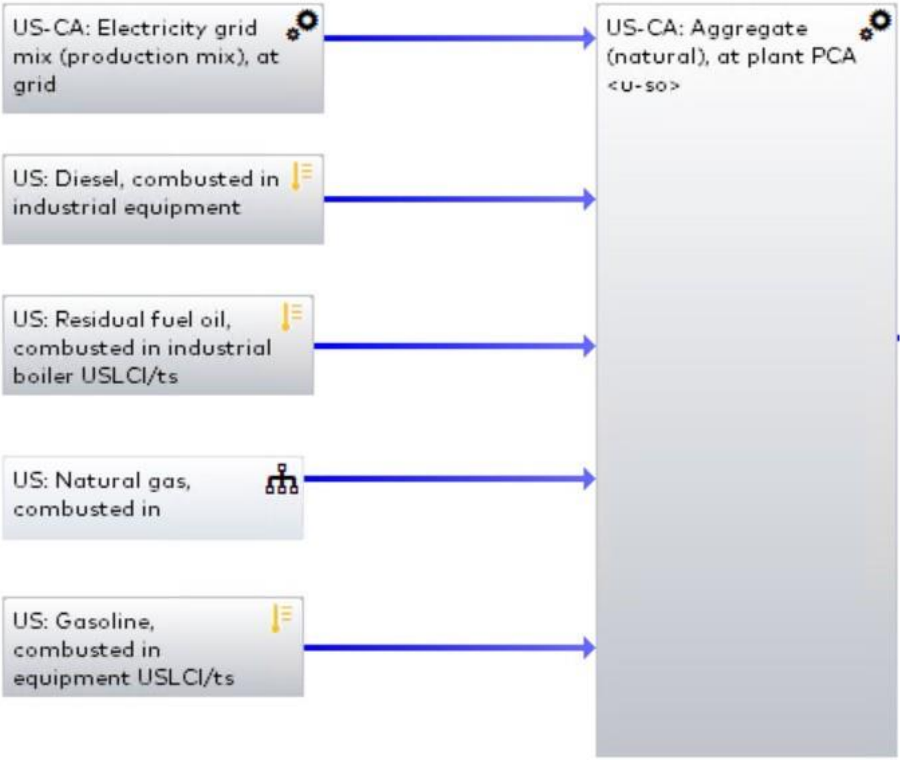
Aggregate (Natural)

The data shown in Table 9 of Marceau et al. *(22)* were used to model natural aggregate production in the plant. That table is reproduced in Table 2.6. Figure 2.5 shows the model developed for natural aggregate. Conversion of values from kJ/ton of aggregate to the values used in *GaBi* was done based on Table 2.5. Figure 2.5 shows the model developed in *GaBi* to calculate the LCI and the LCIA results.

Table 2.6: Aggregate—Natural Production in Plant

Item	Energy/ton Aggregate		
	Amount/ton	Btu/ton	kJ/metric ton
Distillate (light) grade nos. 1, 2, 4, and light diesel fuel, gal.	5.62E-02	7,793	9,060
Residual (heavy) grade nos. 5 and 6, and heavy diesel fuel, gal.	1.26E-02	1,888	2,200
Natural gas, 1,000 ft^3	1.33E-03	1,370	1,590
Gasoline used as fuel, gal.	5.43E-03	679	790
Electricity, 1,000 kWh	2.41E-03	8,210	9,550
Total	—	**19,940**	**23,190**

Source: Reproduction of Table 9, Marceau et al. (2007) *(22)*.

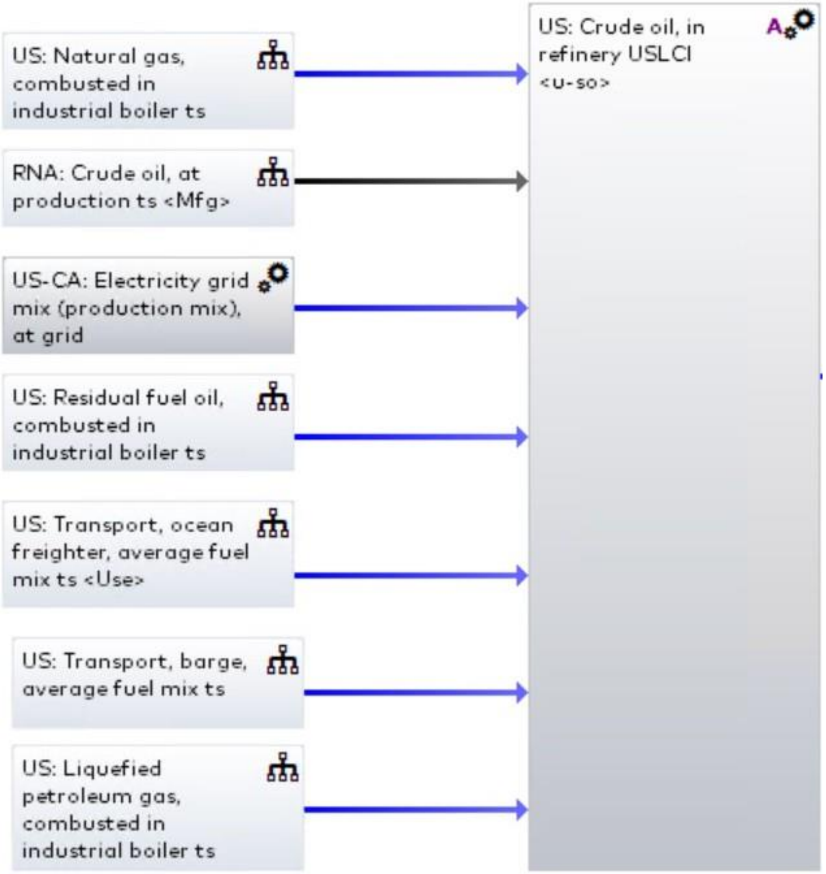


Note: Model developed in *GaBi* using information from Marceau et al. *(22)*.

Figure 2.5: Model developed for natural aggregate production.

Bitumen/Virgin Asphalt Binder

The model for virgin asphalt binder developed in *GaBi* for the UCPRC LCI was based on the USLCI database developed by the NREL *(23)* for an average US refinery. In this study, the electricity process in the *GaBi* model was modified to reflect the electricity grid mixes in California in 2012 and 2019 used to produce virgin asphalt binder. Figure 2.6 shows the adjusted virgin asphalt binder model in *GaBi* that is used in the UCPRC LCI.



Note: Model developed in *GaBi* using information from the California electricity production model and NREL refinery model *(23)*.

Figure 2.6: Model developed for virgin asphalt binder production.

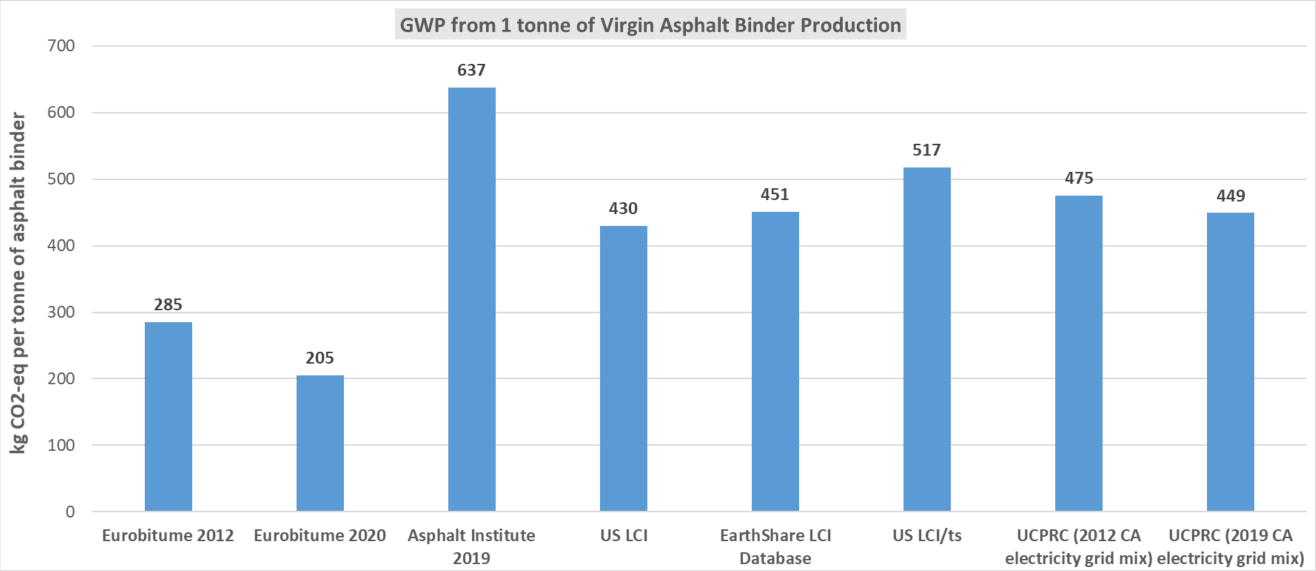
As noted in Table 1.4, there are three methods that can be used to allocate the refinery plant impacts among asphalt binder-related products. For this project, the mass-based allocation approach was used because (1) *GaBi* uses USLCI database results that are mass based and (2) this approach does not provide results before allocation (the LCI for the whole refinery with all the refined products) so that other allocation methods—such as energy-based or economic-based allocations—can also be applied. This study required that the virgin asphalt binder model also be used as a submodel in several other models under development in *GaBi*. Therefore, a decision was made to use mass-based allocations both for consistency and to aid in the development of full LCIs. Because the FHWA framework for pavement LCA *(16)* recommends reporting feedstock energy separately as this energy might be recovered in the future (if it is economically viable), the feedstock energy of asphalt binder (for virgin asphalt binder and asphalt emulsion) was assumed to be 40.2 MJ per kg of residual asphalt binder *(24)*.

It should also be noted that all the LCIs in this report are cradle-to-gate*,* meaning that they include extraction of raw materials from the ground (cradle), transportation of the raw materials to the plant, and all the processes conducted in the plant to get the final material ready to ship at the plant gate. This is particularly important for asphalt binder and materials that use asphalt binder, such as asphalt emulsion, crumb rubber modifier (CRM), and waxes, where the material still contains carbon that can be emitted into the air after it leaves the plant's gate through incineration and/or other processes. Those potential future carbon emissions (i.e., material that is burned or material that might otherwise be converted into airborne carbon emissions in the future) are not included in the LCIs reported in this document.

Figure 2.7 shows the comparison of global warming potential (GWP) values from the production of 1 tonne of bitumen/asphalt binder from this study and values from several other studies that are commonly cited. The Eurobitume GWP numbers are almost half of the UCPRC, USLCI, and EarthShare LCI reported numbers. This indicates that there is uncertainty in using the Eurobitume energy foreground data for the United States as processing in the United States and transport distance impacts might be very different from those in Europe. However, due to unavailability of US data sources in 2016, the UCPRC used Eurobitume foreground data to model asphalt emulsion (see Section 2.2.2).

The Asphalt Institute numbers tend to be the highest since the asphalt binder modeling done in its report considers high percentages of Canadian oil sand (around 44% crude) imports and processing. A slight reduction in GWP values (475 to 449 kg CO2-e) for UCPRC asphalt binder production using the electricity grid mix of 2012 to 2019 is mainly due to the increased use of renewables in the electricity grid mix in 2019 (see Table 2.1; use of renewables for electricity generation are double in the 2019 California electricity grid mix as compared to the 2016 California electricity grid mix). The USLCI/ts (thinkstep) bitumen model is the one modified by the UCPRC (replacing the US electricity grid mix with the California electricity grid mix) to reflect California conditions. It should be noted that GWP value from USLCI/ts are higher than UCPRC GWP values for the asphalt binder. This is because the average US electricity grid mix contains higher percentages of non-renewable resources compared to the California grid mix, resulting in higher GWP emissions.

The UCPRC is currently studying the asphalt binder supply chain for California and Petroleum Administration for Defense Districts 5 (PADD 5). Assumptions as well as refineries and terminal inventories from the Asphalt Institute report, which collected information from 12 Asphalt Institute member refineries and terminals in North America, are being used to model the asphalt binder for California and PADD 5 and will be included in the future UCPRC LCI *(25)*.



Notes:
- Eurobitume 2012 *(26)*.
- Eurobitume 2020 *(27)*.
- Asphalt Institute 2019 report *(25)*.
- USLCI and EarthShare LCI Database GWP numbers are acquired from p. 32, Mukherjee (2016) *(28)*. Note that Mukherjee (2016) states that the USLCI source has incomplete upstream datasets. The EarthShare LCI, on the other hand, is an expanded version of the USLCI database that has been modified using ecoinvent v.2.2 data, along with electricity grid mix data from all 50 US states.
- USLCI/ts is a thinkstep *GaBi* model based on USLCI data.
- UCPRC asphalt binder that uses 2012 electricity grid mix is taken from Table 2.15.
- UCPRC asphalt binder that uses 2019 electricity grid mix is taken from Table 2.16.

Figure 2.7. GWP values of asphalt binder production from several sources.

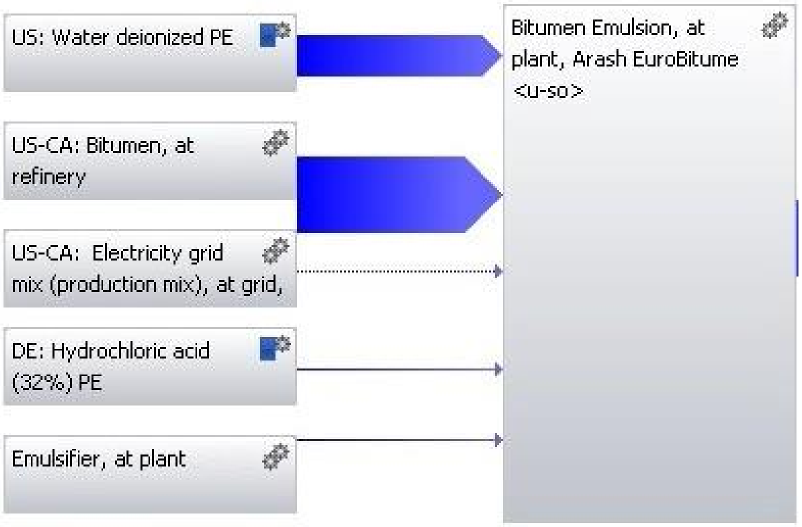
2.2.2 Bitumen/Asphalt Emulsion

LCI data for asphalt emulsion from Section 6.4 of the Eurobitume LCI report *(26)* were used and are reproduced in Table 2.7. Figure 2.8 shows the model developed in *GaBi*.

Table 2.7: Energy and Material Requirements for Asphalt Emulsion Production in Plant (1 Tonne of Residual Asphalt)

Category	Item	Unit	Asphalt Binder	Emulsifier	HCl	Hot Water	Emulsion Milling	Total
Raw Material	Virgin Asphalt Binder at Refinery	kg	1,000	1.1	—	—	—	1,001.1
Energy Resources	Natural Gas	kg	20.1	0.22	0.34	0.08	1.21	21.9
	Crude Oil	kg	40.9	1.4	0.4	1.8	0.4	44.9
	Coal	kg	1.03	0.3	0.67	0.07	3.25	5.32
	Uranium	kg	6.0E-05	2.0E-05	4.0E-05	0.0E+00	2.3E-04	4.0E-04

Source: Data from Section 6.4, Eurobitume (2012) *(26)*.



Note: Model developed in *GaBi*.

Figure 2.8: Model developed for bitumen/asphalt emulsion.

2.2.3 Cements

Different cement types are used for each pavement applications. The following are the main types included in the UCPRC database:

- Ordinary portland cement (OPC)
  - Portland cement Type I/II (for most concrete pavement construction)
  - Portland cement Type III (rapid setting for slab replacement)
- Belite calcium sulfoaluminate cement (CSA, rapid setting for slab replacement)
  - CSA containing high sulfur content (CSA-HS)
  - CSA containing low sulfur content (CSA-LS)
- Cements with supplementary cementitious materials (SCM) for most concrete pavement construction
  - Slag cement
  - Portland-limestone cement (PLC)

It should be noted that the cement types OPC 2016 (modified), OPC 2021, CSA, and PLC have not been part of the external critical review as the models were not updated when the critical review process occurred. The intent is to include these materials in the next external critical review package.

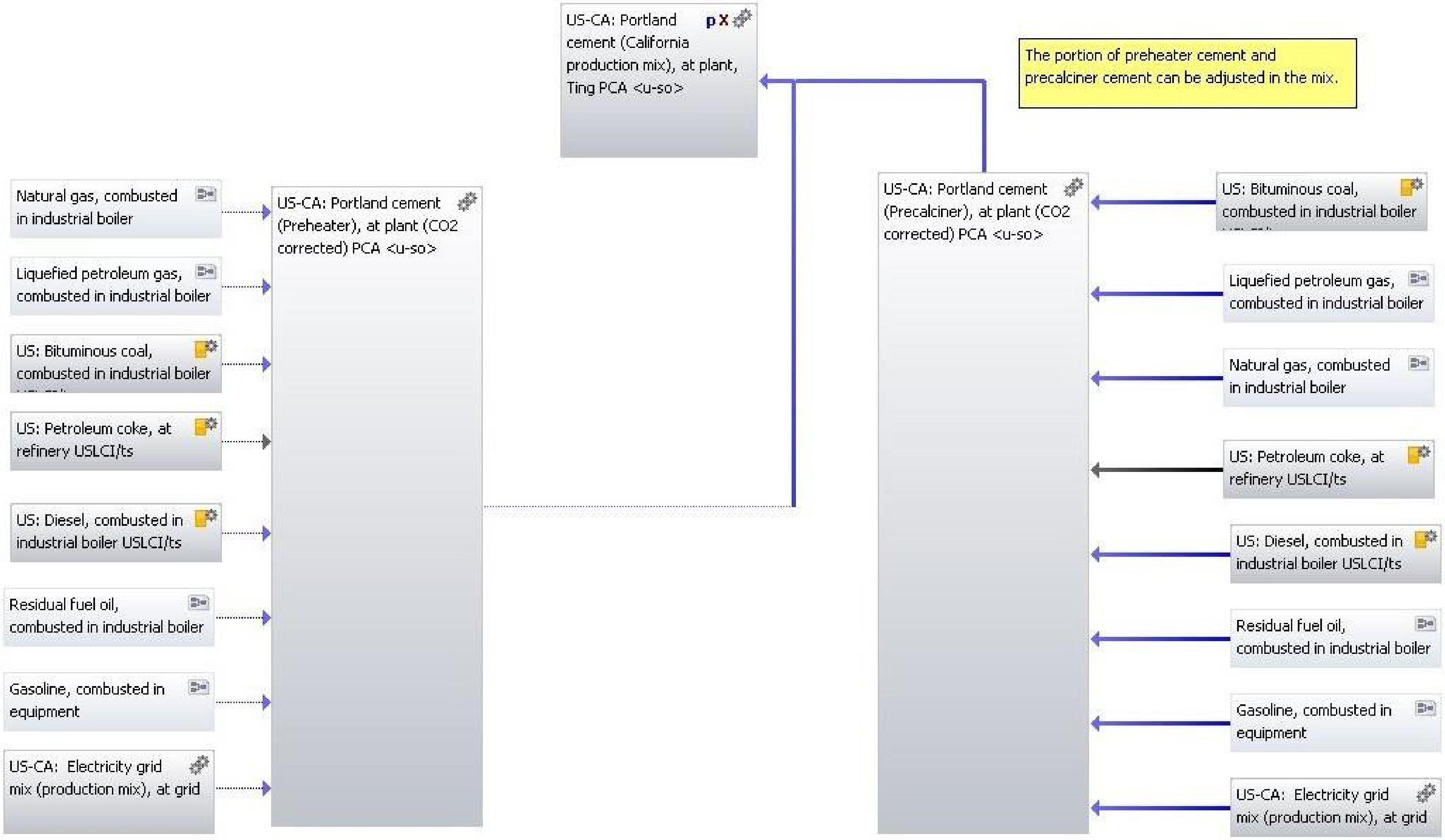
Ordinary Portland Cement 2016

Two cement production methods were considered: precalciner and preheater. The general model developed includes both and allows a user to define what percentage of the final product is made with each method (which enables a user to closely represent average local conditions). The first LCI model for OPC was developed by the UCPRC in 2016 based on the PCA report *(22)*, with the electricity component modified to represent the California grid mix of 2012. Although the process CO_2 was overestimated in the USLCI database due to double counting of the emissions from energy production for heating of minerals to create cement, this was corrected by changing the process CO_2 using Xu et al. *(29)*.

The general model for OPC is presented in Figure 2.9, and Table 2.8 shows the model's input and output flows. In developing this LCI, it was assumed that all cement used in California is produced in the state. Based on correspondence with the California Nevada Cement Association in 2016, it is likely that at least 95% of the cement produced in the state was produced in precalciner plants. Therefore, for the results reported in this memorandum, it was assumed that 100% of the cement was produced by precalciner plants. In 2016, it was also assumed that most of the cement used in California was produced in California or Nevada. As cement use has grown, the expectation is that increasing amounts of cement are being imported into California, and how those cements are being produced is unknown.

For many materials, fuel and electricity consumption are the two major sources of CO_2 emissions during the material production stage, but in cement production the heating of limestone at the pyroprocessing step is a source of CO_2 emissions nearly equal to those two sources. This is due to a process called *calcination* that occurs when limestone and other raw feeds are heated. During calcination, these materials undergo a series of mineral phase transitions, one of which is the formation of calcium oxide (CaO) from calcium carbonate ($CaCO_3$, the primary mineral compound in limestone) as CO_2 is driven out of the latter compound.

The amount of CO_2 released during pyroprocessing can 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. Mineral phase composition of OPC by Quillin *(30)* and shown in Table 2.9 was used to model OPC. The main components of OPC 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 also shown in Table 2.9. The results in the table show that the amount of CO_2 released by calcination is highly dependent on the mineral phases in the clinker used to make a kilogram of cement.



The portion of preheater cement and precalciner cement can be adjusted in the mix.

Note: Model developed in *GaBi* using information from Xu et al. *(29)* and USLCI database data.

Figure 2.9: General model developed for cement production.

Table 2.8: Inputs and Outputs of the General Model for Cement

Parameter	Flow	Quantity	Amount	Unit
Input				
Precalciner	Cement (average) [Minerals]	Mass	1	kg
Preheater	Cement (CEM 1) [Minerals]	Mass	0	kg
Output				
Total	Cement (average) [Minerals]	Mass	1	kg

Note: The model can be modified by a user.

Table 2.9: Mineral Phase Composition of Portland Cement (Type I/II and III) and Calcium Sulfoaluminate Cement

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%
CO_2 release (g)	**579**	**512**	**489**	**362**	**216**

Source: Quillin (2007) *(30).*

The composition of the mineral phases of OPC and CSA cement also change the temperatures used to produce them, which affects the energy use for the pyroprocessing phase. Alite, the main component of OPC, starts to form at temperatures around 1,300°C and belite starts to form at 1,200°C. Thus, OPC is manufactured at about 1,450°C, while CSA cement is produced at about 1,300°C.

Although the mineral phase compositions of Type I and Type III portland cement (PC) are similar, Type III PC is more finely ground. Type I is ground to a surface area of 330 to 380 m^2/kg, while Type III is ground to 400 to 450 m^2/kg. For the purposes of this study, it was assumed that the only difference between Type I and Type III is their surface area, and therefore the only differences in the LCI resulted from the grinding process. 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.

Ordinary Portland Cement 2016 (Modified in 2021)

To update the OPC model with a newer kiln fuel mix, the PCA cement inventory *(22)* was updated using 2019 California data. The existing kiln heating fuel mix used in the cement model that was developed in 2012 (see Figure 2.9) was replaced by the kiln fuel mix published by CARB *(31)* shown in Table 2.10. All the other assumptions and calculations are the same as those discussed in the earlier OPC 2016 section.

Table 2.10: Heating Fuel Mix in a Cement Kiln

UCPRC Fuel names	Percent by Mass (existing from PCA)[a] (%)	Percent by Mass (applied using CARB 2019)[b] (%)
Bituminous Coal	82	70.4
Liquified Petroleum Gas	0	0.0
Natural Gas	4	0.3
Petroleum Coke	11	13.3
Municipal Solid Waste (MSW)[c]	3	16[c]
Biomass	0	
Tires	0	

[a] Percentage of quantity of fuels by weight per fuel type that exists in the current UCPRC OPC model.

[b] Percentage of quantity of fuels by weight per fuel type that were used to update the UCPRC OPC model.

[c] CARB kiln mix reports tires and biomass fuel use as well. It was assumed that biomass and tires waste are part of MSW.

Ordinary Portland Cement 2021

The UCPRC is continuously updating the life cycle models for California based on any new and updated information that is publicly available. The UCPRC LCI draft report was reviewed by external critical reviewers and different industries, including the cement and concrete industries. As an outcome of the review and discussion with the California Nevada Cement Association (CNCA), the UCPRC decided to update the OPC model and use the most up-to-date 2019 California electricity grid mix data *(20)* and CARB heating fuels mix (used in a cement kiln) data *(31)*. *GaBi* was used to model the OPC, and the resulting model is shown in Figure 2.10.

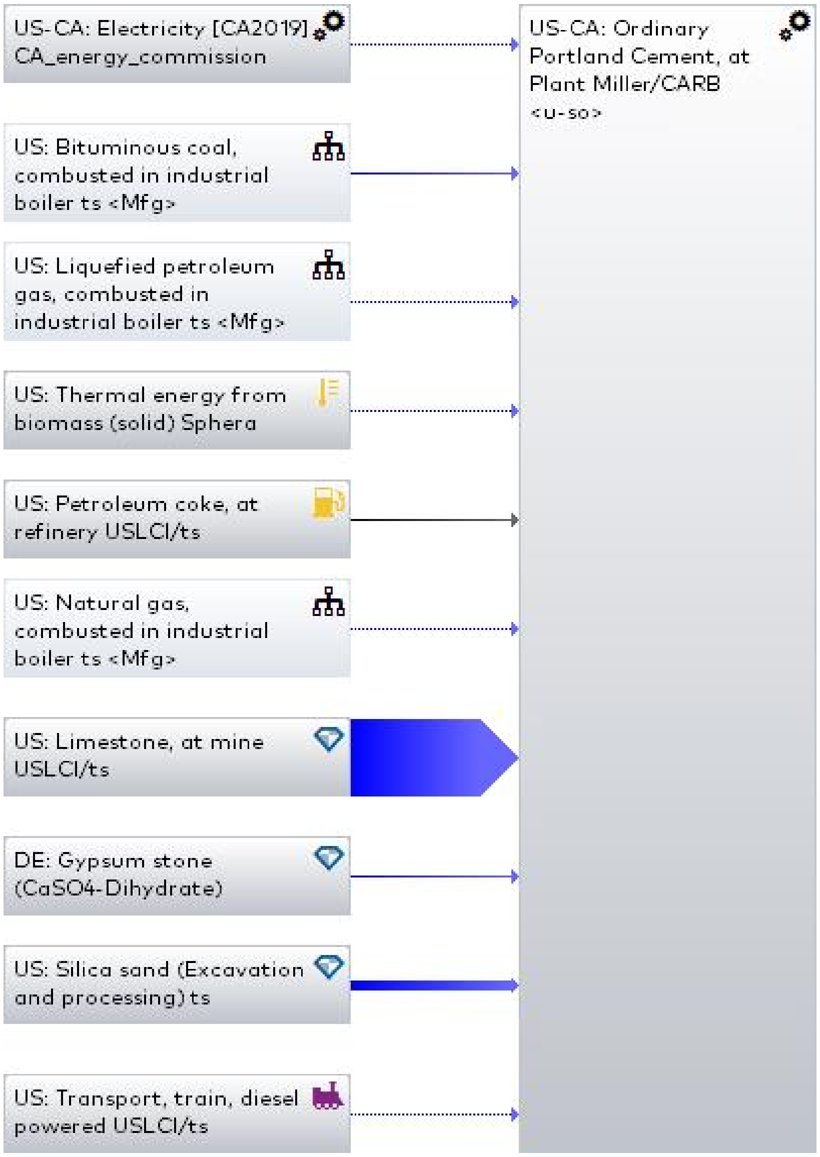


Figure 2.10. The OPC model developed in 2021.

Miller and Myers *(32)* quantified the energy requirement to carry out pyroprocessing of the clinker. This included the chemical reactions in the cement kiln at high temperatures and enthalpies of reactions for the different chemical conversions (raw materials to clinker phases; enthalpy of formation at 77°F). The OPC mineral composition (as shown in Table 2.11), kiln thermal energy (3 MJ), electric energy at the plant (0.517 MJ/kg of OPC), transportation distance for raw materials to cement kiln (874 kg.km), and intrinsic CO_2 emissions of reaction (0.513 g per g of OPC) were taken from Miller and Myers *(32)*. Due to unavailable mineral production models for clay, iron ore, anhydrite, and gypsum, the upstream data for these minerals were not included in the cement model (all minerals production GWP per kg of OPC account for almost 0.139% of the total OPC production GWP as shown by Miller and Myers *[32]*). The kiln fuel mix used in the OPC model is shown in Table 2.12.

Table 2.11: Ordinary Portland Cement Raw Material Inventory

Cement Type	Limestone (kg/kg)	Clay (kg/kg)	Iron Ore (kg/kg)	Anhydrite (kg/kg)	Silica Sand (kg/kg)	Gypsum (kg/kg)
OPC	1.247	0.203	0.031	0.053	0.160	0.053

Source: Miller and Myers (2020) *(32)*.

Table 2.12: Kiln Thermal Energy Mix

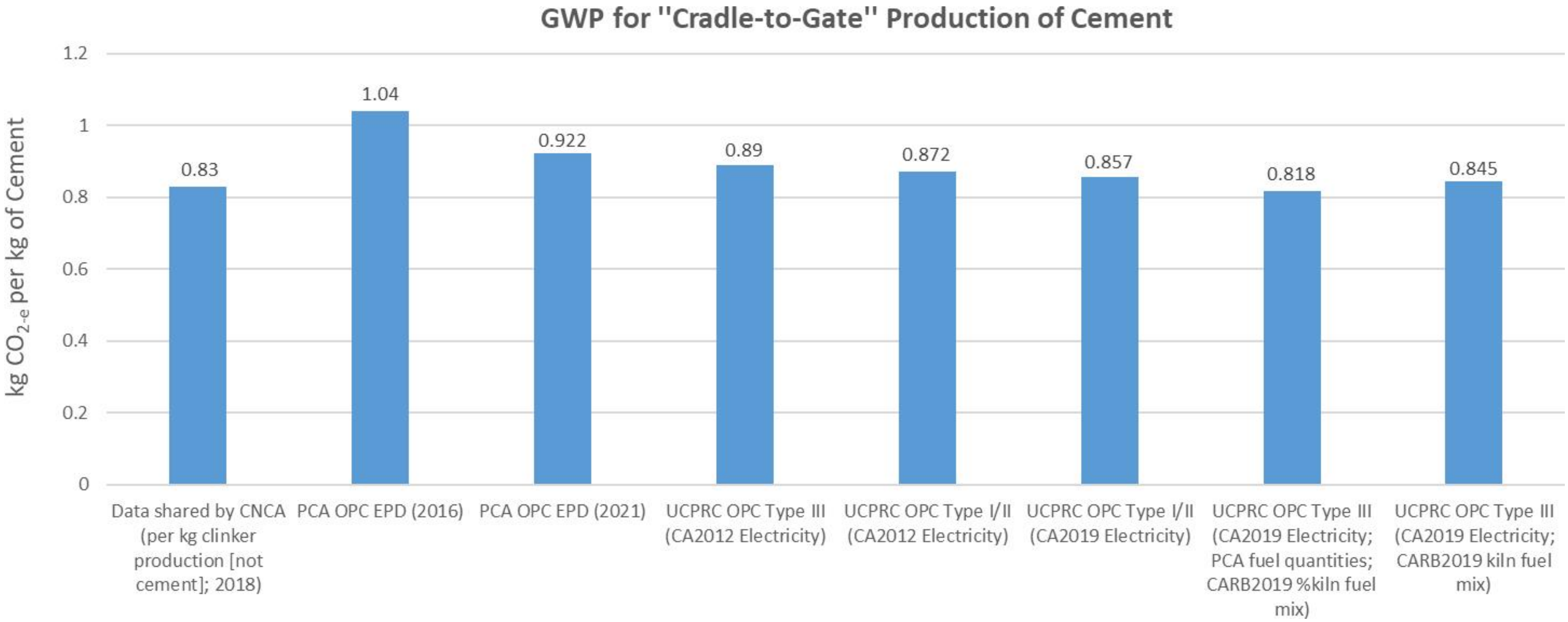
UCPRC Fuels	Percent by Energy (%)	Fuel Mix per kg of OPC	Units
Bituminous Coal	59.66	66.3	kg
Liquified Petroleum Gas	0.002	5.94E-04	m^3
Natural Gas	15.46	12.00	m^3
Petroleum Coke	14.38	12.40	kg
Biomass	3.71	315.1[a]	MJ
Municipal Solid Waste (MSW)	0.75		
Tires	6.05		

Note: Based on data from California Air Resources Board *(31)* and Miller and Myers *(32)*.

[a] Kiln thermal energy from MSW and tires was added to the thermal energy from biomass due to unavailable incineration models of waste tires and MSW.

Global Warming Potential Comparison of Ordinary Portland Cement from Different Data Sources

Figure 2.11 shows a comparison of GWP values for "cradle-to-grave" production of 1 kg of OPC from this study for different cement types (labeled UCPRC) and from several other commonly cited studies. The CNCA GWP numbers for the clinker are the lowest; however, the GWP from processing clinker to cement are not included in this value. The GWP values from the PCA cement EPDs were determined to be high compared to expected California production. As the energy foreground data are not reported in the EPDs, it is hard to identify the reason for such higher values. A slight reduction in GWP values (0.872 to 0.857 kg $CO_{2\text{-}e}$) for UCPRC portland cement Type I/II production using the 2019 electricity grid mix (compared to 2012) is mainly due to the increased use of renewables for the generation of electricity grid mix (use of renewables for electricity generation are double in 2019 California electricity grid mix compared to 2016 California electricity grid mix). The GWP values were found to be the lowest when PCA kiln fuel quantities were recalculated using CARB's 2019 kiln fuel mix percentages (0.818 kg $CO_{2\text{-}e}$), when PCA kiln fuel mix was replaced by CARB's 2019 kiln fuel mix (0.845 kg $CO_{2\text{-}e}$), and when inventories from Miller and Myers *(32)* were used.



Notes:

- Summary results file acquired from personal contact with California Nevada Cement Association (CNCA). The GWP was calculated by divided the CARB GHG emissions data from the production of cement by the US Geological Survey clinker production data for the year 2018.
- Ordinary portland cement (OPC) environmental product declaration (EPD) from Portland Cement Association (2016) *(33)*.
- Ordinary portland cement (OPC) environmental product declaration (EPD) from Portland Cement Association (2021) *(34)*.
- UCPRC cements that use 2012 electricity grid mix are taken from Table 2.15.
- UCPRC cement that uses 2019 electricity grid mix is taken from Table 2.16.

Figure 2.11. GWP values of OPC production from several sources.

Calcium Sulfoaluminate Cement

As mentioned earlier, the UCPRC LCI draft report was reviewed by external critical reviewers and different industries, including the cement and concrete industries. As an outcome of the review and discussion with CTS Cement Manufacturing Corporation and subject experts,[3] the UCPRC decided to develop the CSA cement model mainly based on the methodology that was adopted by Miller and Myers to model different types of cement *(32)*. Two belite-CSA cements were modeled in *GaBi*, shown in Figure 2.12: CSA cement with high sulfur content (CSA-HS) and CSA cement with low sulfur content (CSA-LS). The belite-CSA cement considered contains belite (22% to 71% by mass), ferrite (3% to 7% by mass) and ye'elimite (15% to 65% by mass). It was assumed that the belite-CSA cements were produced in California. Therefore, the most up-to-date 2019 California electricity grid mix *(20)* and CARB heating fuels mix (used in a cement kiln) *(31)* were used for CSA cement modeling.

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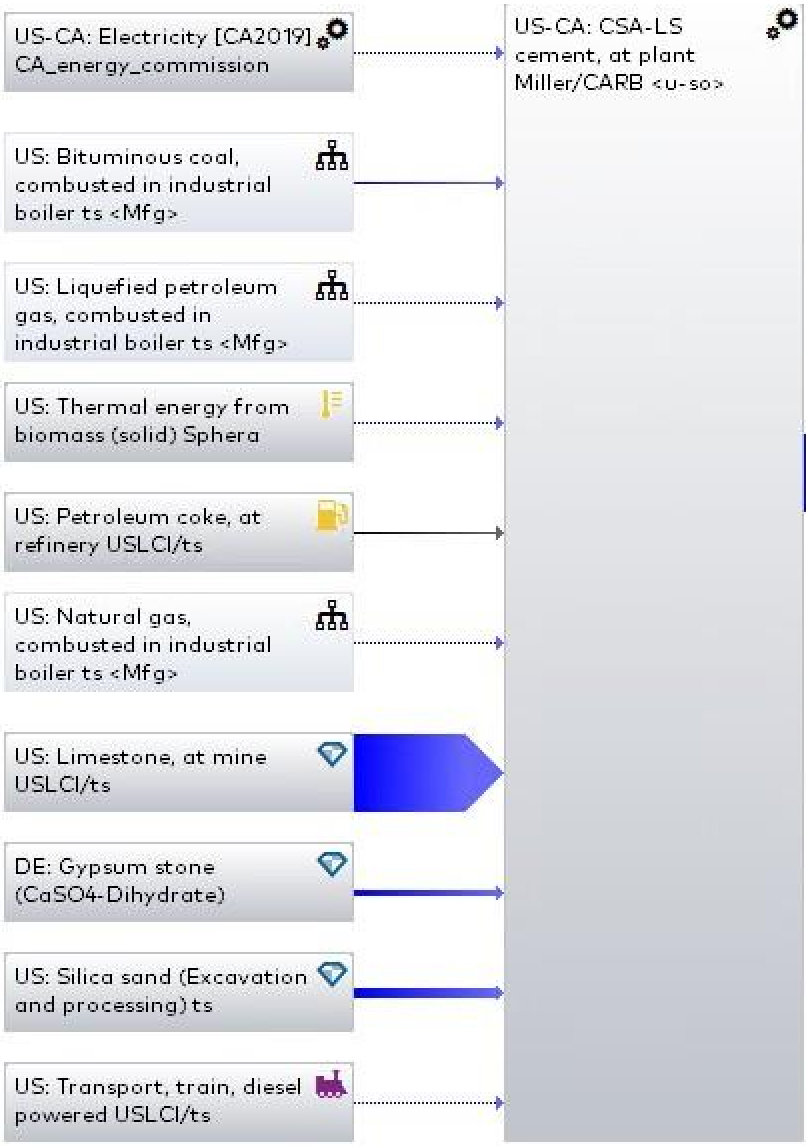
[3] Dr. Sabbie Miller from UC Davis and Dr. Eric P. Bescher from UCLA.



Note: The CSA-HS cement model is like the CSA-LS model. Only the input and output data quantities are different, and silica sand is produced instead of used in the processing *(32)*.

Figure 2.12. CSA-LS cement model.

Calculations by Miller and Myers *(32)* for the considered CSA cements showed that they required 27% to 37% lower net reaction enthalpy and emitted 18% to 48% less process-based CO_2 than OPC clinker. The belite-CSA cement mineral composition, kiln thermal energy, electric energy at the plant (0.517 MJ/kg of CSA cement), transportation distance for raw materials to cement kiln by rail, and intrinsic CO_2 emissions of reaction were obtained from Miller and Myers *(32)* and are summarized in Table 2.13. Due to unavailable mineral production models for clay, iron ore, anhydrite, and gypsum, the upstream data for these minerals were not included in the cement model (all minerals production GWP per kg of CSA cement account for less than 1.6% of the total CSA cement production GWP as shown by Miller and Myers *[32]*). The kiln fuel mix used in the CSA cement models is shown in Table 2.14.

Table 2.13: Input/Output Data Used in the CSA Models

Cement Type	Limestone (kg/kg)	Clay (kg/kg)	Iron Ore (kg/kg)	Anhydrite (kg/kg)	Silica Sand (kg/kg)	Gypsum (kg/kg)	Intrinsic CO_2 Emissions of Reaction (g per g of CSA)	Transport Distance for Raw Materials to Cement Kiln by Rail (kg.km)	Kiln Thermal Energy (enthalpy + inefficiency in MJ)
CSA-HS	0.652	1.382	0.011	0.288	-0.316	0.288	0.268	1152	2.388
CSA-LS	1.025	0.381	0.025	0.115	0.138	0.115	0.422	900	2.547

Source: Miller and Myers (2020) *(32)*.

Table 2.14: Kiln Thermal Fuel Mix

UCPRC Fuels	Percent by Energy (%)	Energy Density of Fuels	Units	Fuel Mix per kg of CSA-HS	Fuel Mix per kg of CSA-LS	Units
Bituminous Coal	59.66	27	MJ/kg	52.8	56.3	kg
Liquified Pet. Gas	0.002	46	MJ/kg	4.73E-04	5.04E-04	m^3
Natural Gas	15.46	38.661	MJ/m^3	9.55	10.19	m^3
Petroleum Coke	14.38	34.8	MJ/kg	9.87	10.52	kg
Biomass	3.71	16	MJ/kg	250.8[a]	267.5 [a]	MJ
Municipal Solid Waste (MSW)	0.75	13.37	MJ/kg			
Tires	6.05	32.564	MJ/kg			

Source: California Air Resources Board *(31)* and Miller and Myers *(32)*.

[a] Kiln thermal energy from MSW and tires was added to the thermal energy from biomass due to unavailable incineration models of waste tires and MSW.

Supplementary Cementing Material Cements

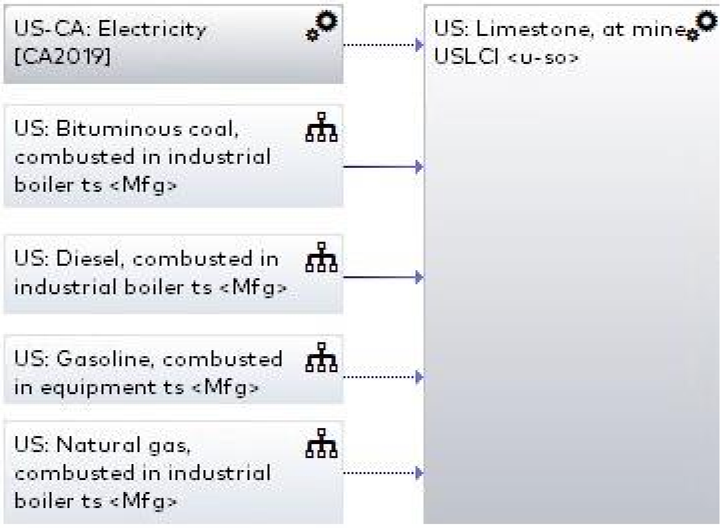
Slag Cement

The LCI for portland cements with 19% slag and 50% slag was taken directly from the ecoinvent database incorporated in the *GaBi* software; however, the models could not be modified to represent the electricity grid mix in California because only the final LCIs were available. The LCIs taken from ecoinvent were developed in 1997 and are based on technology and manufacturing processes in Switzerland *(8)*.

Portland-Limestone Cement

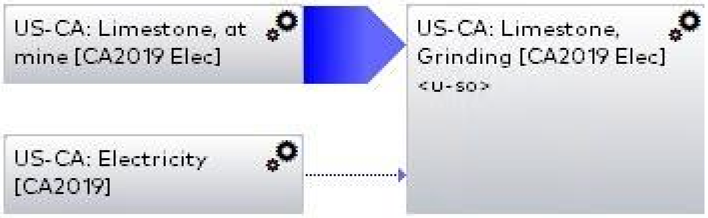
Portland-limestone cement (PLC) is a blended cement that is becoming popular in road construction due to use of 5% to 15% of finely ground limestone. It has been used in other states and countries, and it is being introduced in

California. PLC has lower environmental burden due to use of less clinker. Modeling of several OPCs was discussed earlier. The model for limestone was taken from *GaBi*, and the electricity model was replaced with a model that was developed to represent California local conditions. Figure 2.13 shows the limestone production model, and Figure 2.14 shows the limestone grinding model developed in *GaBi*. The percentage impacts from OPC and grinded limestone are added to get the total impacts of PLC.



Note: Model developed in *GaBi* using California electricity grid mix *(20)*.

Figure 2.13: Model developed for limestone.

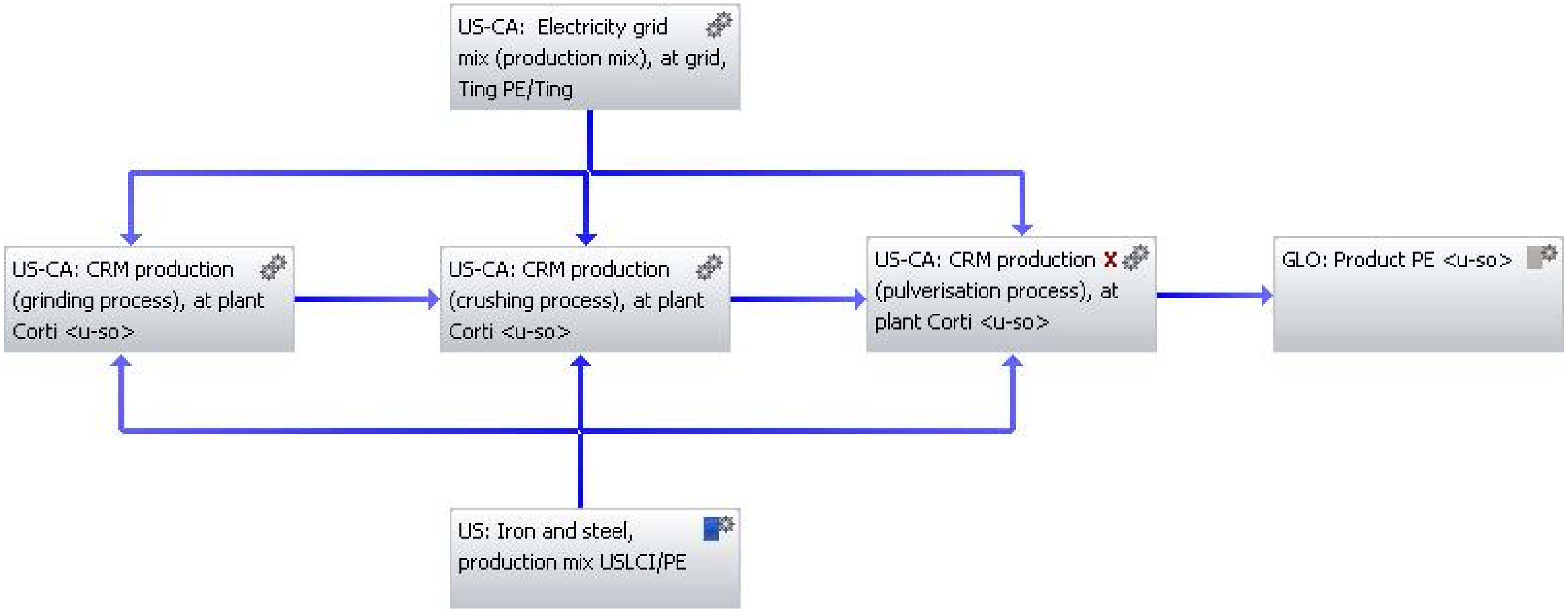


Note: Model developed in *GaBi* using 2019 California electricity grid mix *(20)* and Miller and Myers *(32)* grinding energy value.

Figure 2.14. Model developed for grinding limestone.

2.2.4 Crumb Rubber Modifier

A new model for CRM was developed using *GaBi* based on Corti and Lombardi *(35)*. The model is presented in Figure 2.15. The model's main processes include grinding the tires to 7 to 10 cm followed by the second step called crushing (essentially further grinding) to 2 cm and lastly pulverizing to less than 1 mm. The grinding process is done using water and oil while the crushing process is a dry process. The cutoff method was used as the allocation method for crumb rubber modifier, with all the impacts of producing and using the initial material, the tire, allocated to the upstream processes, and the recycling process impacts that result from producing CRM allocated to the CRM (see Table 1.4).

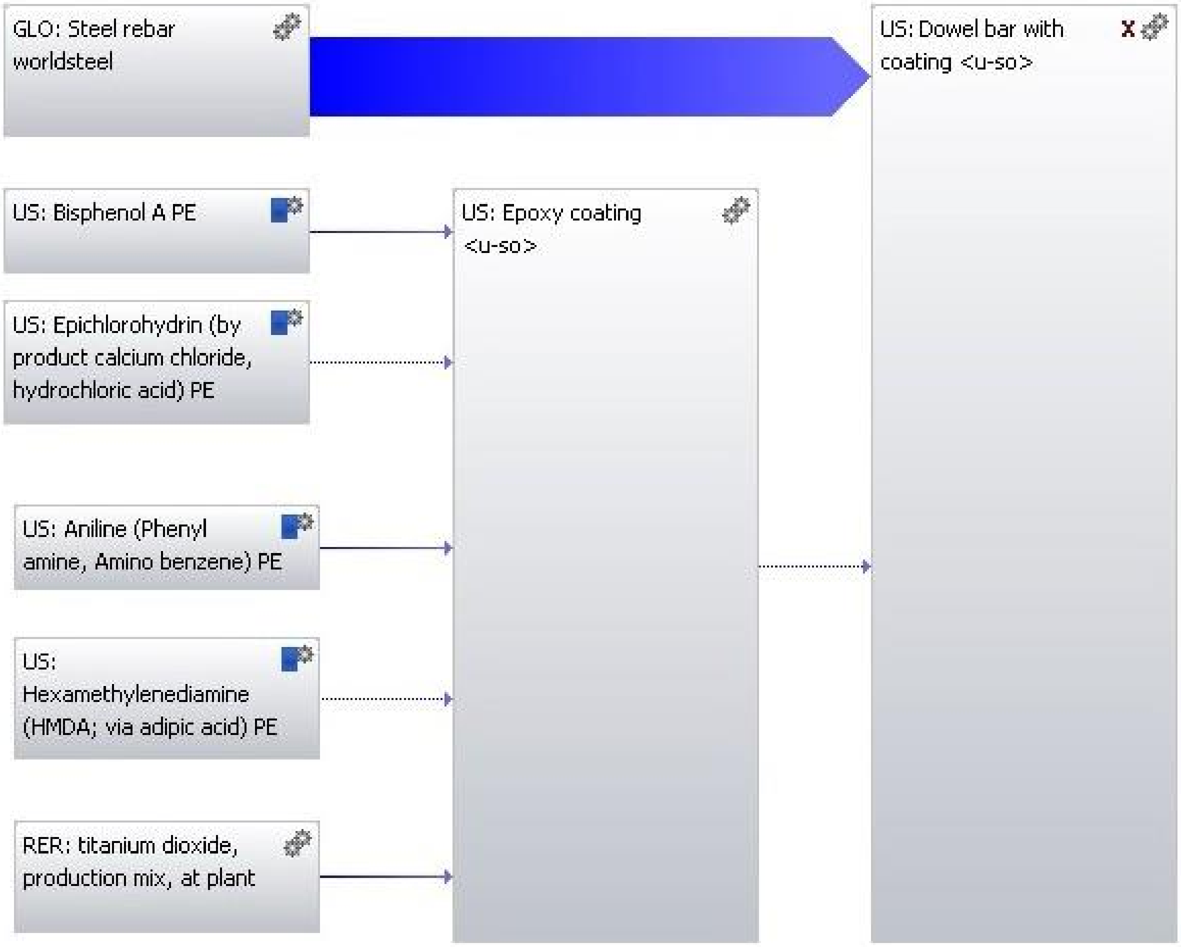


Note: Model developed in *GaBi*.

Figure 2.15: Model developed for CRM.

2.2.5 Dowel and Tie Bar

Dowel and tie bar models were developed in *GaBi* using the software's predefined models for producing the steel and the epoxy coating for covering the bars. The electricity used in the coating process was not included because reliable data were unavailable and because the process energy was assumed to be insignificant compared to the energy consumed to produce the steel and epoxy. Figure 2.16 shows the model developed. The mass of the dowels and tie bars were taken from ASTM A615/A615M and the epoxy specifications were taken from ASTM A775/A775M.



Notes:
- Model developed in *GaBi*.
- Mass of steel and epoxy coating would differ for different bar diameters.

Figure 2.16: Model developed for dowels and tie bars.

2.2.6 Other Materials

The items and materials taken directly from *GaBi* include cement admixtures, hydrated lime (dry slacked), paraffin (wax), quicklime, and styrene butadiene rubber (SBR).

2.2.7 Summary of the Cradle-to-Gate Impacts for Conventional Materials

Table 2.15 summarizes the material stage impacts for the conventional materials included in the database developed in this project. Table 2.16 summarizes the selected LCI and LCIA results for the conventional materials included in the database using the 2019 electricity grid mix. This table only contains the items that could have the electricity process in their model changed.

Table 2.15: Cradle-To-Gate Impacts for Conventional Materials

Item	Functional Unit	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-renewable)[b] [MJ]	Feedstock Energy [MJ]
Aggregate (Crushed)	1 kg	3.43E-03	6.53E-04	1.59E-06	6.04E-02	5.24E-02	0.00E+00
Aggregate (Natural)	1 kg	2.36E-03	4.04E-04	9.54E-07	4.31E-02	3.65E-02	0.00E+00
Virgin Asphalt Binder	1 kg	4.75E-01	8.09E-02	4.10E-04	4.97E+01	4.93E+01	4.02E+01
Asphalt Emulsion	1 kg of Residual Asphalt Binder	5.07E-01	8.23E-02	4.17E-04	5.09E+01	5.04E+01	4.02E+01
Cement (CSA)	1 kg	8.42E-01	7.10E-02	4.61E-04	5.48E+00	5.13E+00	0.00E+00
Cement (Portland Type I/II)	1 kg	8.72E-01	7.28E-02	4.99E-04	5.94E+00	5.58E+00	0.00E+00
Cement (Portland Type III)	1 kg	8.90E-01	7.33E-02	5.01E-04	6.26E+00	5.83E+00	0.00E+00
Cement (Portland with 19% SCM)	1 kg	7.04E-01	2.60E-02	1.78E-04	3.40E+00	3.20E+00	0.00E+00
Cement (Portland with 50% SCM)	1 kg	4.45E-01	1.76E-02	1.23E-04	2.75E+00	2.56E+00	0.00E+00
Cement Admixtures (Accelerator)	1 kg	1.26E+00	5.71E-02	1.88E-04	2.28E+01	n/a	n/a
Cement Admixtures (Air Entraining)	1 kg	2.66E+00	8.68E+00	2.55E-03	2.10E+00	n/a	n/a
Cement Admixtures (Plasticizer)	1 kg	2.30E-01	1.34E-02	5.57E-05	4.60E+00	n/a	n/a
Cement Admixtures (Retarder)	1 kg	2.31E-01	4.23E-02	9.81E-05	1.57E+01	n/a	n/a
Cement Admixtures (Superplasticizer)	1 kg	7.70E-01	4.55E-02	2.33E-04	1.83E+01	n/a	n/a
Cement Admixtures (Waterproofing)	1 kg	1.32E-01	4.00E-02	6.73E-05	5.60E+00	n/a	n/a
Crumb Rubber Modifier (CRM)	1 kg	2.13E-01	6.90E-03	1.05E-04	4.70E+00	3.60E+00	3.02E+02
Dowel with Epoxy Coating (32 mm thick [1.25 in. thick])	1 dowel (0.46 m [18 in.] long)	3.69E+00	1.30E-01	1.39E-03	4.87E+01	4.20E+01	0.00E+00
Hydrated Lime Dry Slaked (agg)	1 kg	9.37E-01	7.52E-03	8.49E-05	4.38E+00	4.34E+00	0.00E+00
Paraffin (Wax)	1 kg	1.37E+00	7.57E-02	4.70E-04	5.46E+01	5.43E+01	0.00E+00
Quicklime	1 kg	1.40E+00	3.52E-02	7.11E-04	7.88E+00	7.88E+00	0.00E+00
Reflective Coating (BPA) [50/50]	1 kg	8.13E-03	1.50E-03	4.60E-06	3.79E-01	3.73E-01	2.41E-01
Styrene Butadiene Rubber (SBR)	1 kg	4.13E+00	1.29E-01	4.48E-04	1.03E+02	1.02E+02	0.00E+00
Tie Bar (19 mm [3/4 in. thick])	1 tie bar (0.76 m [30 in.] long)	2.25E+00	7.99E-02	8.53E-04	3.00E+01	2.60E+01	0.00E+00

Note: Based on 2012 California Electricity Grid Mix *(19)*.

[a] The total primary energy demand excluding the feedstock energy, where feedstock energy is available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[b] Same note as above applies to PED (Non-Renewable). PED from non-renewable resources (net calorific value).

Table 2.16: Cradle-To-Gate Impacts for Materials

Item	Functional Unit	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Renewable)[b] [MJ]	Feedstock Energy [MJ]
Aggregate (Crushed)	1 kg	2.85E-03	6.32E-04	1.46E-06	6.63E-02	4.47E-02	0.00E+00
Aggregate (Natural)	1 kg	1.86E-03	3.86E-04	8.42E-07	4.68E-02	2.98E-02	0.00E+00
Virgin Asphalt Binder	1 kg	4.49E-01	7.99E-02	4.04E-04	4.98E+01	4.90E+01	4.02E+01
Asphalt Emulsion	1 kg of Residual Asphalt Binder	4.71E-01	8.10E-02	4.09E-04	5.12E+01	4.99E+01	4.02E+01
OPC Type I/II (PCA kiln fuel mix)	1 kg	8.57E-01	7.21E-02	4.94E-04	6.50E+00	5.39E+00	0.00E+00
OPC Type III (PCA fuel quantities; CARB2019 kiln %fuel mix)	1 kg	7.94E-01	6.96E-02	2.58E-04	5.47E+00	4.65E+00	0.00E+00
OPC Type III (CARB2019 kiln fuel mix)	1 kg	8.21E-01	7.55E-02	1.69E-04	5.75E+00	4.61E+00	0.00E+00
CSA-HS	1 kg	5.24E-01	7.25E-02	1.57E-04	4.94E+00	3.86E+00	0.00E+00
CSA-LS	1 kg	6.93E-01	7.03E-02	1.55E-04	5.19E+00	4.09E+00	0.00E+00
Limestone, at mine	1 kg	3.66E-03	1.83E-04	1.23E-05	8.14E-02	5.74E-02	0.00E+00
Limestone, grinded	1 kg	1.39E-02	5.01E-04	1.37E-05	4.49E-01	2.51E-01	0.00E+00
Portland-Limestone Cement (PLC)[c]	1 kg	7.31E-01	6.14E-02	4.22E-04	5.59E+00	4.62E+00	0.00E+00
Crumb Rubber Modifier (CRM)	1 kg	2.03E-01	6.70E-03	1.05E-04	4.70E+00	3.59E+00	0.00E+00

Note: Based on 2019 California Electricity Grid Mix *(20)*.

[a] The total primary energy demand excluding the feedstock energy, where feedstock energy is available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[b] Same note as above applies to PED (Non-Renewable). PED from non-renewable resources (net calorific value).

[c] PLC: 85% of OPC Type I/II (PCA kiln fuel mix) and 15% of grinded limestone.

2.3 Recyclable Materials

The production and use of recycled materials is one of the places where allocation issues arise. The waste management process can be divided into two separate categories: (1) waste for landfills and (2) recycling. Currently, the UCPRC does not have highway construction waste as landfill inventories. This process has not been properly developed and has been identified as a major gap in pavement LCAs. The current assumption is that demolished highway materials are 100% recyclable and are used as reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), or other pavement layers. The UCPRC has assumed production of RAP and RCA to be a credit because it replaces virgin materials resulting in less use of energy and resources for production and less emissions to air, land, and water. Therefore, RAP and RCA are allocated zero impacts other than demolition construction processes, transportation, and further processing.

2.3.1 Reclaimed Asphalt Pavement

RAP is the material produced when the asphalt concrete layer is milled. UCPRC has divided the production and use of RAP into two categories: (1) in-place recycling and (2) in-plant recycling.

<u>In-Place Recycling</u>

In this category, UCPRC has modeled full-depth reclamation (FDR) and partial-depth reclamation (PDR) processes where the existing pavement is milled, mixed with new material or materials, if needed, and paved back in a single operation. FDR and PDR processes and details are provided in Appendix E.

<u>In-Plant Recycling</u>

Production and use of RAP material depends on which of the following scenarios is being considered:

(1) A project uses RAP already at the plant
   i. No fractionation or processing: RAP will have zero impacts allocated to it if the asphalt plant is using RAP from stockpiles that are existing at that plant from previous projects. The impacts of milling and transport to the plant will have been part of previous projects in which the plant participated.
   ii. Fractionation and processing: RAP will be allocated the impacts of fractionation used in the current project.

(2) A project uses RAP from a different site
   i. No fractionation or processing: RAP will be allocated the impacts from the transportation of RAP material from RAP stockpiles located elsewhere to the current project site/asphalt plant.
   ii. Fractionation and processing: RAP will be allocated the impacts that arise from the transportation of RAP material from RAP stockpiles located elsewhere to the current project site/asphalt plant, in addition to the impacts from fractionation.

(3) A project produces and uses RAP from the same site
   i. No fractionation or processing: The impacts of milling and RAP transportation from the site to the asphalt plant are allocated to the current project.
   ii. Fractionation and processing: Impacts of milling and RAP transportation from the site to the asphalt plant are allocated to the RAP. Impacts from the fractionation process will only be allocated to the RAP that is used in the current project.

(4) A project produces RAP but does not use it in the current project
   i. No fractionation or processing: The impacts of milling and RAP transportation from the site to the final destination as part of the current project are allocated to the current project.
   ii. Fractionation and processing: Impacts are not applicable to the current project.

Determining a single constant impact value for RAP is difficult as RAP inventories depend on the milling process (which is highly dependent upon the thickness of the milled layer) and transportation distances; both processes require user input. Instead of stating example values, the process for how impacts/LCIAs are calculated is provided in this section.

The user-defined dimensions of the pavement layer that is to be milled are required. Using the milling equipment data (see milling example in Appendix D), total diesel fuel use (needed to mill user-defined pavement structure) is quantified. The total fuel used is then multiplied by the inventory (and impact indicators) of diesel combusted in industrial equipment (Table 2.3) to get to the emissions and environmental impacts of the construction stage.

The transportation impacts are calculated based on (1) the inventories defined in Section 2.1.2 or Section 2.6.1 and (2) the project-specific user-defined materials transport distances. To calculate these impacts, the total mass of RAP produced during the milling process is multiplied by the LCI for 1,000 kg-km of materials being transported by truck. Thus, the total RAP impacts can then be calculated by adding the impacts from combustion of diesel in the industrial equipment plus from the combustion of diesel in the truck. Importantly, impacts of oil extraction, transport to the refinery, and diesel production at the refinery are also included in the calculations. The transportation of fuel to the construction site to fuel the equipment is not included as these impacts are too small to affect the results.

2.3.2 Recycled Concrete Aggregate

RCA is the material produced by breaking the existing concrete slabs. This material is mainly considered to be used as a replacement for natural aggregate. Like RAP, impacts allocated to RCA also depend on the scenario in which it is being used. The same approach for RAP is used for RCA, except that the demolition process and processing for next use are different. RCA is assumed to be used as the aggregate base and can also be used as aggregate in lean concrete base.

Life cycle impacts of RCA (just as for RAP) also depend on what project-specific information the user has. Impacts from diesel combusted to run the guillotine/rubblizer and diesel combusted to transport RCA on trucks results in the LCIAs for RCA for the project defined by the user.

2.4 Material Production Stage for Reflective Coatings

Four major types of reflective coatings were identified after conducting a literature review with colleagues from Chinese universities who had worked extensively with them. Two of the types are epoxy or resin based, and two are water based. Data on the chemical composition and mass breakdown of an example of each coating type were extracted from the literature and sent to thinkstep, the *GaBi* software's parent company. Using these data, thinkstep developed models for each reflective coating type, incorporated them into *GaBi* v6.3, and then provided this study with the LCIs based on the *GaBi* 2014 database.[4] However, thinkstep did not share the actual models with the UCPRC and, therefore, images of the model structure and unit processes cannot be shared.

Table 2.17 shows the chemicals in each of the four coating types, with the mass breakdown. Producing this table required multiple resources *(36-41)*. The table also shows the LCI dataset from *GaBi* v6.3 that was used to model each process. For most cases, matching LCI datasets were found; in cases where matching datasets were not available, proxy datasets were used. The table also shows the region where the LCI datasets were taken from since the production processes for a product can differ from region to region, yielding different LCIs for the same product; US data were given preference. The datasets developed in this project represent the cradle-to-gate system boundary, meaning that all upstream material and energy consumption and emissions and waste are included, from the extraction of raw materials to the transportation and processing in the plant. The LCIs also include an estimated electricity use of 0.1 MJ/kg for mixing the various chemicals together; this accounts for less than 1% of the total primary energy demand of the coating. Table 2.18 summarizes the main inventory items and LCIA categories of interest for the reflective coatings.

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[4] *GaBi* Life Cycle Assessment software, v6.3.

Table 2.17: Chemicals in Each Coating, Mass Breakdown, and LCI Datasets Used

Coating Type	Chemical Name	% Mass	Representative LCI Dataset	Dataset Country/ Region
A. Polyester Styrene	Unsaturated polyester resin	60	Polyester resin unsaturated (UP)	DE
	Styrene	24	Styrene	US
	Titanium dioxide	8	Titanium dioxide pigment	US
	Silicon dioxide	4	Silica sand (flour)	US
	Iron oxide	1	Iron oxide (Fe_2O_3) from iron ore	DE
	Polysiloxane	0.5	Siloxane (cyclic) (from organosilanes)	DE
	Ethylene bis(steramide)	0.5	Ethanediamine	DE
	Cobalt napthenate	2	Cobalt mix	GLO
B. BPA	Bisphenol A epoxy resin	75	Bisphenol A	US
	Titanium dioxide	10	Titanium dioxide pigment	US
	Carbon black	0.5	Carbon black (furnace black; general purpose)	US
	Propylene glycol phenyl ether	3	Dipropyleneglycol dibenzoate plast	EU-27
	Glycerol monostearate	1.5	Stearic acid	DE
	Tetramethylethylenediamine	10	Tetraacetyl ethylenediamine (TAED)	NL
C. Styrene Acrylate (water based)	Styrene	7.7	Styrene	US
	Titanium dioxide	6	Titanium dioxide pigment	US
	Butyl acroylate	13	Butyl acrylate	DE
	Methyl acrylate	5.4	Methyl acrylate from acrylic acid by esterification	DE
	Methacrylic acid	3	Methacrylic acid	US
	Zinc oxide	6	Zinc oxide	GLO
	Ammonium persulfate	0.18	Ammonium sulfate, by product acrylonitrile, hydrocyanic acid	US
	N-dodecyl mercaptan	0.1	Methanthiol (methyl mercaptan)	US
	Ammonium sulfite	0.02	Sodium hydrogen sulfite	EU-27
	HydroxypropanE-1-sulfonate	1.6	Soaping agent (sodium alkyl-benzene sulfonate)	GLO
	Azirdine	1	Hydrazine hydrate/hydrazine	DE
	Ammonium hydroxide	1	Tetramethyl-ammonium hydroxide (TMAH)	US
	Water	55	Water deionized	US
D. Polyurethane (water based)	cis-1,4-cyclohexylene di-isocyanate	8	Isophorone di-isocyanate (IPDI)	DE
	Polyester polyols	18	Long Chain Polyether Polyols mix	EU-27
	Titanium dioxide	12	Titanium dioxide pigment	US
	Silicon dioxide	0.6	Silica sand (flour)	US
	Sodium dodecyl sulfate	2	Detergent (fatty acid sulfonate derivate)	GLO
	1,6-Di-isocyanatohexane	3	Methylene di-isocyanate (MDI)	DE
	2,2-Bis(hydroxymethyl)propionic acid	2	Adipic acid	DE
	Polydimethylsiloxane	0.4	Siloxane (cyclic) (from organosilanes)	DE
	Water	54	Water deionized	US

Note: Information acquired from *Gabi* v6.3 software.

Table 2.18: Cradle-To-Gate Impacts of Reflective Coatings

Item	Functional Unit	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Ren)[b] [MJ]	Feedstock Energy [MJ]
BPA	1 kg	3.73E+00	1.61E-01	1.41E-07	9.08E+01	8.86E+01	0.00E+00
Polyester Styrene	1 kg	4.40E+00	2.08E-01	2.23E-06	9.17E+01	8.74E+01	0.00E+00
Polyurethane	1 kg	2.34E+00	1.02E-01	2.20E-07	5.15E+01	4.90E+01	0.00E+00
Styrene Acrylate	1 kg	1.56E+00	6.34E-02	3.88E-07	3.66E+01	3.54E+01	0.00E+00

[a] The total primary energy demand excluding the feedstock energy, where feedstock energy is available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[b] Same note as above applies to PED (Non-Renewable). PED from non-renewable resources (net calorific value).

2.5 Summary of UCPRC Items/Processes in Inventory as of July 2021

Table 2.19 identifies the sources of each UCPRC item or process and whether the data sources have been internally or externally critically reviewed. Unit processes (denoted as u-so) and cradle-to-gate (also denoted as agg) processes have also been reported for each UCPRC item.

Table 2.19: Data Sources and Data Quality Checks for UCPRC Items/Processes as of July 2021

Electricity	Electricity Grid Mix 2012	California Energy Almanac website.	Primary publicly available data.
	Electricity Grid Mix 2019	California Energy Commission.	Primary publicly available data.
	Unspecified portion of Grid Mix 2012: US: Electricity from Western US USLCI/ts[a] (agg)	Average Western US grid process (based on the US EPA's Emissions & Generation Resource Integrated Database [eGRID]). *GaBi*: This is a cradle-to-gate inventory generated by PE from unit process data in the USLCI database.	Most of the data in the USLCI database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
	US: Electricity from nuclear (West), ts (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from hard coal (West), ts (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from heavy fuel oil (West), ts (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from natural gas (West), ts (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from biomass (solid) (West) (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model Documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from hydro power Sphera (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from wind power Sphera (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from photovoltaic Sphera (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.

	US: Electricity from geothermal (UCPRC) (agg)	*GaBi*: The inventory is based on primary industry data. Data gaps are closed by secondary literature data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from biogas (UCPRC) (agg)	*GaBi*: The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from waste (UCPRC) (agg)	*GaBi*: The inventory is mainly based on industry data and is completed, where necessary, by secondary data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
Diesel	Diesel, combusted in Industrial Equipment (USLCI) (u-so)	*GaBi*: The original datasets and documentation can be found online: lcacommons.gov/nrel/search.	Most of the data in the USLCI database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
	Diesel, at refinery (USLCI) (agg)	*GaBi*: This is a cradle-to-gate inventory generated by PE from unit process data in the USLCI database.	Most of the data in the USLCI database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
	Diesel, combusted in construction Equipment (CARB *Off-Road*) (u-so)	The resulting four emissions values from *Off-Road* are replaced in diesel, combusted in industrial equipment model.	Internally reviewed by the UCPRC.
	Diesel, combusted in transport (EMFAC)[b] (u-so)	The resulting 10 emissions values from EMFAC are all considered to be the emission LCI output of diesel combusted in transport vehicle.	Internally reviewed by the UCPRC.
Natural Gas	Natural Gas, combusted in Industrial Equipment (USLCI) (agg)	*GaBi*: The original datasets and documentation can be found online: lcacommons.gov/nrel/search.	Most of the data in the USLCI database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
Aggregate	Aggregate (crushed) (u-so)	Aggregate production data were acquired from Table 10 of Marceau et al. *(22)*.	The data on which the LCI is based and the LCI results have been peer reviewed by the Portland Cement Association membership and its relevant allied groups.
Sand and Gravel	Aggregate (natural) (u-so)	Aggregate production data were acquired from Table 9, Marceau et al. *(22)*.	The data on which the LCI is based and the LCI results have been peer reviewed by the Portland Cement Association membership and its relevant allied groups.
Virgin Asphalt Binder	Bitumen, at refinery USLCI/ts (u-so)	Asphalt binder production is based on the USLCI database developed by the National Renewable Energy Lab (NREL) and thinkstep. UCPRC replaced US electricity mix with California electricity mix in the asphalt binder model.	Most of the data in the USLCI database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.

Asphalt Emulsion	Bitumen Emulsion, at plant Eurobitume (u-so)	Using input data from Chapter 6, Eurobitume 2012 report *(26)*. Bitumen emulsion model was developed in *GaBi*.	Eurobitume 2012 is critically reviewed by ESU-services Ltd. According to ISO 14040 and 14044. Critical review report provided as Appendix 5 in the Eurobitume 2012 report.
Portland Cement	Portland Cement, at plant (agg)	Portland cement model developed based on the Portland Cement Association report. UCPRC replaced electricity mix with California electricity grid mix in the cement model.	The data on which the LCI is based and the LCI results have been peer reviewed by the representatives of the Portland Cement Association members and cement and concrete industries. No indicators of data quality were assessed in the report as (stated in the Portland Cement Association report) data quality indicators complying with ISO 14041 has not yet been developed.
Cement Admixtures	Cement Admixtures (Accelerator) (agg)	Directly obtained from *GaBi*. The source of the input/output data is from European Federation of Concrete Admixture Associations *(42)*.	—
	Cement Admixtures (Air Entraining) (agg)		
	Cement Admixtures (Plasticizer) (agg)		
	Cement Admixtures (Retarder) (agg)		
	Cement Admixtures (Superplasticizer) (agg)		
	Cement Admixtures (Waterproofing) (agg)		
Hydrated Lime Dry Slacked	Lime Hydrate ($Ca(OH)_2$) slaking, ts (agg)	Directly obtained from *GaBi*. The data set covers all relevant process steps/technologies over the supply chain of the represented cradle-to-gate inventory. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
Paraffin (Wax)	Wax/Paraffins at refinery, PE (agg)	The data set covers the entire supply chain of the refinery products. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.	Well documented. Compliance with ISO14040-14044 reported in *GaBi* model documentation (dependent internal review). No evaluation scores in the external review section.
Quicklime	Quicklime, at plant, USLCI/ts (agg)	Directly obtained from *GaBi*. Data based on USLCI database and thinkstep.	Most of the data in the USLCI database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
Crumb Rubber Modifier	CRM production, at plant, Corti (agg)	Data obtained from Corti et al. *(35)*, which is a peer reviewed published journal article.	Primary data has been acquired and generated by the authors of the journal article.

[a] USLCI: U.S. Life Cycle Inventory Database; ts: thinkstep.

[b] EMFAC: EMission FACtor.

2.6 Transportation And Construction Inventories (Updated in Late 2020)

The approach used for modeling material transportation vehicle use and construction equipment use and the resulting information presented in Chapter 2 were updated in late 2020. The range of transportation vehicle types and construction equipment included in the database of material was expanded, and the data sources and fuel use and emission modeling approaches were updated to better reflect California conditions.

2.6.1 Material Transportation

Transport Modes

The LCI and LCIA results for the four major modes of transportation (truck, rail, barge, ocean freighter) used in the modeling process were all taken directly from *GaBi*. Table 2.20 shows the summary of the main impacts. These four transportation modes were selected as they are the ones that appear explicitly in this study's *GaBi* plans as subprocesses and may therefore be updated later by users.

Table 2.20: Summary of LCI and LCIA for Major Transportation Modes for Functional Unit of 1000 kg-km

Item	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Ren.)[b] [MJ]	Feedstock Energy [MJ]
Barge Transport	3.31E-02	9.58E-03	1.96E-05	4.17E-01	4.17E-01	0.00E+00
Diesel Powered Combination Truck	9.28E-02	1.53E-02	2.52E-05	1.19E+00	1.19E+00	0.00E+00
Diesel Powered Heavy Truck (24 metric tonne capacity)	7.80E-02	1.24E-02	2.49E-05	1.12E+00	1.12E+00	0.00E+00
Ocean Freighter	1.83E-02	1.11E-02	1.87E-05	2.31E-01	2.31E-01	0.00E+00
Rail Transport	2.20E-02	1.29E-02	6.06E-06	2.82E-01	2.82E-01	0.00E+00

Note: Information acquired from *Gabi* v6.3 software.

[a] The total primary energy demand excluding the feedstock energy, where feedstock energy is available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[b] Same note as above applies to PED (Non-Renewable). PED from non-renewable resources (net calorific value).

Truck Transport

To transport materials from one location to another, different types of medium- to heavy-duty trucks are used based on the type of activity. Only one or two types of trucks are typically considered in pavement LCAs. An effort was made to include a range of trucks that are commonly used for material transport in California. Each truck type has a maximum payload capacity. *eLCAP* uses that maximum payload and the total mass or volume of material to be moved to calculate the number of trips from one facility to another. The information gathered for each truck type is presented in Table 2.21.

Table 2.21: Truck Type, Weights, and Engine Horsepower

Truck Type	Manufacturer	Gross Vehicle Weight (lb.)	Curb Weight (empty truck + trailer lb.)	Maximum Payload (lb.)	Engine Horsepower (hp)
End Dump Truck	Obtained from FHWA report [a]	59,460	24,700	34,760	390
Transfer Truck (fuel use from UCPRC measurements[b])	Peterbilt-Chavez[c]	80,000	25,000	55,000	485
Ready Mix Concrete Truck (assumed 8 m^3 capacity)	Cinacharm	55,116	28,880	26,236	290
Concrete End Dump Truck	Obtained from FHWA report [a]	59,460	24,700	34,760	390
Single Bottom Dump Truck	Dura-Haul Trailer + Peterbilt tractor	46,100	18,600	27,500	485
Double Bottom Dump Truck (fuel use from UCPRC measurements *[44]*)	Peterbilt-Chavez[c]	80,000	25,000	55,000	485
Water truck (4,000 gal. capacity)	Peterbilt 384[d]	—	—	33,380	—
Tack/Spray Truck (1,000 gal. capacity)	Stratos DMT-1000[e]	—	—	8,510	—

[a] *Source:* Federal Highway Administration *(43)*.
[b] *Source:* Butt et al. *(44)*.
[c] Information from Chavez Trucking, Dixon, CA.
[d] mylittlesalesman.com/2009-peterbilt-384-water-truck-4000-gallon-10628566.
[e] pavementgroup.com/distributor-trailers/1000-gallon-asphalt-distributor-trailer/.

To capture the local conditions and model material transportation more specific to California conditions, the CARB *EMission FACtor* (EMFAC) model was used to estimate the on-road mobile sources (truck) emissions inventories. The *EMFAC2017* (v1.0.2) web database was used to extract the information for the statewide use of trucks *(45)*. The query used to extract the truck information from the *EMFAC* database included selection of California statewide emissions for 2018 for each vehicle category in *EMFAC*. The truck types identified for inclusion in *eLCAP* were then mapped against the EMFAC trucks, shown in Table 2.22.

eLCAP impact and flow indicators not included in EMFAC were filled using *GaBi* data, as is explained in Section 2.6.3.

Table 2.22: EMFAC and eLCAP Truck Types and Statewide Data

eLCAP Truck Type	EMFAC Vehicle Classification	EMFAC Vehicle	VMT (miles/day)	Trips/Day
End Dump Truck	Heavy Heavy-Duty Diesel Single Unit Construction Truck	T7 single construction	1,214,476	80,269
Transfer Truck	Heavy Heavy-Duty Diesel Tractor Construction Truck	T7 tractor construction	1,001,836	64,699
Ready Mix Concrete Truck	Heavy Heavy-Duty Diesel Single Unit Construction Truck	T7 single construction	1,214,476	80,269
Concrete End Dump Truck	Heavy Heavy-Duty Diesel Single Unit Construction Truck	T7 single construction	1,214,476	80,269
Single Bottom Dump Truck	Heavy Heavy-Duty Diesel Single Unit Construction Truck	T7 single construction	1,214,476	80,269
Double Bottom Dump Truck	Heavy Heavy-Duty Diesel Tractor Construction Truck	T7 tractor construction	1,001,836	64,699
Water Truck	Heavy Heavy-Duty Diesel Single Unit Construction Truck	T7 single construction	1,214,476	80,269
Tack Truck	Medium Heavy-Duty Diesel in-state Truck with GVWR <= 26000 lbs.	T6 in-state small	7,361,685	1,734,513
Spray Truck	Medium Heavy-Duty Diesel in-state Truck with GVWR <= 26000 lbs.	T6 in-state small	7,361,685	1,734,513

Note: All trucks are diesel powered.

The output from *EMFAC* includes vehicle miles traveled (VMT), trips per day, reactive organic gases (ROG), total organic gases (TOG), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2), methane (CH_4), 2.5-micron and 10-micron particulate matter (PM2.5 and PM10, respectively), sulfur oxides (SO_x), nitrous oxide (N_2O), and fuel consumption. Fuel use in gallons per mile was determined for each truck based on the VMT and fuel consumption. The results are presented in Table 2.23 and Table 2.24. It is important to note that the emissions from *EMFAC* are life cycle inventories resulting from the combustion of fuel in the vehicle. This life cycle is also referred to as the pump-to-wheel analysis.

Table 2.23: EMFAC Statewide Fuel Consumption and Average Fuel Use for Each Truck Type

eLCAP Truck Type	Fuel Consumption (1,000 gal./day)	Fuel Use (gal./mi.)
End Dump Truck	2.15E+02	1.77E-01
Transfer Truck	1.79E+02	1.79E-01
Ready Mix Concrete Truck	2.15E+02	1.77E-01
Concrete End Dump Truck	2.15E+02	1.77E-01
Single Bottom Dump Truck	2.15E+02	1.77E-01
Double Bottom Dump Truck	1.79E+02	1.79E-01
Water Truck	2.15E+02	1.77E-01
Tack Truck	7.93E+02	1.08E-01
Spray Truck	7.93E+02	1.08E-01

Table 2.24: EMFAC Average Emission Output for Each Truck Type

eLCAP Truck Type	Fuel Use (gal./mi.)	ROG (kg/mi.)	TOG (kg/mi.)	CO (kg/mi.)	NO_x (kg/mi.)	CO_2 (kg/mi.)	CH_4 (kg/mi.)	PM10 (kg/mi.)	PM2.5 (kg/mi.)	SO_x (kg/mi.)	N_2O (kg/mi.)
End Dump Truck	1.77E-01	7.00E-04	7.97E-04	1.83E-03	9.41E-03	1.94E+00	3.25E-05	2.54E-04	2.43E-04	1.83E-05	3.05E-04
Transfer Truck	1.79E-01	6.95E-04	7.91E-04	1.83E-03	8.86E-03	1.95E+00	3.23E-05	2.07E-04	1.98E-04	1.84E-05	3.06E-04
Ready Mix Concrete Truck	1.77E-01	7.00E-04	7.97E-04	1.83E-03	9.41E-03	1.94E+00	3.25E-05	2.54E-04	2.43E-04	1.83E-05	3.05E-04
Concrete End Dump Truck	1.77E-01	7.00E-04	7.97E-04	1.83E-03	9.41E-03	1.94E+00	3.25E-05	2.54E-04	2.43E-04	1.83E-05	3.05E-04
Single Bottom Dump Truck	1.77E-01	7.00E-04	7.97E-04	1.83E-03	9.41E-03	1.94E+00	3.25E-05	2.54E-04	2.43E-04	1.83E-05	3.05E-04
Double Bottom Dump Truck	1.79E-01	6.95E-04	7.91E-04	1.83E-03	8.86E-03	1.95E+00	3.23E-05	2.07E-04	1.98E-04	1.84E-05	3.06E-04
Water Truck	1.77E-01	7.00E-04	7.97E-04	1.83E-03	9.41E-03	1.94E+00	3.25E-05	2.54E-04	2.43E-04	1.83E-05	3.05E-04
Tack Truck	1.08E-01	3.24E-04	3.69E-04	9.71E-04	4.60E-03	1.19E+00	1.50E-05	1.66E-04	1.58E-04	1.13E-05	1.88E-04
Spray Truck	1.08E-01	3.24E-04	3.69E-04	9.71E-04	4.60E-03	1.19E+00	1.50E-05	1.66E-04	1.58E-04	1.13E-05	1.88E-04

Note: Definitions of acronyms for emission types are shown in the List of Abbreviations at the beginning of this technical memorandum.

2.6.2 Construction Equipment

Many pavement LCAs consider the environmental impacts of a limited equipment set in the construction stage—typically, the paver, rollers, and milling machine. Limited equipment sets were used in the initial UCPRC pavement LCA study, shown in Table E.8. However, there is a longer list of equipment used in pavement construction, and the total environmental impacts during the construction stage may be greater than what is typically calculated. Consequently, an effort was made to identify all the equipment that might be used to construct the different pavement layers commonly built in California, shown in Table 2.25.[5] The default equipment per pavement construction layer type has been implemented in the *eLCAP* software. A literature review was conducted to identify a range of engine power ratings (horsepower: low, medium, and high) for each type of construction equipment. This was done so that later engine horsepower and emission rate plots for each equipment type could be developed for use in determining emissions per hour for the equipment.

The goal of the project was to develop models and use data that are specific to Caltrans operations and California conditions. Therefore, CARB's *Off-Road* emissions inventory was used to determine the emission rates and fuel consumption for each off-road equipment type *(46)*. In *Off-Road,* equipment is grouped according to whether it uses gasoline or diesel fuel. For this project, most of the pavement construction equipment considered burns diesel. To determine the equipment load factors and emissions factors, the equipment in *Off-Road* was mapped against the construction equipment in *eLCAP* (Table 2.25).

CARB's *Off-Road* database is primarily based on the US EPA's certification data. Diesel used in California has extra standards for reduced sulfur content, which needs to be accounted for in any California diesel model that CARB accounted for in the calculations. Further details on how CARB used the US EPA data for adjusting emission factors is reported in CARB's report *(47)*. To compare reasonableness of resulting emissions, an example of paver equipment fuel rate is provided in Appendix C where the fuel rate of a paver from US EPA's *Nonroad* and CARB's *Off-Road* databases are compared.

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[5] A PDF document with information about the equipment used for the construction of each layer type is available to download at: escholarship.org/content/qt8v36909g/supp/LCI_Construction_Equipment_List_UCPRC-TM-2020-01.pdf.

Table 2.25: List of eLCAP Construction Equipment Mapped Against Off-Road Equipment with Load Factors

eLCAP Construction Equipment	Off-Road Equipment	Load Factors
Miller/Cold Planer	Paving Equipment	0.3551
Sweeper	Sweepers/Scrubbers	0.4556
Water Truck	Tractors/Loaders/Backhoes	0.3685
Front Loader	Rubber-Tired Loaders	0.3618
Tacker (emulsion)	Tractors/Loaders/Backhoes	0.3685
Asphalt Paver	Pavers	0.4154
Material Transfer Vehicle (MTV)	Tractors/Loaders/Backhoes	0.3685
Vibratory Steel Roller	Rollers	0.3752
Pneumatic Tire Roller	Rollers	0.3752
Smooth Steel Roller	Rollers	0.3752
Striping Paint Machine	Surfacing Equipment	0.3015
Pulverizer (Recycling machine)	Other Construction Equipment	0.4154
Padfoot Roller with Blade	Rollers	0.3752
Prime Spray Truck	Tractors/Loaders/Backhoes	0.3685
Concrete Paver	Pavers	0.4154
Grinding and Grooving Machine	Paving Equipment	0.3551
Scraper	Scrapers	0.4824
Soil Hauler (off road)	Crawler Tractors	0.4288
Tractor/Backhoe	Crawler Tractors	0.4288
Guillotine	Other Construction Equipment	0.4154
Cold Central Plant Recycling (CCPR) Mixer	Paving Equipment	0.3551
Concrete Saw	Other Construction Equipment	0.4154
Slurry and Microsurfacing Truck	Tractors/Loaders/Backhoes	0.3685
Boom Truck and Crane	Cranes	0.2881
Vibratory Compactor	Rollers	0.3752
Rubblizer/Concrete Road Breaker	Paving Equipment	0.3551
Vibrating Screed	Crawler Tractors	0.4288
Grindings Recovery Truck	Tractors/Loaders/Backhoes	0.3685
Crack Sealant Truck and Trailer	Tractors/Loaders/Backhoes	0.3685
Big Backhoe	Tractors/Loaders/Backhoes	0.3685
Air Compressor	Paving Equipment	0.3551
Chip Spreader	Paving Equipment	0.3551
Grader	Tractors/Loaders/Backhoes	0.3685
Portable Crushing and Sizing Equipment	Other Construction Equipment	0.4154

The input required by the *Off-Road* database to generate emission rates and fuel consumption rates are presented in Table 2.26. The model year for all the equipment was assumed to be 2015, and it was assumed that all the equipment was four years old at the time of data extraction in 2019. The *Off-Road* output includes fuel consumption and four vehicle exhaust emissions: total hydrocarbons (THC), nitrogen oxides (NO_x), carbon dioxide (CO_2), and particulate matter (PM2.5).

Table 2.26: Description of Each Input Required in Off-Road

Input	Description
Horsepower (hp)	Three engine hps were identified for each equipment type used in California (low hp, medium hp and high hp)
Model year	Model year for all the equipment was assumed to be 2015
Calendar year	All equipment was assumed to be 4 years old
Activity (annual hours)	Calculations were performed to get emissions per hour
Accumulated hours on equipment	4 years (6,000 hours)
Load factor	As shown in Table 2.25

The fuel consumption equation used in *Off-Road* is the following:

$$FC = Pop * HP * LF * Activity * BSFC$$

Where: *FC* = Fuel consumption (lb./year)

Pop = Equipment population

HP = Maximum rated horsepower (hp)

LF = Load factor (unitless efficiency measure)

Activity = Activity or annual operation (hr/yr)

BSFC = Brake-specific fuel consumption (lb/hp-hr)

Brake-specific fuel consumption (BSFC) is a measure of fuel use rate (lb./hp-hr), which CARB's *Off-Road* obtained from the US EPA's *Nonroad* model *(48)*. A BSFC value of 0.408 lb/hp-hr is used for engines with horsepower less than or equal to 100, and a value of 0.367 lb/hp-hr is used for engines with horsepower greater than 100.

To calculate the exhaust emissions, an equation like the fuel use equation was used, but BSFC was replaced by emission factors (EFs) that are measured in gram/hp-hr *(48)*. The following is the equation for emissions:

$$Emissions = Pop * HP * LF * Activity * EF$$

Where: *Emissions* = the emission of interest (THC, NO_x, CO_2, or PM2.5)

EF = emission factor (gram/hp-hr)

The emissions factors are functions of zero-hour emission rates and deterioration rates *(49)*. The equation to calculate EF is the following:

$EF = Zh + DR * CHrs$

Where: Zh = zero-hour emission rate when the equipment is new (gram/hp-hr)
DR = deterioration rate or the increase in zero-hour emissions as the equipment gets used (gram/hp.hr^2)
$CHrs$ = Cumulative hours or total number of hours accumulated on the equipment (maximum value is 12,000 hours)

To cover any new equipment in the scope of this study, one-year-old equipment was also modeled in *Off-Road.* The resulting fuel consumption (gal./hr) and emissions (kg/hr) for the updated construction equipment in *eLCAP* are presented in Appendix C.

Engine horsepower and fuel consumption were plotted for each equipment type and a linear relationship was obtained. The same procedure was followed to determine the vehicle exhaust emission rates for NO_x, PM, THC, and CO_2.

An example plot for a paver is shown in Figure 2.17. Similar trends were observed for all the equipment types, but the slopes were different for each equipment type. The relationships for fuel consumption rate (gal./hp-hr) and emission rate (kg/hr) are shown in Table 2.27.

Light towers are commonly used during nighttime road construction hours. One tower is usually attached to a generator and the whole unit is connected to a trailer that can be easily moved from one site to another. The specifications for the light tower assumed in *eLCAP* is shown in Table 2.28. The total number of light tower units can be determined for a project using the illumination area information provided in Table 2.28 and the expected work zone area, and the fuel use rate can be determined from the number of units and the work hours.

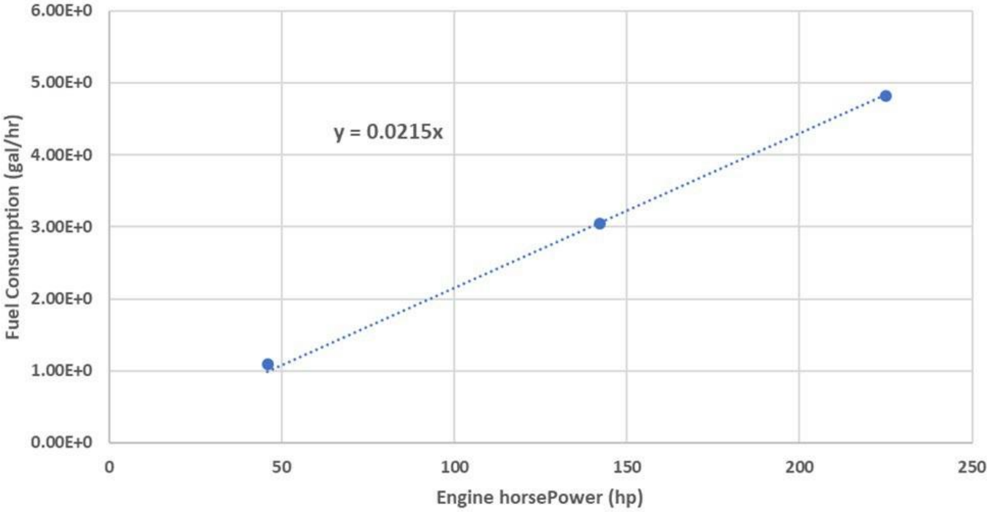


Figure 2.17: Fuel consumption rate versus engine horsepower for a paver.

Table 2.27: Fuel Consumption Rate and Emission Factor for All eLCAP Equipment from Off-Road

eLCAP Equipment	Fuel Rate (gal./hp-hr)	NO_x (kg/hp-hr)	PM (kg/hp-hr)	THC (kg/hp-hr)	CO_2 (kg/hp-hr)
CCPR Mixer	0.0183	0.0004	0.00002	0.00004	0.1872
Cold Planer/Miller	0.0183	0.0007	0.00002	0.00002	0.1872
Concrete Mixer	0.0183	0.0003	0.00001	0.00004	0.1872
Boom Truck/Crane	0.0149	0.0002	0.00001	0.00003	0.1519
Front Loader	0.0187	0.0003	0.00001	0.00004	0.1907
Groover and Grinder	0.0183	0.0003	0.00001	0.00004	0.1872
Guillotine	0.0238	0.0015	0.00005	0.0001	0.2434
Material Transfer Vehicle (MTV)	0.019	0.0003	0.00001	0.00004	0.1942
Asphalt Paver	0.0215	0.0004	0.00002	0.00005	0.2197
Pneumatic Tire Roller	0.0194	0.0003	0.00001	0.00004	0.1978
Pulverizer	0.0214	0.0003	0.00002	0.00004	0.219
Scraper	0.0249	0.0004	0.00002	0.00005	0.2543
Sweeper-Scrubber combo	0.0239	0.0004	0.00002	0.00005	0.2438
Soil Hauler	0.0246	0.0012	0.00006	0.00007	0.2513
Smooth Steel (static) Roller	0.0194	0.0003	0.00002	0.00004	0.1982
Tractor/Backhoe	0.0229	0.0008	0.00005	0.00006	0.2341
Vibratory Steel Roller	0.0202	0.0005	0.00002	0.0005	0.2067
Prime Spray Truck	0.019	0.0003	0.00001	0.00004	0.1942
Slurry/Microsurfacing/Spreader	0.0157	0.0003	0.00002	0.00003	0.1601
Water Spray Truck	0.019	0.0003	0.00001	0.00004	0.1942
Tacker	0.019	0.0003	0.00001	0.00004	0.1942
Concrete Paver	0.0215	0.0004	0.00002	0.00005	0.2197
Striping Paint Machine	0.0183	0.0003	0.00002	0.00004	0.1872
Padfoot Roller	0.0194	0.0003	0.00002	0.00004	0.1982
Concrete Saw	0.0238	0.0015	0.00005	0.0001	0.2434
Grader	0.019	0.0003	0.00001	0.00004	0.1942
Chip Spreader	0.0183	0.0003	0.00002	0.00004	0.1872
Portable Crushing and Sizing Equipment	0.0238	0.0003	0.00002	0.00004	0.219
Rubblizer/Concrete Road Breaker	0.0183	0.0007	0.00002	0.00002	0.1872

Table 2.28: Light Tower Generator Specifications

Light Tower Generator Information[a]	Values	Units
Illumination coverage at 5 footcandle = lum/ft^2 (54 lux)	12,960	ft^2
Lamp type	Metal halide	
Lamp mast height	30	ft.
Power	19.5	kW
Fuel type	Diesel #2 – ULSD (used for on-road vehicles)	
Operating hp	40	hp
Fuel tank capacity	14.25	gal.
Fuel usage	1.58	gal./hr

[a] constructioncomplete.com/media/downloadable/brochure/WKR-WIDELIGHTTOWERS-B.pdf

2.6.3 Implementation of Updated Transportation Vehicles and Construction Equipment in eLCAP

eLCAP is programmed to allow a user to "add" or "remove" a layer when conducting an analysis. Each pavement layer type in *eLCAP* has been assigned default material transportation vehicles and construction equipment. The logic used for calculating the default equipment use time for each equipment type and for the number of hauling trips for material transportation have been included in *eLCAP*. Still, a user can choose to change the use time and hauling trip values. Some example calculations for construction use time are presented in Appendix D.

The emissions modeling in *eLCAP* is mainly done using *GaBi* databases *(7)*. However, a hybrid approach was followed to make equipment and transportation emissions specific to California. The *GaBi*-modeled pump-to-wheel (or combustion) emissions were replaced with emissions that were modeled using *Off-Road* or *EMFAC* for the emissions included in those databases. For construction equipment in *Off-Road,* these emissions are NO_x, CO_2, PM, and THC; for trucks in *EMFAC*, they are CO, NO_x, CO_2, CH_4, PM10, PM2.5, SO_x, and N_2O. The process diagram for construction equipment is shown in Figure 2.18, and the process diagram for transportation is shown in Figure 2.19.

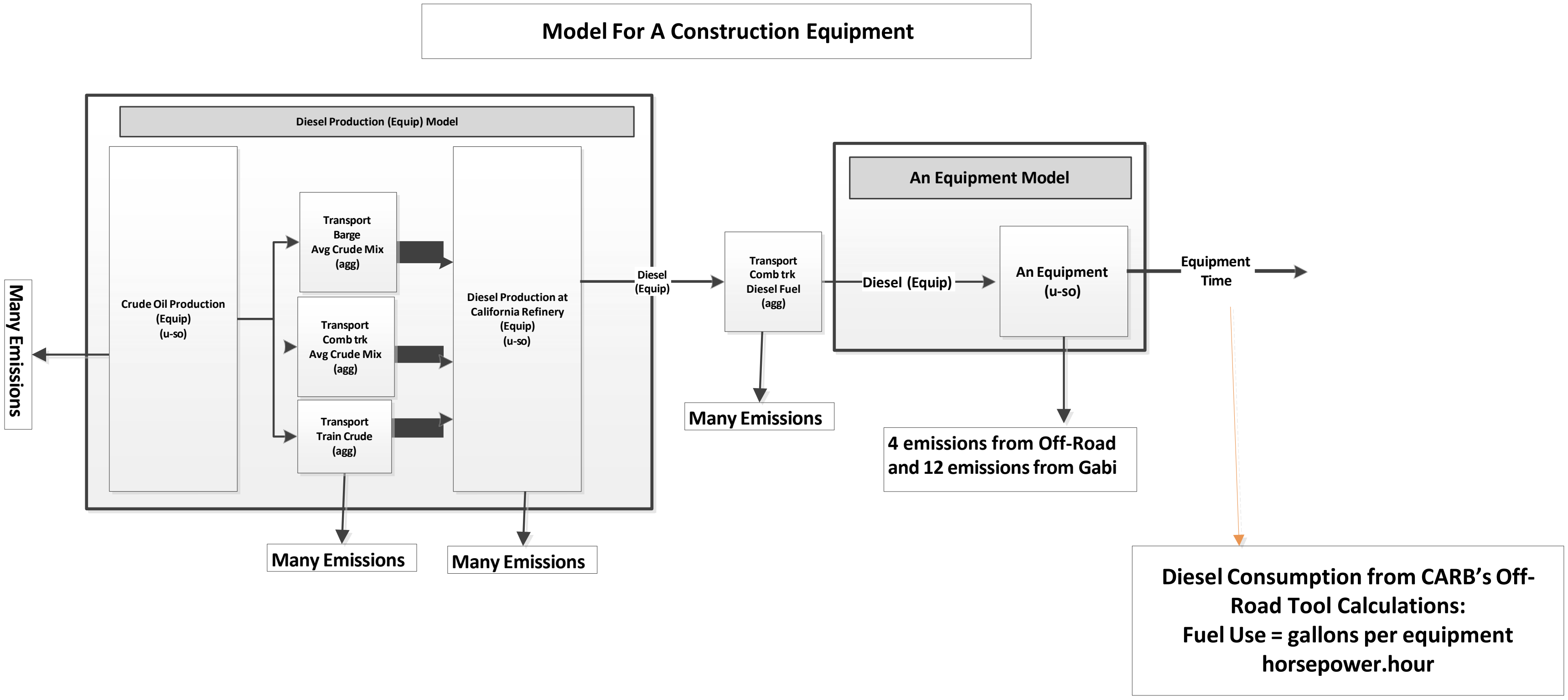
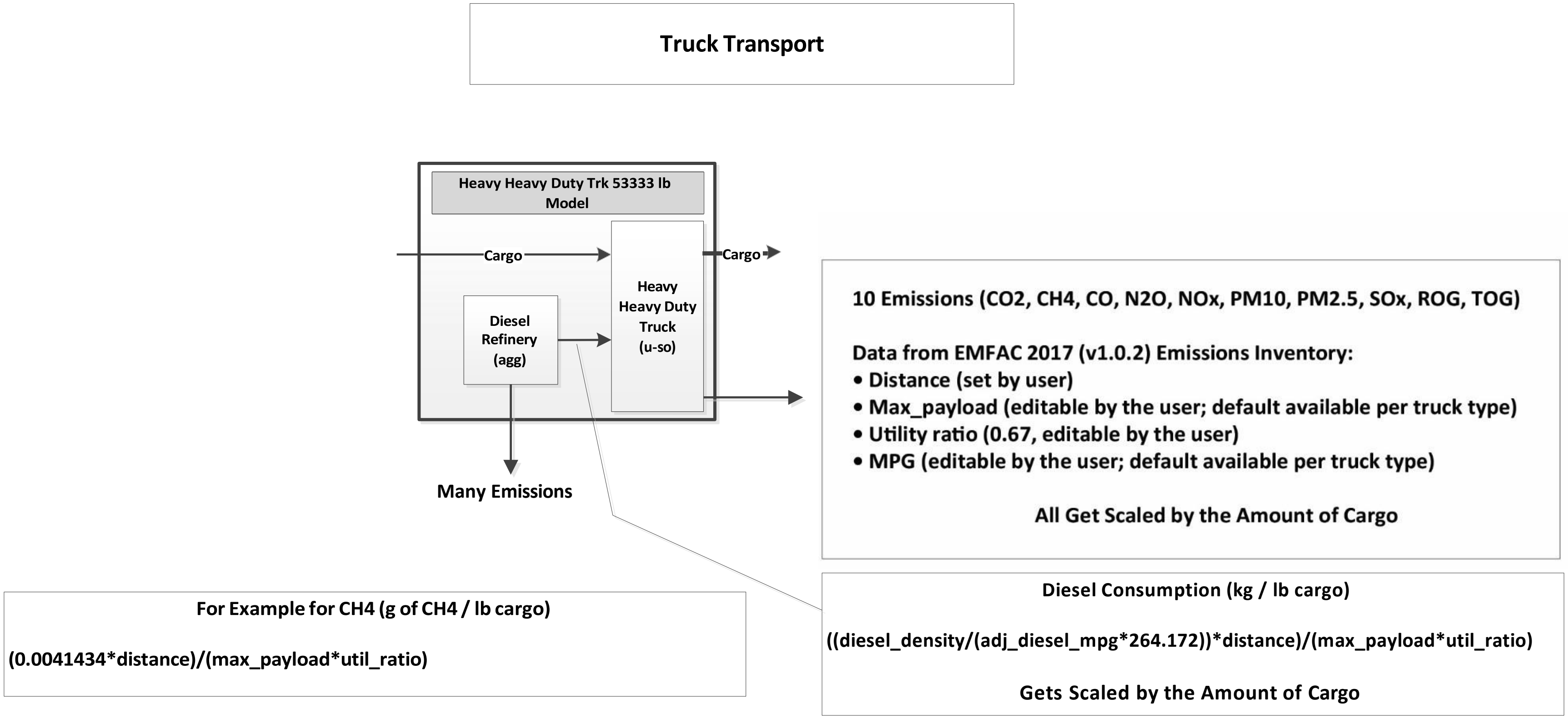


Figure 2.18: Construction equipment model.



10 Emissions (CO2, CH4, CO, N2O, NOx, PM10, PM2.5, SOx, ROG, TOG)

Data from EMFAC 2017 (v1.0.2) Emissions Inventory:

- **Distance (set by user)**
- **Max_payload (editable by the user; default available per truck type)**
- **Utility ratio (0.67, editable by the user)**
- **MPG (editable by the user; default available per truck type)**

All Get Scaled by the Amount of Cargo

For Example for CH4 (g of CH4 / lb cargo)

(0.0041434*distance)/(max_payload*util_ratio)

Diesel Consumption (kg / lb cargo)

((diesel_density/(adj_diesel_mpg*264.172))*distance)/(max_payload*util_ratio)

Gets Scaled by the Amount of Cargo

Figure 2.19: Material transportation vehicle model.

In summary, the following steps are used to arrive at the final LCIA emissions for construction equipment or truck transportation:

1. Well-to-Pump (W2P) emissions are modeled for diesel using *GaBi.*
2. Pump-to-Wheel (P2W) analysis is done using a hybrid approach:
    a. P2W emissions are modeled using *GaBi.*
    b. P2W emissions are obtained from *Off-Road* (for construction equipment) and *EMFAC* (transport vehicles).
    c. P2W *GaBi* emission (diesel combusted in industrial equipment) LCI outputs are replaced by *Off-Road* emission LCI output for those emission types that are available in both databases, and *GaBi* emission LCI output are retained for those emission types not included in the *Off-Road* database.
    d. P2W emissions (diesel combusted in transport vehicle) are all from *EMFAC* emission LCI outputs.
3. Well-to-Wheel (W2W) emissions
    a. Construction equipment = W2P emission LCI output + hybrid P2W emission LCI output from *GaBi* and *Off-Road*.
    b. Transport vehicles = W2P emission LCI output + P2W emission LCI output from *EMFAC*.

Characterization factors are then multiplied by the set of emissions LCIs to calculate the impact categories.

2.7 Cradle-To-Lay Examples Performed for Caltrans

To demonstrate how the UCPRC LCIs can be used for the cradle-to-gate material stage and transportation of materials) and cradle-to-lay (material stage, transportation of materials stage, and construction stage) scopes of pavement projects, the UCPRC performed several example calculations for different pavement layer types that can be found in Appendix E. The calculations were conducted in *Excel*. The functional unit for all surface treatments was set as 1 lane-kilometer (ln-km). For reporting purposes, typical thicknesses or application rates for surface treatments were selected based on common practice or Caltrans specifications, where applicable. Furthermore, the construction activities were modeled using the state of practice that was determined using Caltrans specifications as of 2016, consultations with local experts, and a literature review. The pavement material mix designs for different pavement layer types, including the construction stage (removing/adding of pavement layers) examples for Caltrans are presented in detail in Appendix E.

3 DATA QUALITY REQUIREMENTS AND DATA VALIDATION PRIOR TO 2020

ISO 14040 requires defining data quality requirements (DQRs) as part of an LCA study's goal and scope definition phase. Data validation is a part of the life cycle inventory phase where the collected data are evaluated based on the DQRs. For data validation, ISO requires that "a check on data validity shall be conducted during the process of data collection to confirm and provide evidence that the DQRs for the intended application have been fulfilled." This following discussion first reviews the definition of the DQR according to the goal and scope of the previously discussed studies and then reviews the data validation according to the defined DQR.

3.1 Defining Data Quality Requirements

The data quality assessment presented in this chapter is based on ISO 14044 as the main guideline*,* as well as the FHWA pavement LCA framework *(16)*. The DQRs should be determined based on the goal and scope of the study for which the dataset is going to be used. Considering the scope of studies defined in Section 1.2 of this document, the following are required in terms of data quality (where applicable, Table 3.1 was used for assessing the data quality):

- *Time-related coverage.* It is required that all the data sources used for developing the LCI were collected within the last 10 years, with the assumption that the technology, production/construction procedures, and energy sources did not change drastically during that time. Use of older data sources is only permitted if the data are still representative of current practices and technology and no newer data source is available.
- *Geographical coverage.* At minimum, all the data sources should be based on average national data, though the use of locally collected data is strongly advised. Use of international data sources is only permitted when there are no sources of national data and it can be proven that the international data are representative of US practice.
- *Technology coverage.* It is required that the data be representative of technologies used at the national level at least, though use of data sources that represent local technologies is strongly advised. Use of international data sources is only permitted when there are no sources of national data and it can be proven that the international data is representative of technologies used in the United States. Also, the data should represent the particular technology used in the area of the study; in the case of a lack of such data, modeling based on a mix of technologies used within US borders is permitted.
- *Completeness.* The data used for developing the inventory should include all the flows related to the goal and scope of the study.
- *Consistency.* The study methodology should have been applied uniformly to the various components of the analysis.

- *Reproducibility.* The reproducibility of results is required, except for cases where data are taken from internationally accepted sources of data such as *GaBi,* ecoinvent*,* or similar databases.
- *Sources of data.* These should be reported for each item.
- *Uncertainty.* Sources of uncertainty should be clearly stated. The uncertainty could be due to uncertainty in data, models, or assumptions.

Table 3.1: Quality Assessment Methodology Used for Selected Criteria Prior to Late 2020

Criteria	Poor	Fair	Good	Excellent
Time Coverage	15+-year-old data	10-year-old to 15-year-old data	5-year-old to 10-year-old data	Less than 5-year-old data
Geographical Coverage	International data	National data	Modified to represent local practice	Primary data collected from local plants/contractors
Technology	International data, not similar to the US practice	International data, close to the US practice	National-level average	Technology specifically used in the area under study
Completeness (% of flow that is measured)	<50%	<75%	<90%	>90%

3.2 Data Validation

The data validation process for this LCI database consists of data quality assessment and comparison of the results with widely accepted and/or highly cited results taken from other sources and the literature. Table 3.2 shows the results of the data quality assessment of the UCPRC LCI database (only constituent materials and transportation modes) considering the DQRs defined in the previous section. Table 3.3 shows a similar table for the composite materials in the database. It should be noted that the results in this section constitute an assessment of the representativeness of the LCI data for the goal and scope of the studies outlined in Section 1.2. The representativeness of each item was calculated by averaging the score that the item received in each of the four categories identified in Table 3.1 (between 1 for Poor and 4 for Excellent). This score was then converted back to the Poor-to-Excellent scale for representativeness of the data.

Table 3.4 shows the result of comparing GWP and primary energy demand for some of the items in the inventory using different sources. Appendix B provides more details for the main processes taken directly from *GaBi* that were used to build the UCPRC models. Table 3.4 also includes comparison of the UCPRC results versus results from other sources in form of ratios of “UCPRC value / value from the other source.”

However, as stated earlier, the model developed by UCPRC for portland cement concrete (PCC) is a general model where the mix proportions can be modified. The values presented in Table 3.4 are only example mix designs, and these values can change significantly depending on the specified PCC mix design. The other major difference is between the UCPRC and Athena *(50,* as of 2006*)* GHG values for natural aggregates and the values from Stripple *(51)*. A comparison of 2006 Athena numbers for crushed and natural aggregates reveals a difference of two orders of magnitude, and no documentation is available to explain why this significant difference exists. However, PED numbers for crushed and natural aggregate between the UCPRC and Athena are close. Therefore, it was assumed that the Stripple numbers for aggregates were not accurate for the North American context and no further investigation was conducted.

Table 3.2: Data Quality Assessment—Constituent Materials and Transportation Modes

Item		Time Cov.[a]	Geog. Cov.[b]	Tech. Cov.[c]	Comp.[d]	Represent.[e]	Reprod.[f]	Source of Data	Uncertainty	Notes
Aggregate (Crushed)		Good	Good	Good	Good	Good	Y	*GaBi*/Lit.	Data variability in plant energy consumption	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
Aggregate (Natural)		Good	Good	Good	Good	Good	Y	*GaBi*/Lit.	Data variability in plant energy consumption	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
Virgin Asphalt Binder		Excellent	Good	Good	Good	Good	Y	*GaBi*/Lit.	Variability in refinery output for mass-based allocation, also uncertainty in relative prices of products for economic-based allocation	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
Asphalt Emulsion		Excellent	Poor	Fair	Good	Fair	Y	*GaBi*/Lit.	Variability in refinery output for mass-based allocation, also uncertainty in relative prices of products for economic-based allocation	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
Crumb Rubber Modifier (CRM)		Good	Good	Good	Good	Good	Y	*GaBi*/Lit.	Model imprecision	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
Dowel and Tie Bar		Good	Good	Good	Good	Good	Y	*GaBi*/Lit.	Model imprecision in energy consumption in plant	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
Energy Sources	Diesel Burned in Equipment	Excellent	Fair	Good	Good	Good	Y	*GaBi*	—	Taken directly from *GaBi*
	Electricity	Excellent	Good	Excellent	Good	Good	Y	*GaBi*/ CPUC	Uncertainty regarding +15% of the grid electricity sources	Used *GaBi* for modeling the CA electricity grid mix
	Natural Gas Combusted in Industrial Eq.	Excellent	Fair	Good	Good	Good	Y	*GaBi*	—	Taken directly from *GaBi*
Hydrated Lime dry slacked		Excellent	Fair	Good	Good	Good	N	*GaBi*	—	Taken directly from *GaBi*
Paraffin (Wax)		Excellent	Fair	Good	Good	Good	N	*GaBi*	—	Taken directly from *GaBi*
Portland Cement	Type I/II	Fair	Good	Good	Fair	Fair	Y	*GaBi*/Lit.	Input uncertainties and input data variability in terms of plant energy consumption	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
	Slag Cement (19% Slag)	Poor	Poor	Poor	Poor	Poor	Y	*GaBi*/Lit.	Model imprecision in terms of time relevancy and geographical and technological coverage	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel
	Slag Cement (50% Slag)	Poor	Poor	Poor	Poor	Poor	Y	*GaBi*/Lit.	Model imprecision in terms of time relevancy and geographical and technological coverage	Used *GaBi* for modeling based on literature and calibrated based on CA grid mix and plant fuel

Item		Time Cov.[a]	Geog. Cov.[b]	Tech. Cov.[c]	Comp.[d]	Represent.[e]	Reprod.[f]	Source of Data	Uncertainty	Notes
Portland Cement Admixtures	Accelerator	Excellent	Poor	Fair	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
	Air Entraining	Excellent	Poor	Fair	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
	Plasticizer	Excellent	Poor	Fair	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
	Retarder	Excellent	Poor	Fair	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
	Superplasticizer	Excellent	Poor	Fair	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
	Waterproofing	Excellent	Poor	Fair	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
Reclaimed Asphalt Pavement (RAP)		Excellent	Fair	Good	Good	Good	Y	*GaBi*/Lit.	Allocation method	Modeled in *Excel* for allocation comparison
Styrene Butadiene Rubber (SBR)		Excellent	Fair	Good	Fair	Fair	N	*GaBi*	Model imprecision	Taken directly from *GaBi*
Barge		Good	Fair	Good	Good	Fair	N	*GaBi*	—	Taken directly from *GaBi*
Combination truck, diesel powered		Excellent	Fair	Good	Good	Good	N	*GaBi*	—	Taken directly from *GaBi*
Heavy Truck (24 Tonne)		Excellent	Fair	Good	Good	Good	N	*GaBi*	—	Taken directly from *GaBi*
Ocean Freighter		Good	Fair	Good	Good	Fair	N	*GaBi*	—	Taken directly from *GaBi*

[a] Time Cov. = Time Coverage
[b] Geographic Cov. = Geographic Coverage
[c] Technical Cov. = Technical Coverage
[d] Comp. = Completeness
[e] Represent. = Representativeness
[f] Reprod. = Reproducibility

Table 3.3: Data Quality Assessment—Composite Materials

Surface Treatment	Life Cycle Stage	Time Cov.[a]	Geog. Cov.[b]	Tech. Cov.[c]	Comp.[d]	Represent.[e]	Reprod.[f]	Source of Data	Uncertainty	Notes
Cape Seal	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Chip Seal	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Fog Seal	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Conventional Asphalt Concrete (Mill-and-Fill)	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Conventional Asphalt Concrete (Overlay)	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	

Surface Treatment	Life Cycle Stage	Time Cov.[a]	Geog. Cov.[b]	Tech. Cov.[c]	Comp.[d]	Represent.[e]	Reprod.[f]	Source of Data	Uncertainty	Notes
Conventional Interlocking Concrete Pavement (Pavers)	Material Production	Good	Good	Good	Fair	Fair	Y	Local Manufacturer EPD	Model imprecision (used EPD, details of modeling not available) and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Estimated based on needed equipment	Variability in construction process and the equipment used on site	
Permeable Asphalt Concrete	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Permeable Portland Cement Concrete	Material Production	Fair	Good	Good	Good	Fair	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Poor	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Portland Cement Concrete	Material Production	Fair	Good	Good	Good	Fair	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Portland Cement Concrete with Supplementary Cementitious Materials	Material Production	Poor	Poor	Poor	Good	Poor	Y	Local Manufacturer Mix Designs	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	

Surface Treatment	Life Cycle Stage	Time Cov.[a]	Geog. Cov.[b]	Tech. Cov.[c]	Comp.[d]	Represent.[e]	Reprod.[f]	Source of Data	Uncertainty	Notes
Reflective Coating	Material Production	Good	Poor	Fair	Fair	Fair	Y	Literature	Mix design variability and the uncertainties identified for the constituent materials	Developed by PE Int'l, only the LCI results were provided
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Rubberized Asphalt Concrete (Mill-and-Fill)	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Rubberized Asphalt Concrete (Overlay)	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Sand Seal	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	
Slurry Seal	Material Production	Good	Good	Good	Good	Good	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/*CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	

Surface Treatment	Life Cycle Stage	Time Cov.[a]	Geog. Cov.[b]	Tech. Cov.[c]	Comp.[d]	Represent.[e]	Reprod.[f]	Source of Data	Uncertainty	Notes
Bonded Concrete Overlay of Asphalt (BCOA)	Material Production	Fair	Good	Good	Good	Fair	Y	Caltrans Manual	Mix design variability and the uncertainties identified for the constituent materials	
	Transportation	Good	Fair	Good	Poor	Fair	N	State Hauling Average	Transportation distance	
	Construction	Excellent	Excellent	Excellent	Good	Good	Y	Caltrans Manual/ *CA4PRS*/ Experts and Contractors	Variability in construction process and the equipment used on site	

[a] Time Cov. = Time Coverage
[b] Geographic Cov. = Geographic Coverage
[c] Technical Cov. = Technical Coverage
[d] Comp. = Completeness
[e] Represent. = Representativeness
[f] Reprod. = Reproducibility

Table 3.4: Comparison of Results for Some of the Database Items with Other Sources

GWP (kg CO2-e)

Item	Unit	UCPRC	ecoinvent	UCPRC/ ecoinvent	Stripple	UCPRC/ Stripple	Athena	UCPRC/ Athena
Aggregate (Crushed)	kg	3.43E-03	n/a	n/a	1.43E-03	240%	n/a	n/a
Aggregate (Natural)	kg	2.36E-03	n/a	n/a	7.35E-05	3211%	n/a	n/a
Virgin Asphalt Binder	kg	4.75E-01	4.29E-01	111%	1.73E-01	275%	n/a	n/a
Portland Cement	kg	8.72E-01	7.18E-01	121%	8.06E-01	108%	n/a	n/a
HMA[a]	kg	4.77E-02	n/a	n/a	3.44E-02	139%	5.92E-02	81%
PCC[b]	kg	1.96E-01	1.09E-01	180%	1.37E-01	143%	1.20E-01	164%

PED (MJ)

Item	Unit	UCPRC	ecoinvent	UCPRC/ ecoinvent	Stripple	UCPRC/ Stripple	Athena	UCPRC/ Athena
Aggregate (Crushed)	kg	6.04E-02	n/a	n/a	7.86E-02	77%	5.76E-02	105%
Aggregate (Natural)	kg	4.31E-02	n/a	n/a	7.67E-02	56%	3.60E-02	120%
Virgin Asphalt Binder	kg	4.97E+01	5.20E+01	96%	4.31E+01	115%	4.55E+01	109%
Portland Cement	kg	5.94E+00	3.38E+00	176%	4.34E+00	137%	4.97E+00	120%
HMA	kg	4.45E-01	n/a	n/a	5.51E-01	81%	5.31E-01	84%
RHMA[c]	kg	5.47E-01	n/a	n/a	4.04E-01	135%	3.75E-01	146%
PCC	kg	1.24E+00	6.04E-01	205%	8.67E-01	143%	n/a	n/a

[a] HMA: hot mix asphalt

[b] PCC: portland cement concrete

[c] RHMA: rubberized hot mix asphalt

4 METADATA AND DATA QUALITY MATRIX UPDATED IN 2020

The metadata approach and the data quality matrix in *eLCAP* were updated in 2020, and the metadata are now more complete. The data quality matrix reflects the complete matrix proposed by the Federal LCA Commons effort, which is compatible with the FHWA spreadsheet tool, *LCA Pave (10)*.

4.1 Metadata

Included now in *eLCAP* are three metadata fields that were also developed for the FHWA tool project: administrative, descriptive, and structural metadata. A description of each item within the metadata field is presented in Table 4.1.

Table 4.1: Metadata Fields Included in eLCAP

Administrative Metadata—Information that helps in managing the data	
Recorder/Reviewer/Organization	Names or initials of who records the data, who reviews the data, and their affiliations.
Data Source	Source from which the data was acquired. This could be a webpage link, published report, literature, or the name of the organization/person from whom the data were obtained.
Publication Date	Date the data were produced or published (YYYY).
Data Accessed	Date the data were accessed (MM/DD/YYYY).
Descriptive Metadata—Information that describes the data	
Original Process Name	Name of the product or process.
Data Produced Location	Location where the data was produced. If the information is available, it is preferred that the city, state, and country be reported.
Descriptive Properties	Any helpful descriptive information about the product or process (e.g., shapes and sizes of aggregates, cement type, PG binder grade, etc.).
Structural Metadata—Information that identifies the content of the data	
Quantity	Quantity of product (1, 10, 100, etc.).
Units	Units of the quantity (US tons, gal., BTU, etc.).
Structural Properties	Information that shows the content of the product/process (e.g., compressive strength value of concrete, mix design/job mix formula of asphalt concrete, aggregate gradation information, etc.).
Other Information	Miscellaneous information about the product/process that is helpful for identifying and reproducing the data and that can increase confidence in acceptance of the data.

4.2 Data Quality Assessment

All data for materials, unit processes, energy resources, equipment, and transportation have been evaluated using an enhanced data quality assessment that is based on the US EPA's pedigree matrix *(11)*. The US EPA's pedigree matrix was enhanced to standardize the practice of data quality assessment for use in pavement LCAs *(10)*. Table 4.2 shows the data quality assessment matrix that was used in *eLCAP*.

Table 4.2: Data Quality Assessment Matrix in eLCAP

Quality Indicators	Indicator Sub-Categories	Indicator Description	1 (Excellent)	2 (Very Good)	3 (Good)	4 (Poor)	5 (Unsatisfactory)
Reliability	**Data Checks**	Is the inventory data checked for mass/ energy balance, recalculation etc.?	Verified data based on measurements	Verified data based on a calculation or non-verified data based on measurements	Non-verified data based on a calculation	Documented estimate	Undocumented estimate
	Data Support	What is the status quo for the ownership and continuous support of data?	Hosts and owns	Owns but does not host	Hosts but does not own	Hosts and owns partially	Does not host or own
	Data Updates	Are the data regularly updated?	Regular updates	Less frequent updates	No updates	—	—
Data Collection Methods	**Representativeness**	How representative are the data of the market?	Representative data from >80% of the relevant market, over an adequate period	Representative data from 60%-79% of the relevant market, over an adequate period **OR** representative data from >80% of the relevant market, over a shorter period of time	Representative data from 40%-59% of the relevant market, over an adequate period **OR** representative data from 60%-79% of the relevant market, over a shorter period of time	Representative data from <40% of the relevant market, over an adequate period of time **OR** representative data from 40%-59% of the relevant market, over a shorter period of time	Unknown **OR** data from a small number of sites **and** from shorter periods
	Seasonal Variations	Do the data capture seasonal variations?	Seasonal variations captured	Seasonal variation not captured	—	—	—
	TRACI Compatibility	How compatible is the life cycle inventory data with TRACI 2.1 impact assessment method?	100% TRACI compatible	75% TRACI compatible	50% TRACI compatible	25% TRACI compatible	TRACI incompatible

Quality Indicators	Indicator Sub-Categories	Indicator Description	1 (Excellent)	2 (Very Good)	3 (Good)	4 (Poor)	5 (Unsatisfactory)
Time Period	**Data Quality Objective**	How well is the data collection date related to the data quality objective and the relevant time period of the analysis?	Less than 3 years of difference	Less than 6 years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years
	Correlated to Relevant Periods	Have the data been adjusted for the relevant time period?	Data **fully** adjusted for relevant time periods of analysis	Data fully adjusted for relevant time periods but with **medium** level of uncertainty	Data fully adjusted for relevant time periods but with **high** level of uncertainty	**Some** data adjusted for relevant time periods but with **high** level of uncertainty	Data **unadjusted** for relevant time periods
Geography	**Data Origin**	How well is the geography of the data correlated with the data quality objective?	Data from same resolution **AND** same area of study	Within one level of resolution **AND** a related area of study	Within two levels of resolution **AND** a related area of study	Outside of two levels of resolution **BUT** a related area of study	From a different or unknown area of study
Technology	**Categories Equivalent**	How well is the technology of the data correlated with the data quality objective?	All technology categories are equivalent	Three of the technology categories are equivalent	Two of the technology categories are equivalent	One of the technology categories are equivalent	None of the technology categories are equivalent
	Relevant Coverage	Is the relevant technology covered?	Yes	No	—	—	—
Process Review	**Review Check**	How well is the process reviewed?	Documented reviews by a minimum of two types of third-party reviewers	Documented reviews by a minimum of two types of reviewers, with one being a third party	Documented review by a third-party reviewer	Documented review by an internal reviewer	No documented review
Process Completeness	**Completeness Check**	How complete is the process?	>80% of determined flows have been evaluated and given a value	60%-79% of determined flows have been evaluated and given a value	40%-59% of determined flows have been evaluated and given a value	<40% of determined flows have been evaluated and given a value	Process completeness not scored

4.3 Implementation in eLCAP

The metadata and data quality assessment for the materials, transportation, and construction equipment in *eLCAP* were updated following the matrix shown in Table 4.1 and Table 4.2, and they are available in the *eLCAP* software *(3)*.

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APPENDIX A: SUMMARY OF CRITICAL REVIEWS COMPLETED IN 2016 AND 2021

Inventory elements included in the critical reviews completed in 2016 and 2021 are summarized in Table A.1. The final letter from the critical reviewers for both reviews follows the table.

Table A.1: Summary of Inventory Elements Critically Reviewed in September 2016 and August 2021

Item	Category	Verified by Third Party	
Electricity	Energy	Sep 2016	Aug 2021
Diesel, combusted	Energy	Sep 2016	Aug 2021
Natural gas, combusted	Energy	Sep 2016	Aug 2021
Aggregate (Crushed)	Materials	Sep 2016	Aug 2021
Aggregate (Natural)	Materials	Sep 2016	Aug 2021
Virgin Asphalt Binder	Materials	Sep 2016	Aug 2021
Asphalt Emulsion	Materials	Sep 2016	Aug 2021
Calcium Sulfoaluminate Cement (CSA)	Materials	Sep 2016	—[a]
Ordinary Portland Cement (OPC Type I/II; based on PCA report)	Materials	Sep 2016	Aug 2021
OPC (Type III; based on PCA report)	Materials	Sep 2016	Aug 2021
OPC (Type III; based on CARB data)	Materials	—	—[a]
Portland-Limestone Cement	Materials	—	—[a]
Cement (Portland with 19% SCM)	Materials	Sep 2016	Aug 2021
Cement (Portland with 50% SCM)	Materials	Sep 2016	Aug 2021
Cement Admixtures (Accelerator)	Materials	Sep 2016	Aug 2021
Cement Admixtures (Air Entraining)	Materials	Sep 2016	Aug 2021
Cement Admixtures (Plasticizer)	Materials	Sep 2016	Aug 2021
Cement Admixtures (Retarder)	Materials	Sep 2016	Aug 2021
Cement Admixtures (Superplasticizer)	Materials	Sep 2016	Aug 2021
Cement Admixtures (Waterproofing)	Materials	Sep 2016	Aug 2021
Crumb Rubber Modifier (CRM)	Materials	Sep 2016	Aug 2021
Dowel	Materials	Sep 2016	Aug 2021
Limestone	Materials	Sep 2016	Aug 2021
Hydrated lime dry slaked	Materials	—	Aug 2021
Paraffin (Wax)	Materials	Sep 2016	Aug 2021
Quicklime	Materials	Sep 2016	Aug 2021
Reclaimed Asphalt Pavement (RAP)	Materials	Sep 2016	Aug 2021
Recycled Concrete Aggregate (RCA)	Materials	—	Aug 2021
Reflective Coating (BPA) [50/50]	Materials	Sep 2016	Aug 2021
Styrene Butadiene Rubber (SBR)	Materials	Sep 2016	Aug 2021
Tie Bar (3/4 in)	Materials	Sep 2016	Aug 2021
BPA	Materials	Sep 2016	Aug 2021
Polyester Styrene	Materials	Sep 2016	Aug 2021
Polyurethane	Materials	Sep 2016	Aug 2021
Styrene Acrylate	Materials	Sep 2016	Aug 2021

Item	Category	Verified by Third Party	
Rail Transport	Transportation	—	Aug 2021
Barge Transport	Transportation	Sep 2016	Aug 2021
Combination Truck, diesel powered	Transportation	Sep 2016	Aug 2021
Heavy Truck (24 metric tonne capacity)	Transportation	Sep 2016	Aug 2021
Ocean Freighter	Transportation	Sep 2016	Aug 2021
End Dump Truck	Transportation	—	Aug 2021
Transfer Truck	Transportation	—	Aug 2021
Ready Mix Concrete Truck	Transportation	—	Aug 2021
Concrete End Dump Truck	Transportation	—	Aug 2021
Single Bottom Dump Truck	Transportation	—	Aug 2021
Double Bottom Dump Truck	Transportation	—	Aug 2021
Water truck	Transportation	—	Aug 2021
Tack Truck	Transportation	—	Aug 2021
Spray Truck	Transportation	—	Aug 2021
Miller/Cold Planer	Construction Equipment	—	Aug 2021
Sweeper	Construction Equipment	—	Aug 2021
Water Truck	Construction Equipment	—	Aug 2021
Front Loader	Construction Equipment	—	Aug 2021
Tacker (emulsion)	Construction Equipment	—	Aug 2021
Asphalt Paver	Construction Equipment	—	Aug 2021
Material Transfer Vehicle (MTV)	Construction Equipment	—	Aug 2021
Vibratory Steel Roller	Construction Equipment	—	Aug 2021
Pneumatic Tire Roller	Construction Equipment	—	Aug 2021
Smooth Steel Roller	Construction Equipment	—	Aug 2021
Striping Paint Machine	Construction Equipment	—	Aug 2021
Pulverizer (recycling machine)	Construction Equipment	—	Aug 2021
Padfoot Roller with Blade	Construction Equipment	—	Aug 2021
Prime Spray Truck	Construction Equipment	—	Aug 2021
Concrete Paver	Construction Equipment	—	Aug 2021
Grinding and Grooving Machine	Construction Equipment	—	Aug 2021
Scraper	Construction Equipment	—	Aug 2021
Soil Hauler (off road)	Construction Equipment	—	Aug 2021
Tractor/Backhoe	Construction Equipment	—	Aug 2021
Guillotine	Construction Equipment	—	Aug 2021
Cold Central Plant Recycling (CCPR) Mixer	Construction Equipment	—	Aug 2021
Concrete Saw	Construction Equipment	—	Aug 2021
Slurry and Microsurfacing Truck	Construction Equipment	—	Aug 2021
Boom Truck and Crane	Construction Equipment	—	Aug 2021
Vibratory Compactor	Construction Equipment	—	Aug 2021
Rubblizer/Concrete Road Breaker	Construction Equipment	—	Aug 2021
Vibrating Screed	Construction Equipment	—	Aug 2021
Grindings Recovery Truck	Construction Equipment	—	Aug 2021
Crack Sealant Truck and Trailer	Construction Equipment	—	Aug 2021
Big Backhoe	Construction Equipment	—	Aug 2021

Item	Category	Verified by Third Party	
Air Compressor	Construction Equipment	—	Aug 2021
Chip Spreader	Construction Equipment	—	Aug 2021
Grader	Construction Equipment	—	Aug 2021
Portable Crushing and Sizing Equipment	Construction Equipment	—	Aug 2021
Bonded Concrete Overlay of Asphalt (BCOA) OP139SCM139	Surface Treatments	Sep 2016	—[b]
Bonded Concrete Overlay of Asphalt (BCOA) OP267SCM71	Surface Treatments	Sep 2016	—[b]
Bonded Concrete Overlay of Asphalt (BCOA) OP448SCM0	Surface Treatments	Sep 2016	—[b]
Cape Seal	Surface Treatments	Sep 2016	—[b]
Cement Concrete (PC284 SCM50) for Lane Replacement	Surface Treatments	Sep 2016	—[b]
Cement Concrete (PC335 SCM0) for Minor Concrete	Surface Treatments	Sep 2016	—[b]
Cement Concrete (PC418 SCM0) for Local Streets	Surface Treatments	Sep 2016	—[b]
Cement Concrete (CSA390 SCM0) for Slab Replacement (CSA Cement)	Surface Treatments	Sep 2016	—[b]
Cement Concrete (PCIII475 SCM0) for Slab Replacement (Type III)	Surface Treatments	Sep 2016	—[b]
Chip Seal	Surface Treatments	Sep 2016	—[b]
Fog Seal	Surface Treatments	Sep 2016	—[b]
Conventional Asphalt Concrete (Mill-and-Fill) Mix 1 (15% RAP)	Surface Treatments	Sep 2016	—[b]
Conventional Asphalt Concrete (Overlay) Mix 1 (15% RAP)	Surface Treatments	Sep 2016	—[b]
Conventional Asphalt Concrete (Mill-and-Fill) Mix 1 (No RAP)	Surface Treatments	Sep 2016	—[b]
Conventional Asphalt Concrete (Overlay) Mix 2 (No RAP)	Surface Treatments	Sep 2016	—[b]
Conventional Interlocking Concrete Pavement (Pavers)	Surface Treatments	Sep 2016	—[b]
Permeable Asphalt Concrete	Surface Treatments	Sep 2016	—[b]
Permeable Portland Cement Concrete	Surface Treatments	Sep 2016	—[b]
Reflective Coating – BPA	Surface Treatments	Sep 2016	—[b]
Reflective Coating – Polyester Styrene	Surface Treatments	Sep 2016	—[b]
Reflective Coating – Polyurethane	Surface Treatments	Sep 2016	—[b]
Reflective Coating – Styrene Acrylate	Surface Treatments	Sep 2016	—[b]
Rubberized Asphalt Concrete (Mill-and-Fill)	Surface Treatments	Sep 2016	—[b]
Rubberized Asphalt Concrete (Overlay)	Surface Treatments	Sep 2016	—[b]
Sand Seal	Surface Treatments	Sep 2016	—[b]
Slurry Seal	Surface Treatments	Sep 2016	—[b]
CIR (4 in. [10 cm] milled + mechanical stabilization) with 1 in. (2.5 cm) of HMA overlay	Surface Treatments	Sep 2016	—[b]
CIR (4 in. [10 cm] milled + mechanical stabilization) with Chip Seal	Surface Treatments	Sep 2016	—[b]

Item	Category	Verified by Third Party	
FDR (10 in. [25 cm] milled + no stabilization) with 2.4 in. (6 cm) RHMA overlay	Surface Treatments	Sep 2016	—[b]
FDR (10 in. [25 cm] milled + 4% AE + 1% PC) with 2.4 in. (6 cm) RHMA overlay	Surface Treatments	Sep 2016	—[b]
FDR (10 in. [25 cm] milled + 3% FA + 1% PC) with 2.4 in. (6 cm) RHMA overlay	Surface Treatments	Sep 2016	—[b]
FDR (10 in. [25 cm] milled + 2% PC) with 2.4 in. (6 cm) RHMA overlay	Surface Treatments	Sep 2016	—[b]
FDR (10 in. [25 cm] milled + 4% PC) with 2.4 in. (6 cm) RHMA overlay	Surface Treatments	Sep 2016	—[b]
FDR (10 in. [25 cm] milled + 6% PC) with 2.4 in. (6 cm) RHMA overlay	Surface Treatments	Sep 2016	—[b]

[a] UCPRC is continuously updating the life cycle inventories per requests from Caltrans and industries. These inventories were added after the critical review process and will be included in the next critical review cycle in 2022.

[b] Mix designs and treatments were not in the scope of the 2021 critical review.

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TRAFIKVERKET
SWEDISH TRANSPORT ADMINISTRATION

Prof. John Harvey
University of California Pavement Research Center
University of California, Davis
Department of Civil and Environmental Engineering
2001 Ghausi Hall
One Shields Ave
Davis, CA 95616
USA

Dear Prof. Harvey,

My colleagues and I, as identified by the signatures below, have been contracted by the University of California Pavement Research Center (UCPRC) to perform an external review of background life cycle inventory (LCI) data used in current and future UCPRC pavement life cycle assessment (LCA) studies for the region of California. We were requested to comment on four specific tasks:

- The methods used to carry out the LCI are consistent with the ISO 14044:2006 (with primary focus on Section 4.3).
- The methods used to carry out the LCI are scientifically and technically valid.
- The data used are appropriate and reasonable in relation to the data requirements (ISO 14044 Section 4.2.3.6) called for in the goal of the studies documented in the document we are sending you for review.
- The LCI documentation is transparent and consistent.

It is important to note that our review applies only to the background LCI data detailed in the report and supplementary spreadsheets provided to us by UCPRC. It is not a review of LCA studies conducted using the LCI data because it does not include foreground inventories for pavement designs, maintenance schedules, building designs, and vehicle traffic levels and fuel consumption that would be required for such LCAs. In addition, our review does not encompass background information for use phase elements that maybe included in pavement LCAs such as excess fuel consumption due to pavement-vehicle interaction, lighting, carbonation, and albedo effects due to radiative forcing. The only exception is the review of LCI datasets for electricity and natural gas consumed due to building energy consumption associated with pavement albedo, but the report does not include models used to quantify that energy consumption.

We first received a report detailing the contents of the background LCI data on February 26, 2016. We provided comments on that report and two additional versions of the report. This letter constitutes the response from our fourth round of reviews of this content, based on a draft dated August, 2016, and the accompanying set of responses to our prior comments transmitted by you on August 24, 2016.

Based on the updates to the most recent version of the report and responses to our comments, our panel finds that the revised content is in conformance with the sections of ISO 14044:2006 pertaining to LCI data (Sections 4.2.3.6

and 4.3), the methods used to carry out the LCI are scientifically and technically valid, and the LCI documentation is transparent and consistent. We believe that the data quality assessment tables in Section 3 of the report will be particularly valuable to include in LCA studies conducted using the background LCI data to facilitate interpretation of results in those studies.

However, we have several remaining comments on these updated drafts that, although they do not prevent a finding of standards conformance, are important to consider and to address as you see appropriate in finalizing the document. We have articulated these comments below. Please feel free to contact us if any of the below information is unclear or if we can be of further service in this review.

Sincerely,

Robert Karlsson

Robert Karlsson, Swedish Transport Administration (Trafikverket)

Jeremy Gregory, Massachusetts Institute of Technology

Amlan Mukherjee, Michigan Technical University

Comments

1. Section 2.2.9, pg. 40 (in Word file, which is 5 higher than the page numbers on the page): the fourth sentence should be changed to "Furthermore, the process CO2 was overestimated in the US LCI database due to double counting the emissions from energy production."
2. Section 2.2.9, pg. 40: the last sentence of the paragraph contains an embedded figure caption that should be removed.
3. Section 2.2.12, pg. 49: there is an extra period in the last line of the first paragraph.
4. Section 2.4.16, pg. 68, Table 2-22: change second column heading to "Life-Cycle" (fixing "LiFE" typo).
5. Section 3.2, pg. 75: reference to metadata in Appendix A should be removed or modified.
6. Section 3.2, pg. 75, Table 3-2: change fourth column title to "ecoinvent" (fixing "econinvent" typo).
7. Section 3.2, pg. 75: There is no reference to the Stripple study in the references section. Please add it. Then I suggest noting the year for the Stripple study to emphasize the age of the data, which may explain some of the differences.
8. The first page of Appendix A should be changed. It is no longer the metadata - it is a list of Gabi processes. I suggest removing it, or changing the title.

Critical Review Statement

Review of the *eLCAP* Software and Documentation

Critical Review Panel: Arpad Horvath, Consultant; Berkeley, CA (Chair)
Jeremy Gregory, Consultant; Cambridge, MA
Amlan Mukherjee, Consultant; Houghton, Ml

Valid as of: l:!!!y_, 2021

Scope of the Critical Review

The Critical Review Panel's (CRP) scope included the review of the web-based *eLCAP* software (May 14, 2021 version) and two accompanying documents, all by the Pavement Research Center at the University of California, Davis (UCPRC):

Jon Lea, John Harvey, Arash Saboori, and Ali Butt, "eLCAP: A Web Application for Environmental Life Cycle Assessment for Pavements." Report No. UCPRC-TM-2018-04, May 14, 2021

Arash Saboori, Ali Butt, John Harvey, Maryam Ostovar, Hui Li, and Ting Wang, "UCPRC Life Cycle Inventories (LCis) from Three Studies." Report No. UCPRC-TM-2020-01, May 14, 2021 and August 5, 2021.

The goal of *eLCAP* is to provide a tool with which decision makers can evaluate the life cycle impacts of various pavement structures, materials, construction processes, roughness standards, and life cycle maintenance and rehabilitation, considering the life cycle stages and processes of material extraction and production, construction, transport of pavement materials, use stage interaction of vehicles with pavement roughness, and end oflife of the pavement over the user-defined analysis period.

The CRP focused on reviewing (1) the model embedded in *eLCAP* against LCA expectations and practices, (2) life cycle inventory (LCI) data appropriateness, quality, and documentation, (3) the calculations oflife cycle impacts and resource flows, and (4) reporting of results.

Critical Review Process

The review was conducted by exchanging comments and responses within the Critical Review Panel, during a call with the UC Davis research team, and using an Excel spreadsheet based on Annex A of ISO/TS 14071:2014. There were two formal rounds of comments. A copy of the review spreadsheet containing all comments and responses is available from the UCPRC upon request.

Evaluation

The CRP has made comments and recommendations on *eLCAP* software and the underlying methods, data, and documentation. Some comments have already been addressed, others are promised to be at a later stage of the project. The review spreadsheet contains the list of outstanding issues.

In general, we find that *eLCAP's* scope was set appropriately and data had been collected or are promised to be collected to support the goal of establishing a comprehensive LCA of pavements. Scientifically valid technical knowledge and methodological proficiency are displayed in the model, tool, and the accompanying documentation. Representativeness of the technical and LCA approaches and data are aimed for, with the goal of developing defensible results consistent with the stated goals and scope of the project.

eLCAP is state of the art, well documented, and as user friendly as it can be given the existing constraints with respect to decision-support tools and data for pavement environmental assessments.

In general, the *eLCAP* model aims to follow the best LCA practices available in this field today, and it will get even better once all CRP comments are implemented. It is bound to help users quantify the life cycle environmental effects for pavement projects. Local materials, construction practices, technologies and models have been taken into consideration so that the LCis and life cycle impact assessments (LCIA) reflect California-specific conditions as much as feasible today.

This review statement only applies to the named and reviewed *eLCAP* and documentation versions, but not to any other versions, derivative reports, excerpts, press releases, and similar documents.

A Horvath

Arpad Horvath

Jeremy Gregory

Amlan Mukherjee

APPENDIX B: DATA SOURCES FOR MODELS TAKEN DIRECTLY FROM GABI

This appendix provides the sources of data for the main processes that were taken directly from *GaBi* to develop the UCPRC models. Table B.1 provides a general summary.

Table B.1: General Summary of Processes Taken from GaBi

Item	Source	Location Coverage	Time Coverage
Diesel, combusted in industrial equipment	USLCI/ts[a]	RNA[b]	2009 – 2016
Electricity from biogas (West)	ts	US	2010 – 2018
Electricity from biomass (solid) (West)	ts	US	2010 – 2018
Electricity from geothermal	ts	US	2010 – 2018
Electricity from hard coal (West)	ts	US	2010 – 2018
Electricity from heavy fuel oil (HFO) (West)	ts	US	2010 – 2018
Electricity from hydro power	ts	US	2010 – 2018
Electricity from natural gas (West)	ts	US	2010 – 2018
Electricity from nuclear (West)	ts	US	2010 – 2018
Electricity from photovoltaic	ts	US	2010 – 2018
Electricity from waste	ts	US	2010 – 2018
Electricity from wind power	ts	US	2010 – 2018
Electricity, at grid (Western US)	ts	US	2010 – 2018
Heavy-duty diesel truck	ts	US	2015 – 2018
Natural gas, combusted in industrial equipment	USLCI/ts	RNA	2009 – 2016
Ocean freighter, average fuel mix	USLCI/ts	US	2009 – 2016
Transport, barge, average fuel mix	USLCI/ts	RNA	2009 – 2016
Transport, combination truck, diesel powered	USLCI/ts	US	2009 – 2016
Transport, train, diesel powered	USLCI/ts	US	2009 – 2016

[a] USLCI: U.S. Life Cycle Inventory Database; ts: thinkstep

[b] RNA: Region-North America

APPENDIX C: CONSTRUCTION EQUIPMENT MODEL DATA FROM OFF-ROAD

Table C.1: One-Year-Old and Four-Year-Old Construction Equipment, Engine Power, and Resulting Fuel Consumption

Equipment	Engine Power (hp)	Fuel Consumption (gal./hr)	NO_x (kg/hr)	PM (kg/hr)	THC (kg/hr)	CO_2 (kg/hr)	NO_x Emission Factors (g/hp-hr)	PM Emission Factors (g/hp-hr)	THC Emission Factors (g/hp-hr)
Paver (1 yr)	46	1.10E+0	5.83E-2	1.45E-3	2.75E-3	1.12E+1	3.05E+0	7.59E-2	1.44E-1
	142	3.05E+0	6.43E-2	2.53E-3	3.59E-3	3.11E+1	1.09E+0	4.29E-2	6.08E-2
	225	4.83E+0	5.84E-2	2.68E-3	5.68E-3	4.93E+1	6.25E-1	2.87E-2	6.08E-2
Paver (4 yr)	46	1.10E+0	6.36E-2	2.07E-3	5.85E-3	1.12E+1	3.33E+0	1.08E-1	3.06E-1
	142	3.05E+0	6.81E-2	3.03E-3	6.38E-3	3.11E+1	1.15E+0	5.13E-2	1.08E-1
	225	4.83E+0	6.18E-2	3.11E-3	1.01E-2	4.93E+1	6.62E-1	3.32E-2	1.08E-1
Crane (1 yr)	110	1.64E+0	3.46E-2	1.36E-3	1.93E-3	1.67E+1	1.09E+0	4.29E-2	6.08E-2
	365	5.43E+0	8.28E-2	3.53E-3	6.39E-3	5.54E+1	7.87E-1	3.36E-2	6.08E-2
	550	8.18E+0	1.25E-1	5.32E-3	9.63E-3	8.35E+1	7.87E-1	3.36E-2	6.08E-2
Crane (4 yr)	110	1.64E+0	3.66E-2	1.63E-3	3.43E-3	1.67E+1	1.15E+0	5.13E-2	1.08E-1
	365	5.43E+0	8.76E-2	4.09E-3	1.14E-2	5.54E+1	8.33E-1	3.89E-2	1.08E-1
	550	8.18E+0	1.32E-1	6.16E-3	1.71E-2	8.35E+1	8.33E-1	3.89E-2	1.08E-1
Vibratory Roller (1 yr)	46	9.91E-1	5.27E-2	1.31E-3	2.49E-3	1.01E+1	3.05E+0	7.59E-2	1.44E-1
	100	2.15E+0	4.09E-2	1.61E-3	2.28E-3	2.20E+1	1.09E+0	4.29E-2	6.08E-2
	134	2.60E+0	5.48E-2	2.16E-3	3.06E-3	2.65E+1	1.09E+0	4.29E-2	6.08E-2
Vibratory Roller (4 yr)	46	9.91E-1	5.75E-2	1.87E-3	5.28E-3	1.01E+1	3.33E+0	1.08E-1	3.06E-1
	100	2.15E+0	4.33E-2	1.92E-3	4.06E-3	2.20E+1	1.15E+0	5.13E-2	1.08E-1
	134	2.60E+0	5.80E-2	2.58E-3	5.44E-3	2.65E+1	1.15E+0	5.13E-2	1.08E-1
Static Roller (1 yr)	75	1.62E+0	7.42E-2	4.95E-3	1.71E-3	1.65E+1	2.64E+0	1.76E-1	6.08E-2
	325	6.30E+0	9.60E-2	4.10E-3	7.41E-3	6.43E+1	7.87E-1	3.36E-2	6.08E-2
	449	8.70E+0	1.33E-1	5.66E-3	1.02E-2	8.88E+1	7.87E-1	3.36E-2	6.08E-2
Static Roller (4 yr)	75	1.62E+0	7.85E-2	5.92E-3	3.04E-3	1.65E+1	2.79E+0	2.10E-1	1.08E-1
	325	6.30E+0	1.02E-1	4.74E-3	1.32E-2	6.43E+1	8.33E-1	3.89E-2	1.08E-1
	449	8.70E+0	1.40E-1	6.55E-3	1.82E-2	8.88E+1	8.33E-1	3.89E-2	1.08E-1
Pneumatic Roller (1 yr)	235	4.55E+0	5.51E-2	2.53E-3	5.36E-3	4.65E+1	6.25E-1	2.87E-2	6.08E-2
	325	6.30E+0	9.60E-2	4.10E-3	7.41E-3	6.43E+1	7.87E-1	3.36E-2	6.08E-2
	415	8.04E+0	1.23E-1	5.23E-3	9.47E-3	8.21E+1	7.87E-1	3.36E-2	6.08E-2

Equipment	Engine Power (hp)	Fuel Consumption (gal./hr)	NO$_x$ (kg/hr)	PM (kg/hr)	THC (kg/hr)	CO$_2$ (kg/hr)	NO$_x$ Emission Factors (g/hp-hr)	PM Emission Factors (g/hp-hr)	THC Emission Factors (g/hp-hr)
Pneumatic Roller (4 yr)	235	4.55E+0	5.83E-2	2.93E-3	9.54E-3	4.65E+1	6.62E-1	3.32E-2	1.08E-1
	325	6.30E+0	1.02E-1	4.74E-3	1.32E-2	6.43E+1	8.33E-1	3.89E-2	1.08E-1
	415	8.04E+0	1.30E-1	6.06E-3	1.68E-2	8.21E+1	8.33E-1	3.89E-2	1.08E-1
Scraper (1 yr)	290	7.22E+0	8.75E-2	4.01E-3	8.50E-3	7.37E+1	6.25E-1	2.87E-2	6.08E-2
	451	1.12E+1	1.71E-1	7.31E-3	1.32E-2	1.15E+2	7.87E-1	3.36E-2	6.08E-2
	600	1.49E+1	2.76E-1	1.33E-2	1.76E-2	1.53E+2	9.55E-1	4.60E-2	6.08E-2
Scraper (4 yr)	290	7.22E+0	9.26E-2	4.65E-3	1.51E-2	7.37E+1	6.62E-1	3.32E-2	1.08E-1
	451	1.12E+1	1.81E-1	8.46E-3	2.35E-2	1.15E+2	8.33E-1	3.89E-2	1.08E-1
	600	1.49E+1	2.93E-1	1.54E-2	3.13E-2	1.53E+2	1.01E+0	5.33E-2	1.08E-1
MTV (1 yr)	225	4.28E+0	5.18E-2	2.38E-3	5.04E-3	4.37E+1	6.25E-1	2.87E-2	6.08E-2
	260	4.95E+0	5.99E-2	2.75E-3	5.82E-3	5.05E+1	6.25E-1	2.87E-2	6.08E-2
	300	5.71E+0	8.70E-2	3.71E-3	6.72E-3	5.83E+1	7.87E-1	3.36E-2	6.08E-2
MTV (4 yr)	225	4.28E+0	5.49E-2	2.76E-3	8.97E-3	4.37E+1	6.62E-1	3.32E-2	1.08E-1
	260	4.95E+0	6.34E-2	3.18E-3	1.04E-2	5.05E+1	6.62E-1	3.32E-2	1.08E-1
	300	5.71E+0	9.21E-2	4.30E-3	1.20E-2	5.83E+1	8.33E-1	3.89E-2	1.08E-1
Pulverizer (1 yr)	380	8.15E+0	1.24E-1	5.30E-3	9.60E-3	8.32E+1	7.87E-1	3.36E-2	6.08E-2
	400	8.58E+0	1.31E-1	5.58E-3	1.01E-2	8.76E+1	7.87E-1	3.36E-2	6.08E-2
	500	1.07E+1	1.64E-1	6.98E-3	1.26E-2	1.09E+2	7.87E-1	3.36E-2	6.08E-2
Pulverizer (4 yr)	380	8.15E+0	1.31E-1	6.14E-3	1.71E-2	8.32E+1	8.33E-1	3.89E-2	1.08E-1
	400	8.58E+0	1.38E-1	6.46E-3	1.80E-2	8.76E+1	8.33E-1	3.89E-2	1.08E-1
	500	1.07E+1	1.73E-1	8.08E-3	2.25E-2	1.09E+2	8.33E-1	3.89E-2	1.08E-1
Front Loader (1 yr)	350	6.54E+0	9.97E-2	4.25E-3	7.70E-3	6.67E+1	7.87E-1	3.36E-2	6.08E-2
	430	8.03E+0	1.22E-1	5.23E-3	9.46E-3	8.20E+1	7.87E-1	3.36E-2	6.08E-2
	510	9.53E+0	1.45E-1	6.20E-3	1.12E-2	9.73E+1	7.87E-1	3.36E-2	6.08E-2
Front Loader (4 yr)	350	6.54E+0	1.05E-1	4.93E-3	1.37E-2	6.67E+1	8.33E-1	3.89E-2	1.08E-1
	430	8.03E+0	1.30E-1	6.05E-3	1.68E-2	8.20E+1	8.33E-1	3.89E-2	1.08E-1
	510	9.53E+0	1.54E-1	7.18E-3	2.00E-2	9.73E+1	8.33E-1	3.89E-2	1.08E-1
Groover and Grinder (1 yr)	260	4.77E+0	5.77E-2	2.65E-3	5.61E-3	4.87E+1	6.25E-1	2.87E-2	6.08E-2
	400	7.33E+0	1.12E-1	4.77E-3	8.64E-3	7.49E+1	7.87E-1	3.36E-2	6.08E-2
	575	1.05E+1	1.61E-1	6.86E-3	1.24E-2	1.08E+2	7.87E-1	3.36E-2	6.08E-2

Equipment	Engine Power (hp)	Fuel Consumption (gal./hr)	NO_x (kg/hr)	PM (kg/hr)	THC (kg/hr)	CO_2 (kg/hr)	NO_x Emission Factors (g/hp-hr)	PM Emission Factors (g/hp-hr)	THC Emission Factors (g/hp-hr)
Groover and Grinder (4 yr)	260	4.77E+0	6.11E-2	3.07E-3	9.99E-3	4.87E+1	6.62E-1	3.32E-2	1.08E-1
	400	7.33E+0	1.18E-1	5.53E-3	1.54E-2	7.49E+1	8.33E-1	3.89E-2	1.08E-1
	575	1.05E+1	1.70E-1	7.94E-3	2.21E-2	1.08E+2	8.33E-1	3.89E-2	1.08E-1
Tractor/ Backhoe (1 yr)	47	1.16E+0	6.15E-2	1.53E-3	2.90E-3	1.18E+1	3.05E+0	7.59E-2	1.44E-1
	80	1.97E+0	9.05E-2	6.04E-3	2.09E-3	2.01E+1	2.64E+0	1.76E-1	6.08E-2
	102	2.26E+0	4.77E-2	1.88E-3	2.66E-3	2.31E+1	1.09E+0	4.29E-2	6.08E-2
Tractor/ Backhoe (4 yr)	47	1.14E+0	6.62E-2	2.15E-3	6.08E-3	1.16E+1	3.33E+0	1.08E-1	3.06E-1
	80	1.94E+0	9.44E-2	7.12E-3	3.66E-3	1.98E+1	2.79E+0	2.10E-1	1.08E-1
	102	2.23E+0	4.98E-2	2.21E-3	4.67E-3	2.27E+1	1.15E+0	5.13E-2	1.08E-1
CCPR Mixer (1 yr)	105	1.92E+0	4.07E-2	1.60E-3	2.27E-3	1.97E+1	1.09E+0	4.29E-2	6.08E-2
	140	2.57E+0	5.42E-2	2.13E-3	3.02E-3	2.62E+1	1.09E+0	4.29E-2	6.08E-2
	174	3.19E+0	6.74E-2	2.65E-3	3.76E-3	3.26E+1	1.09E+0	4.29E-2	6.08E-2
CCPR Mixer (4 yr)	105	1.92E+0	4.30E-2	1.91E-3	4.03E-3	1.97E+1	1.15E+0	5.13E-2	1.08E-1
	140	2.57E+0	5.74E-2	2.55E-3	5.38E-3	2.62E+1	1.15E+0	5.13E-2	1.08E-1
	174	3.19E+0	7.13E-2	3.17E-3	6.68E-3	3.26E+1	1.15E+0	5.13E-2	1.08E-1
Concrete Mixer (1 yr)	340	6.23E+0	9.50E-2	4.06E-3	7.34E-3	6.36E+1	7.87E-1	3.36E-2	6.08E-2
	430	7.88E+0	1.20E-1	5.13E-3	9.28E-3	8.05E+1	7.87E-1	3.36E-2	6.08E-2
	510	9.35E+0	1.43E-1	6.08E-3	1.10E-2	9.55E+1	7.87E-1	3.36E-2	6.08E-2
Concrete Mixer (4 yr)	340	6.23E+0	1.01E-1	4.70E-3	1.31E-2	6.36E+1	8.33E-1	3.89E-2	1.08E-1
	430	7.88E+0	1.27E-1	5.94E-3	1.65E-2	8.05E+1	8.33E-1	3.89E-2	1.08E-1
	510	9.35E+0	1.51E-1	7.04E-3	1.96E-2	9.55E+1	8.33E-1	3.89E-2	1.08E-1
Cold Planer (1 yr)	228	4.18E+0	5.06E-2	2.32E-3	4.92E-3	4.27E+1	6.25E-1	2.87E-2	6.08E-2
	469	8.60E+0	1.31E-1	5.59E-3	1.01E-2	8.78E+1	7.87E-1	3.36E-2	6.08E-2
	650	1.19E+1	2.20E-1	1.06E-2	1.40E-2	1.22E+2	9.55E-1	4.60E-2	6.08E-2
Cold Planer (4 yr)	228	4.18E+0	5.36E-2	2.69E-3	8.76E-3	4.27E+1	6.62E-1	3.32E-2	1.08E-1
	469	8.60E+0	1.39E-1	6.48E-3	1.80E-2	8.78E+1	8.33E-1	3.89E-2	1.08E-1
	650	1.19E+1	2.33E-1	1.23E-2	2.50E-2	1.22E+2	1.01E+0	5.33E-2	1.08E-1
Miller (1 yr)	550	1.01E+1	1.54E-1	6.56E-3	1.19E-2	1.03E+2	7.87E-1	3.36E-2	6.08E-2
	671	1.23E+1	2.28E-1	1.10E-2	1.45E-2	1.26E+2	9.55E-1	4.60E-2	6.08E-2
	766	1.40E+1	8.01E-1	1.71E-2	1.65E-2	1.43E+2	2.94E+0	6.28E-2	6.08E-2

Equipment	Engine Power (hp)	Fuel Consumption (gal./hr)	NO_x (kg/hr)	PM (kg/hr)	THC (kg/hr)	CO_2 (kg/hr)	NO_x Emission Factors (g/hp-hr)	PM Emission Factors (g/hp-hr)	THC Emission Factors (g/hp-hr)
Miller (4 yr)	550	1.01E+1	1.63E-1	7.60E-3	2.11E-2	1.03E+2	8.33E-1	3.89E-2	1.08E-1
	671	1.23E+1	2.41E-1	1.27E-2	2.58E-2	1.26E+2	1.01E+0	5.33E-2	1.08E-1
	766	1.40E+1	8.47E-1	2.10E-2	2.94E-2	1.43E+2	3.11E+0	7.73E-2	1.08E-1
Guillotine (1 yr)	5	1.19E-1	7.65E-3	2.58E-4	2.99E-4	1.22E+0	3.68E+0	1.24E-1	1.44E-1
	12	2.86E-1	1.84E-2	6.19E-4	7.18E-4	2.92E+0	3.68E+0	1.24E-1	1.44E-1
	20	4.77E-1	3.06E-2	1.03E-3	1.20E-3	4.87E+0	3.68E+0	1.24E-1	1.44E-1
Guillotine (4 yr)	5	1.19E-1	7.65E-3	2.58E-4	6.36E-4	1.22E+0	3.68E+0	1.24E-1	3.06E-1
	12	2.86E-1	1.84E-2	6.19E-4	1.53E-3	2.92E+0	3.68E+0	1.24E-1	3.06E-1
	20	4.77E-1	3.06E-2	1.03E-3	2.54E-3	4.87E+0	3.68E+0	1.24E-1	3.06E-1
Vibratory Compactor (1 yr)	50	1.08E+0	4.90E-2	6.83E-4	2.32E-3	1.10E+1	2.61E+0	3.64E-2	1.24E-1
	114	2.21E+0	4.67E-2	1.83E-3	2.60E-3	2.25E+1	1.09E+0	4.29E-2	6.08E-2
	214	4.15E+0	5.02E-2	2.30E-3	4.88E-3	4.23E+1	6.25E-1	2.87E-2	6.08E-2
Vibratory Compactor (4 yr)	50	1.08E+0	5.18E-2	9.35E-4	4.22E-3	1.10E+1	2.76E+0	4.98E-2	2.25E-1
	114	2.21E+0	4.94E-2	2.19E-3	4.63E-3	2.25E+1	1.15E+0	5.13E-2	1.08E-1
	214	4.15E+0	5.31E-2	2.67E-3	8.69E-3	4.23E+1	6.62E-1	3.32E-2	1.08E-1
Scrubber (4 yr)	50	1.31E+0	5.95E-2	8.30E-4	2.82E-3	1.33E+1	2.61E+0	3.64E-2	1.24E-1
	99	2.59E+0	1.19E-1	7.94E-3	2.74E-3	2.64E+1	2.64E+0	1.76E-1	6.08E-2
	280	6.59E+0	7.98E-2	3.66E-3	7.76E-3	6.72E+1	6.25E-1	2.87E-2	6.08E-2
Scrubber (4 yr)	50	1.31E+0	6.29E-2	1.14E-3	5.13E-3	1.33E+1	2.76E+0	4.98E-2	2.25E-1
	99	2.59E+0	1.26E-1	9.49E-3	4.88E-3	2.64E+1	2.79E+0	2.10E-1	1.08E-1
	280	6.59E+0	8.44E-2	4.24E-3	1.38E-2	6.72E+1	6.62E-1	3.32E-2	1.08E-1
Soil Hauler (1 yr)	51	1.26E+0	5.71E-2	7.96E-4	2.71E-3	1.28E+1	2.61E+0	3.64E-2	1.24E-1
	55	1.35E+0	6.16E-2	8.59E-4	2.92E-3	1.38E+1	2.61E+0	3.64E-2	1.24E-1
	94	2.31E+0	1.06E-1	7.09E-3	2.45E-3	2.36E+1	2.64E+0	1.76E-1	6.08E-2
Soil Hauler (4 yr)	51	1.26E+0	6.04E-2	1.09E-3	4.92E-3	1.28E+1	2.76E+0	4.98E-2	2.25E-1
	55	1.35E+0	6.52E-2	1.18E-3	5.31E-3	1.38E+1	2.76E+0	4.98E-2	2.25E-1
	94	2.31E+0	1.12E-1	8.48E-3	4.36E-3	2.36E+1	2.79E+0	2.10E-1	1.08E-1

Equipment	**Engine Power (hp)**	**Fuel Consumption (gal./hr)**	**NO_x (kg/hr)**	**PM (kg/hr)**	**THC (kg/hr)**	**CO_2 (kg/hr)**	**NO_x Emission Factors (g/hp-hr)**	**PM Emission Factors (g/hp-hr)**	**THC Emission Factors (g/hp-hr)**
Tacker/Emulsion Distributor Truck/Spray Truck (1 yr)	260	4.95E+0	5.99E-2	2.75E-3	5.82E-3	5.05E+1	6.25E-1	2.87E-2	6.08E-2
	300	5.71E+0	8.70E-2	3.71E-3	6.72E-3	5.83E+1	7.87E-1	3.36E-2	6.08E-2
	485	9.23E+0	1.41E-1	6.00E-3	1.09E-2	9.42E+1	7.87E-1	3.36E-2	6.08E-2
Tacker/Emulsion Distributor Truck/Spray Truck (4 yr)	260	4.95E+0	6.34E-2	3.18E-3	1.04E-2	5.05E+1	6.62E-1	3.32E-2	1.08E-1
	300	5.71E+0	9.21E-2	4.30E-3	1.20E-2	5.83E+1	8.33E-1	3.89E-2	1.08E-1
	485	9.23E+0	1.49E-1	6.95E-3	1.93E-2	9.42E+1	8.33E-1	3.89E-2	1.08E-1
Slurry/ Microsurfacing Machines (1 yr)	99	1.71E+0	7.87E-2	5.25E-3	1.81E-3	1.75E+1	2.64E+0	1.76E-1	6.08E-2
	150	2.33E+0	4.93E-2	1.94E-3	2.75E-3	2.38E+1	1.09E+0	4.29E-2	6.08E-2
	335	5.21E+0	7.95E-2	3.39E-3	6.14E-3	5.32E+1	7.87E-1	3.36E-2	6.08E-2
Slurry/ Microsurfacing Machines (4 yr)	99	1.71E+0	8.33E-2	6.28E-3	3.23E-3	1.75E+1	2.79E+0	2.10E-1	1.08E-1
	150	2.33E+0	5.22E-2	2.32E-3	4.89E-3	2.38E+1	1.15E+0	5.13E-2	1.08E-1
	335	5.21E+0	8.41E-2	3.93E-3	1.09E-2	5.32E+1	8.33E-1	3.89E-2	1.08E-1

Example Calculation Comparing Paver Emissions Data from US EPA's Nonroad and CARB's Off-Road

Equipment = Paver

Horsepower = 165 hp

Gallon to grams = 3,785

US EPA *Nonroad* Paver BSFC = **13,364 g/hr** for a paver with 100 < hp <= 175

CARB *Off-Road* Paver BSFC = 0.0215 gal./hp-hr from Table 2.27 in Section 2.6

CARB *Off-Road* Paver BSFC for 101 hp Paver = 0.0215 x 101 x 3,785 = **8,219 g/hr**

CARB *Off-Road* Paver BSFC for 175 hp Paver = 0.0215 x 175 x 3,785 = **14,241 g/hr**

It can be seen from the example above that for the US EPA *Nonroad* paver, with engine horsepower between 100 and 175 hp, the fuel rate (13,364 g/hr) lies in between the 8,219 and 14,241 g/hr fuel rate of the CARB *Off-Road* paver. The US EPA has provided the fuel rate for a range of engine horsepower; however, the UCPRC has modeled CARB *Off-Road* fuel rates per engine horsepower.

APPENDIX D: EXAMPLE CONSTRUCTION EQUIPMENT CALCULATIONS

Wheel Asphalt Paver[6] (225 hp)

Paving speed (max with vibratory screed) = 250 ft./min

Paving depth = 3 in./lift (max as per compaction limits)

Paving width = 144 in./run

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / paving width (always round up)

Number of passes needed based on pavement thickness = total pavement layer thickness / paving depth (always round up)

Example

Number of hours required to pave a 10 in. thick, 1 lane-mile pavement:

Effective paving speed = 250 * 70/100 = 175 ft./min

Paving length = 5,280 ft. (1 mi.)

Number of passes based on lane width = 144/144 = 1

Number of lifts based on pavement thickness (3 in. maximum lift thickness) = 10/3 = 4

Hours of service using the Paver = 5,280/175 * 1 * 4 = 121 min = 2 hr

Check Based on Equipment Throughput

Maximum throughput capacity =1,766 tons/hr

Density of asphalt = 145 lb./ft^3

Volume of asphalt (based on example above) = 5,280 * 12 * 10/12 = 52,800 ft^3

Asphalt quantity = 145 * 52,800 * 0.0005 = 3,828 tons

Hours of throughput = 3,828/1,766 = 2 hr

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[6] cat.com/en_US/products/new/equipment/asphalt-pavers/wheel-asphalt-pavers/1000000900.html

Cold Planer/Miller[7] (630 hp)

Milling speed (max) = 328 ft./min

Maximum milling depth = 13 in./pass

Milling width = 79.1 in./pass

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / miller blade width (always round up)

Number of passes needed based on pavement thickness = total pavement layer thickness / milling depth (always round up)

<u>Example:</u>

Number of hours required to mill a 10 in. thick, 1 lane-mile pavement:

Effective milling speed = 328 * 70/100 = 230 ft./min

Length to mill = 5,280 ft. (1 mi.)

Number of passes based on lane width = 144/79.1 = 2

Number of passes based on pavement thickness (maximum milling depth 13 in.) = 10/13 = 1

Hours of service using the miller = 5,280/230 * 2 * 1 = 46 min = 0.77 hr

Concrete Paver[8] (175 hp)

Paving speed (max operational mode) = 35 ft./min

Paving width = 144 in./run

Paving depth = 10 in.

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / paving width (always round up)

Number of passes needed based on pavement thickness = total pavement layer thickness/paving depth (always round up)

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[7] holtca.com/new/cat-construction-equipment/cold-planers/cold-planer/pm620

[8] gomaco.com/Resources/gp2400specs.html

Example:

Number of hours required to pave 10 in. thick, 1 lane-mile pavement:

Effective paving speed = 35 * 70/100 = 24.5 ft./min

Length to pave = 5,280 ft. (1 mi.)

Number of passes based on lane width = 144/144 = 1

Number of passes based on lane depth (no limit) = 10/10 = 1

Hours of service using the paver = 5,280/24.5 * 1 *1 = 216 min = 3.6 hr

Pulverizer[9] (also called road reclaimer; 415.7 hp)

Pulverizing speed (max) = 2.97 mi./hr

Pulverizing depth = 20 in./run

Pulverizing width = 96 in./run

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / pulverizer blade width (always round up)

Number of passes needed based on pavement thickness = total pavement layer thickness / pulverizing depth (always round up)

Example:

Number of hours required to pulverize a 10 in. thick, 1-lane-mile pavement:

Effective pulverizing speed = 2.97 * 70/100 = 2.08 mi./hr

Pavement length to pulverize = 1 mi.

Number of passes based on lane width (inches) = 144/96 = 2

Number of passes based on pavement thickness (maximum milling depth 20 in.) = 10/20 = 1

Hours of service using the pulverizer = 1/2.08 * 2 * 1 = 1 hr

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[9] cat.com/en_US/products/new/equipment/road-reclaimers/road-reclaimer/104320.html

Scraper[10] (407 hp)

Scraping speed (operating) = 33.5 mi./hr

Scraping depth of spread = 10.3 in./run

Scraping width = 10.3 ft./run

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / scraper blade width (always round up)

Number of passes needed based on pavement thickness = total pavement layer thickness / scraping depth (always round up)

<u>Example:</u>

Number of hours required to scrape a 10 in. thick, 1 lane-mile pavement:

Effective scraper speed = 33.5 * 70/100 = 23.45 mi./hr

Pavement length to scrape = 1 mi.

Number of passes based on lane width = 12/10.3 = 2

Number of passes based on pavement thickness (ft.) = 10/10.3 = 1

Hours of service using the scraper = 1/23.45 * 2 * 1 = 0.085 hr

Sweeper and Scrubber Combo (SSC)[11]

SSC productivity (theoretical) = 67,000 ft^2/hr

SSC width = 52 in./run

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / SSC brush width (always round up)

<u>Example:</u>

For a 1 lane-mile pavement, number of hours needed to complete the sweep and scrub process:

Effective SSC productivity = 67,000 * 70/100 = 46,900 ft^2/hr

Area required to sweep and scrub = 5,280 * 12 = 63,360 feet^2 (1 lane-mile)

Number of passes based on lane width = 144/52 = 3

Hours of service using the SSC = 63,360/46,900 * 3 = 4.05 hr

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[10] cat.com/en_US/products/new/equipment/wheel-tractor-scrapers/elevating-scrapers/18576198.html

[11] totalcleanequip.com/wp-content/uploads/2018/08/Commander_T82_Brochure_2016.pdf

Soil Hauler[12] (764 hp)

Top speed (loaded)	= 41.6 mi./hr
Target payload (can be used instead of volume calculations)	= 61 tons
Struck capacity (can be used)	= 34.33 yd^3
Heaped capacity (assuming max material is hauled per trip)	= 46.41 yd^3
Assume efficiency	= 70%
Hauling distance	= 5 mi. (2.5 mi. loaded and 2.5 mi. unloaded back to site)

Example:

Number of hours required to haul soil material for a 10 in. thick, 1 lane-mile pavement using off-road soil hauler:

Effective speed	= 41.6 * 70/100 = 29.12 mi./hr
Payload	= (34.33+46.41)/2 = 40.37 yd^3 (assuming that the payload is neither struck nor heaped)
Volume needed to haul	= 10/12 * 5,280 * 12 = 52,800 ft^3 = 1,956 yd^3 (1 lane-mile)
Number of trips based on heaped capacity	= 1,956/46.41 = 49 trips
Hours of service using the soil hauler	= 5/29.12 * 49 = 8.41 hr

Slurry/Microsurfacing /Spreader[13]

Application rate	= 0.35 gal./yd^2
Application width per pass	= 12 ft.
Application speed	= 3.5 mi./hr = "brisk" walking pace
Number of passes (default)	= 2

Example:

For a 1 lane-mile pavement, number of hours needed for microsurfacing:

Hours of service by slurry/microsurfacing/spreader = 1/3.5 * 12/12 * 2 = 0.57 hr

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[12] cat.com/en_US/products/new/equipment/off-highway-trucks/off-highway-trucks/18256806.html

[13] pavementnetwork.com/services/seal-coating/slurry-seal-features-benefits/

Striping Paint Machine[14] (5.5 hp)

Application speed = 10 mi./hr = “brisk” walking pace

Number of passes (default) = 2 (left and right sides)

<u>Example:</u>

Number of hours required to paint striping on a 1 lane-mile road:

Hours of service by striping paint machine = 1/10 * 2 = 0.2 hr

Chip Spreader[15] (260 hp)

Spreader speed (max) = 5 mi./hr

Spreader width = 12 ft./run

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / spreader width (always round up)

Number of passes needed based on pavement thickness = assuming 1 single chip, 1 pass

<u>Example:</u>

Number of hours needed by a chip spreader to spread material on a 1 lane-mile road:

Effective spreader speed = 5 * 70/100 = 3.5 mi./hr

Length to spread chip = 1 mi.

Number of passes based on lane width = 12/12 = 1

Hours of service by spreader = 1/3.5 * 1 = 0.286 hr

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[14] usscproducts.com//striping-machines/road-street-line-marking-machines/ride-on-paint-sprayers/graco-linedriver/p/197/423

[15] parkerplant.com/bitumen-and-surfacing/spray-and-chip/chip-spreader

Portable Crushing and Sizing Equipment[16]

Equipment capacity = 880 tons/hr

Example:

Number of hours required to complete crushing and sizing process for a 10 in. thick, 1 lane-mile pavement:

Aggregate volume needed to be crushed = 10/12 * 5,280 * 12 = 52,800 ft^3 (1 lane-mile)

Assume aggregate is 95% of the mix = 52,800 * 0.95/100 = 50,160 ft^3

Assume density of aggregate = 150 lb./ft^3 = 0.075 ton/ft^3

Total aggregate to crush and size = 0.075 * 50,160 = 3,762 tons

Hours of service using the crusher and sizer = 3,762/880 = 4.275 hr

Concrete Saw

The cutting rate of concrete saw = 8 ft./min = 0.09 mi./hr

Rubblizer/Concrete Road Breaker[17]

Milling speed = 3.5 mi./hr

Milling width = 12.5 ft./run

Number of passes needed based on pavement width = pavement OR lane width / miller blade width (always round up)

Example:

For a 10 in. thick 1 lane-mile pavement, number of hours needed to complete the milling process:

Length of milling = 1 mi.

Number of passes based on lane width = 12/12.5 = 1

Hours of service using the rubblizer = 1/3.5 * 1 = 0.286 hr

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[16] metso.com/globalassets/saleshub/documents---episerver/lokotrack-mobile-crusher-screen-plants-en-2930.pdf

[17] antigoconstruction.com/breaker-specifications/mhb-badger-breaker---

Rollers[18,19] (101 hp)

Roller speed (travel) = 12 mi./hr

Rolling speed (assumed) = 3 mi./hr

Rolling layer (depth) = 3 in./run (from Caltrans *Highway Design Manual*, tied to maximum lift thickness)

Rolling width = 84 in./run

Assume efficiency = 70%

Laps per lane = 3/run

Number of passes needed based on pavement width = pavement OR lane width / rolling width (always round up)

Number of passes needed based on pavement thickness = total pavement layer thickness / rolling layer depth (always round up)

Example:

Number of hours required to compact a 10 in. thick, 1 lane-mile pavement:

Effective rolling speed = 3 * 70/100 = 2.1 mi./hr

Pavement length = 1 mi.

Number of passes based on lane width = 144/84 = 2

Number of passes based on pavement thickness = 10/3 = 4

Laps per lane = 3/run

Hours of service using the roller = 1/2.1 * 1 * 2 * 4 * 3 = 11.5 hr

Seal Coat Truck and Trailer[20]

Speed (max operational mode) = 2 mi./hr

Paving width = 144 in./run

Assume efficiency = 70%

Number of passes needed based on pavement width = pavement OR lane width / paving width (always round up)

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[18] cat.com/en_US/products/new/equipment/compactors/pneumatic-rollers/3593458251382080.html

[19] cat.com/en_US/products/new/equipment/compactors/tandem-vibratory-rollers/3074593387675271.html

[20] royallasphaltandsealcoating.com/

Example:

For a 1 lane-mile pavement, number of hours needed to run the seal coat truck:

Effective paving speed = 2 * 70/100 = 1.4 mi./hr

Paving length = 1 mi.

Number of passes based on lane width = 144/144 = 1

Hours of service by the truck = 1/1.4 * 1 = 0.714 hr

Air Compressor[21] (130 hp)

Fuel usage = 4.07 gal./hr

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[21] elgi.com/us/wp-content/uploads/2020/04/D425.pdf

APPENDIX E: CRADLE-TO-LAY EXAMPLE CASES FOR DIFFERENT PAVEMENT TYPES

Mix Designs and Material Production Stage of Various Pavement Surface Treatments

Table E.1 lists the pavement surface treatments that were considered in this study. Each treatment's impacts can be divided between material production, transportation to the site, and construction activities. In this section, the mix design for each surface treatment is discussed first to provide a basis for the calculations for the material production stage. The inventories developed in Sections 2.1, 2.2, and 2.3 were used alongside the mix designs to calculate the material production stage impacts for each treatment. The transportation distance was assumed to be 50 miles (80 km), a typical hauling distance in California, for all surface treatments. To represent project-specific conditions, a user can change the default hauling distance in the models.

Other than the material production stages of conventional asphalt concrete (or HMA), portland cement concrete (PCC), and rubberized HMA (RHMA), none of LCIs in this section were modeled with *GaBi* software. Consequently, no figures here show the plant or unit processes for those LCIs. The LCIs and LCIAs of the energy sources and materials developed in Section 2.1 and Section 2.2 were used in an *Excel* file with most of the mix design information taken from the Caltrans *Maintenance Technical Advisory Guide* (*MTAG*) *(52)* to calculate the LCI and LCIA of the material production stage for each surface treatment.

Table E.1: Pavement Surface Treatment Alternatives Considered

Surface Treatments
Bonded Concrete Overlay on Asphalt (BCOA)
Cement Concrete (Various Applications)
Cape Seal
Chip Seal
Conventional Asphalt Concrete (Mill-and-Fill)
Conventional Asphalt Concrete (Overlay)
Conventional Interlocking Concrete Pavement (Pavers)
End-of-Life Treatment (Cold In-Place Recycling)
End-of-Life Treatment (Full-Depth Reclamation)
Fog Seal
Permeable Asphalt Concrete
Permeable Portland Cement Concrete
Reflective Coating (BPA)
Reflective Coating (Polyester Styrene)
Reflective Coating (Polyurethane)
Reflective Coating (Styrene Acrylate)
Rubberized Asphalt Concrete (Mill-and-Fill)
Rubberized Asphalt Concrete (Overlay)
Sand Seal
Slurry Seal

Bonded Concrete Overlay of Asphalt

Bonded concrete overlay on asphalt (BCOA) consists of placing a concrete overlay on an existing asphalt concrete surface. For the purposes of this study, the default thickness was selected as 5 in. (12.5 cm) (though the thickness can be selected by a designer). BCOA construction consists of milling the existing asphalt layer (0.5 to 2 in. [1.25 to 5 cm], assumed to be 1 in. [2.5 cm] in this study), sweeping it multiple times and airblasting it, wetting the surface, placing the concrete, and finally sawing and sealing the joints every 2 to 6 ft. (60 to 180 cm) *(42)*. As with the model for portland cement concrete construction, sawing and joint sealing are not included in this model. Mix designs for the BCOA mixes used in the CARB/Caltrans/LBNL heat island and cool pavement project are listed in Table E.2, and construction details are presented in Table E.8.

Table E.2: Mix Designs for 1 m^3 of BCOA with Three Levels of SCM

Item[a]	Cement (kg)	Slag (kg)	Fly Ash (kg)	Coarse Agg (kg)	Fine Agg (kg)	Water (kg)	Fiber (kg)	Air Entraining (kg)	Retarder (kg)	Water Reducer (kg)	Total SCM (kg/m^3) [%]
BCOA (PC139-SCM139)	139	56	84	1,038	817	173	0	0	0	0	139 [50%]
BCOA (PC267-SCM71)	267	0	71	1,085	764	145	2	0	0	0	71 [19%]
BCOA (PC448-SCM0)	448	0	0	1,071	598	161	2	1	2	2	0 [0%]

[a] PC: portland cement; SCM: supplementary cementitious materials. The number that follows each item is the amount (in kg) per cubic meter of parlance cement concrete.

Cape Seal

The *MTAG (52)* defines a cape seal as a slurry seal over a chip seal.

Chip Seal

It was assumed that chip seals are constructed with 0.4 gal./yd^2 (1.8 L/m^2) of asphalt emulsion and 35 lb./yd^2 (19 kg/m^2) of aggregate. The construction process consists of sweeping, application of asphalt emulsion, spreading of aggregate, embedding of aggregate with pneumatic tire rollers, and a final round of sweeping. Aggregates are assumed to be angular and crushed *(52)*. Construction details for chip seal are presented in Table E.8.

Conventional Asphalt Concrete (Mill-and-Fill and Overlay-Only)

The model developed in *GaBi* for conventional asphalt concrete (also referred to as "hot mix asphalt" [HMA]) is shown in Figure E.1. The mix design and the percentage of each of the ingredients can be changed within the model to facilitate calculating LCIs for the various mix designs used in different construction projects.

Notes:

- Proportions of mix constituents can be changed; transportation of binder from refinery to the plant is not shown in the figure and was not considered in the example.
- Model developed in *GaBi* using information from the California electricity production model and USLCI data.

Figure E.1: The model developed for default HMA.

The LCIs for two mixes were prepared differently, one with 15% RAP content and the other with no RAP (taken from the initial UCPRC pavement LCA study) *(4,5)* the former of which represents a typical mix used by Caltrans for rehabilitation projects. It was assumed that the RAP materials had a binder content of 5% by mass with a 90% binder recovery ratio, resulting in an effective RAP binder content of 4.5%. Therefore, the total binder content for HMA baseline is 4.7% (0.04 + 0.15 * 0.045 = 0.047). The details of both mixes are shown in Table E.3 (construction details for asphalt concrete are presented in Table E.8). Also note, that while the specification allows up to 15% RAP binder, actual contents under that specification average about 11%.

Table E.3: HMA with RAP Mix Design (Percent by Mass)

Item	Mix 1 (with 15% RAP)	Mix 2 (No RAP)
Aggregate Crushed	81	94
Virgin Asphalt Binder	4	6
Reclaimed Asphalt Pavement (RAP)	15	0

Table E.4 shows the asphalt concrete plant energy mix from two sources, the Athena Institute *(50)* and the National Asphalt Pavement Association (NAPA) *(28)*. The energy mix data in the Athena Institute report is for asphalt concrete plants in Quebec and Ontario in Canada. The primary energy data in the NAPA report is based on 34 asphalt concrete plants for energy and 32 plants for electricity; the asphalt plants are located in seven US regions: Northcentral, Midwest, Northeast, Northwest, Southeast, Southwest and Mid-Atlantic. It should be noted that there are more fuel types (such as diesel fuel and residual fuel oil) reported in the Athena Institute and NAPA studies. Due to strict emission standards, asphalt concrete plants in California mostly use natural gas instead of diesel fuel. Thus, energy from use of diesel fuel has been backcalculated to determine the quantity of natural gas in this study.

Table E.4: Energy Mix Used in the Asphalt Plant

	Energy Input[a] MJ/kg of Asphalt Concrete	
Fuel Type[b]	**UCPRC 2016 (calculated based on Athena Institute)**	**UCPRC 2021[c] (calculated based on NAPA[d])**
Electricity	7.6319E-03	1.3175E-02
Natural Gas	3.9652E-01	3.3611E-01

[a] MJ energy calculations are based on: Electricity 1 kWh = 3.6 MJ; Natural Gas 1 m^3 = 38.4 MJ (see Table 2.3).

[b] Due to strict emission standards, diesel fuel is not used in the asphalt plants for heating aggregates or for other mixing operations; natural gas is mostly used.

[c] Recently (in 2021), the UCPRC 2016 HMA energy mix at the plant has been replaced by the UCPRC 2021 energy mix.

[d] Electricity = 3.32 kWh/ton of HMA; Energy (based on California conditions, it is assumed to be all from natural gas in this study) = 2.89E+05 Btu/ton of HMA. This data is based on primary data from 34 US plants for energy and 32 US plants for electricity.

The typical thickness of the asphalt concrete placed was assumed to be 2.4 in. (6 cm). Two construction options are considered for the use of asphalt concrete. The first option is mill-and-fill, where construction consists of milling 1.8 in. (4.5 cm) of the surface (assumed thickness) followed by application of a tack coat, laying down new asphalt concrete, and compacting the layer with three types of rollers (vibratory, pneumatic, and static). The second option is overlay-only with a similar mix design and thickness. The only difference between the two approaches is in the construction stage, where milling of the top surface is not conducted. Instead, in the overlay-only approach, a tack coat is applied on the old surface and then the new HMA is put directly on top. The thickness of the new asphalt concrete is a variable, and a user can change it. The LCI results can be linearly scaled based on the default thickness used in this section and the new design thickness.

A quick sensitivity check for the asphalt plant two energy input (see Table E.4) shows that the GWP for 1 tonne of Mix 2 (no RAP; see Table E.3) using the UCPRC 2016 plant energy mix is reported to be 2.55E+01 kg$CO_{2\text{-e}}$, and 2.21E+01 kg $CO_{2\text{-e}}$ when using UCPRC 2021 plant energy mix. A slight reduction in the GWP value using plant energy mix data from NAPA's report *(28)* can be explained due to less use of non-renewable energy (natural gas) in the plant. It should also be noted that the foreground data (plant energy mix) is from NAPA's report, but the background data (electricity grid mix) being used by UCPRC is based on California-specific data. Recently, *eLCAP* has been updated to use UCPRC 2021 plant energy mix data.

Conventional Interlocking Concrete Pavement (Pavers)

No data on pavers was available. Therefore, an environmental product declaration (EPD) developed by Angelus Block Inc. was used *(53)* to determine the environmental impacts of interlocking concrete pavement blocks, also referred to as pavers. These data are mainly used for the heat island study, which is mentioned in Section 1.2.1 of the report. The EPD reported the impacts for two separate functional units: first, for a functional unit of 1 m^3 of concrete paver materials and then for a concrete masonry unit (CMU) that has the dimensions 8 in. × 8 in. × 16 in. (20 cm × 20 cm × 40 cm) and 50% air voids. Construction details for concrete pavers are presented in Table E.8.

Fog Seal

The *MTAG (52)* states that the emulsion application rate for fog seals should be between 0.1 to 0.15 gal./yd^2 (0.45 to 0.7 L/m^2), with the average used in this study. Construction consists of sweeping, spraying of emulsion, and the optional application of sand, which was not assumed in this study. Construction details for fog seals are presented in Table E.8.

Permeable Asphalt Concrete Pavement

Permeable asphalt concrete was assumed to consist of a base of thickness of 0.5 ft. (15 cm) made from 100% crushed and angular aggregate, topped with 0.35 ft. (11 cm) of open-graded asphalt concrete, according to Caltrans recommendations *(54)*. Construction details for permeable asphalt concrete are presented in Table E.8.

Permeable Portland Cement Concrete

Permeable PCC was assumed to consist of a 0.5 ft. (15 cm) open-graded portland cement concrete layer on top of a 0.5 ft. (15 cm) granular base layer, according to Caltrans recommendations *(54)*. Construction details for permeable PCC are presented in Table E.8.

Portland Cement Concrete

Figure E.2 shows the model developed in *GaBi* for portland cement concrete (PCC). It is a general model, and the mix design can be modified to cover the various PCCs used in construction projects. The construction processes for concrete mixes with cement types other than portland cement, such as calcium sulfoaluminate cement, are similar. Figure E.2 shows the model, and the user can change the inputs based on their project information.

The general model for PCC was used to develop LCIs for the following applications:

- lane replacement
- slab replacement (two mixes)
- local streets
- minor concrete

The selected mix designs for slab replacement were taken from the initial UCPRC pavement LCA study *(4,5)*, which presents a typical mix design with high early strength used for slab replacements in Caltrans rehabilitation projects constructed using overnight closures. For lane replacement, a typical mix design used by Caltrans for state highway projects was used; the design incorporates use of supplementary cementitious materials (SCMs). The mix designs for local streets and minor concrete were taken from projects in the cities of Santa Rosa and Davis. The mix designs are presented in Table E.5 and construction details are available in Table E.8.

Notes:
- Proportions of mix constituents can be changed.
- Model developed in *GaBi* using information from the California electricity production model and USLCI data.

Figure E.2: Model developed for default PCC.

Table E.5: Mix Designs for PCC Items (Mass per 1 m^3 of Mix)

Application	Item[a]	Cement (kg)	Fly Ash (kg)	Coarse Agg (kg)	Fine Agg (kg)	Water (kg)	Accelerator (kg)	Air Entraining (kg)	Retarder (kg)	Water Reducer (kg)	Total SCM (kg/m^3) [%]
Local Streets (Santa Rosa Mix for Local Streets)	PCC (PC418 SCM0)	418	0	892	869	184	4.2	0	0	3.4	0 [0%]
Lane Replacement (Caltrans Mix for State Highways)	PCC (PC284 SCM50)	284	50	1,068	822	149	0	0.1	0	1.2	50 [18%]
Minor Concrete (City of Davis Mix for Sidewalks and Footings)	PCC (PC335 SCM0)	335	0	1,129	812	163	0	0	0	1	0 [0%]
Slab Replacement (with Cement Type III)	PCC (PCIII475 SCM0)	475	0	1,128	609	166	37.4	0	0.7	2.6	0 [0%]
Slab Replacement (with CSA Cement)	PCC (CSA390 SCM0)	390	0	1,064	794	156	0	0	2.1	1.2	0 [0%]

[a] Abbreviations used in the item codes:
- CSA: calcium sulfoaluminate cement
- PC: portland cement (Type I/II unless explicitly stated as Type III)
- SCM: supplementary cementitious materials

The number that follows PC and SCM shows the amount (in kg) per cubic meter of portland cement concrete.

The PCC layer thickness was assumed to be 6.8 in. (17.5 cm) as a default (though a designer can define the PCC thickness). The construction process consisted of grinding of the old surface, sweeping, and laying down the PCC layer using a paver. Saw cutting and curing were assumed to only make a small contribution to the inventories so their impacts were not included. The new portland cement concrete's thickness is a variable that can be changed by a designer. The LCI results can be linearly scaled based on the default thickness used in this section and the new design thickness. For slab replacement, average slab size was assumed to be 12 ft. (3.6 m) wide, 15 ft. (4.5 m) long, and 9 in. (22.5 cm) thick.

Reflective Coatings

In the reflective coating construction process, the pavement surface is swept and the coating is then applied by a tanker. The application rates assumed for this study were based on the average of ranges found in the literature review (see Table 2.17). Construction details for reflective coatings are presented in Table E.8.

Rubberized Asphalt Concrete (Mill-and-Fill and Overlay-Only)

The mix design for rubberized asphalt concrete (rubberized hot mix asphalt, RHMA) was taken from the initial UCPRC pavement LCA study *(4,5)*. which presents a typical rubberized asphalt concrete mix used in Caltrans rehabilitation projects. That mix design is presented in Table E.6, but the mix constituent proportions can be changed.

Table E.6: Rubberized Asphalt Concrete Mix Design

Item	Percent by Weight (%)
Aggregate	**92.5**
Coarse	68
Fine	27
Dust	5
Asphalt Binder	**7.5**
Virgin Asphalt Binder	77.5
CRM	20
Extender Oil	2.5
RAP	**0**

As with conventional asphalt concrete, two options are provided here: mill-and-fill and overlay-only. The construction process was assumed to be like of the conventional asphalt concrete. The thickness of the treatment for both cases was assumed to be 2 in. (5 cm) (though this thickness is a variable that a designer can change). The LCI results can be linearly scaled based on the default thickness used in this section and the new design thickness, as with HMA and PCC, can be modified by a user. Construction details for RHMA are presented in Table E.8.

Sand Seal

Sand sealing consists of the application of asphalt emulsion followed by deposition of a layer of sand on top of it. A pneumatic roller is then often used to stabilize the sand. The range of emulsion application is between 0.1 to 0.25 gal./yd^2 (0.45 to 1.15 L/m^2), and sand is applied at 18 to 25 lb./ yd^2 (9.5 to 13.5 kg/m^2). The averages of the ranges were used in both cases in this study *(52)*. Construction details for sand seal are presented in Table E.8.

Slurry Seal

A Type II slurry mix design was selected with an application rate of 10 to 15 lb./ yd^2 (5.5 to 8 kg/m^2) of angular aggregate and residual asphalt content of 7.5% to 13.5% by weight of aggregate. The averages of the ranges were used in both cases in this study *(52)*. Construction details for slurry seal are presented in Table E.8.

End-of-Life Treatments: Cold In-Place Recycling and Full-Depth Recycling

The end-of-life (EOL) treatments in the following matrix were modeled using current Caltrans practices in California. The treatments considered are presented in Table E.7. The cutoff method was used for the allocation of impacts between the upstream and downstream projects (see Table 1.4). The transport distance for all the mixes and materials from plant to site was assumed to be 50 miles one way; for other transportation distances, the numbers can be linearly calibrated. Construction process details for cold in-place recycling (CIR) and full-depth reclamation (FDR) are presented in Table E.9.

Table E.7: Typical In-Place End-of-Life Recycling Treatments in California

Treatment Type
CIR (4 in. [10 cm] milled + mechanical stabilization) with 1 in. (2.5 cm) of HMA OL
CIR (4 in. [10 cm] milled + mechanical stabilization) with Chip Seal
FDR (10 in. [25 cm] milled + no stabilization) with 2.4 in. (6 cm) RHMA OL
FDR (10 in. [25 cm] milled + 4% AE + 1% PC) with 2.4 in. (6 cm) RHMA OL
FDR (10 in. [25 cm] milled + 3% FA + 1% PC) with 2.4 in. (6 cm) RHMA OL
FDR (10 in. [25 cm] milled + 2% PC) with 2.4 in. (6 cm) RHMA OL
FDR (10 in. [25 cm] milled + 4% PC) with 2.4 in. (6 cm) RHMA OL
FDR (10 in. [25 cm] milled + 6% PC) with 2.4 in. (6 cm) RHMA OL

Notes:

- HMA: hot mix asphalt
- RHMA: rubberized hot mix asphalt
- OL: overlay
- AE: asphalt emulsion
- PC: portland cement
- FA: foamed asphalt

Construction Stage for Various Surface Treatments

The construction stage was modeled based on the sequence of construction activities, the equipment used in each step, the horsepower and hourly gas consumption of the equipment, the speed of the equipment, and the required number of passes over the section. These were used to calculate the total fuel consumption for the functional unit, which was then multiplied by the *GaBi* values for the LCI and LCIA of "fuel combusted in equipment" to calculate the construction stage environmental impacts. The *GaBi* values included both the well-to-pump impacts (diesel production impacts) and the pump-to-wheel impacts (impacts due to fuel combustion in equipment).

Table E.8 shows the construction process for each of the surface treatments considered in this study. As stated earlier, these processes were modeled using information collected from Caltrans specifications, consultation with local experts, and guidelines obtained in the literature survey. Table E.9 shows similar details for the EOL treatments.

Table E.8: Construction Process for Different Surface Treatments

Case	Equipment/Activity	Engine Power (hp)	Hourly Fuel Use (gal./hr)	Speed (ft./min)	Speed (km/h)	Time (hr) for 1 Pass over 1 lane-km	Number of Passes	Fuel Used (gal.)[b]	Total Fuel Used (gal.)
Bonded Concrete Overlay of Asphalt (BCOA)	Milling[a]	700	20	10	0.183	5.47	1	109.36	129
	Sweeping	80	2	100	1.829	0.55	2	2.19	
	Wetting	80	2	100	1.829	0.55	1	1.09	
	Concrete placement	90	3	10	0.183	5.47	1	16.4	
Chip Seal	Sweeping	80	2	100	1.829	0.55	2	2.19	68
	Emulsion application	350	7.2	25	0.457	2.19	1	15.75	
	Aggregate application	350	7.2	25	0.457	2.19	1	15.75	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Sweeping	80	2	100	1.829	0.55	2	2.19	
Fog Seal	Sweeping	80	2	100	1.829	0.55	2	2.19	17.9
	Emulsion application	350	7.2	25	0.457	2.19	1	15.75	
Conventional Asphalt Concrete (Mill-and-Fill)	Milling[a]	700	20	10	0.183	5.47	1	109.36	284.5
	Tack coat application	350	7.2	25	0.457	2.19	1	15.75	
	HMA placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
Conventional Asphalt Concrete (Overlay)	Tack coat application	350	7.2	25	0.457	2.19	1	15.75	175.1
	HMA placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
Conventional Interlocking Concrete Pavement (Pavers)	Base compaction	150	8.1	25	0.457	2.19	1	17.72	57.1
	Paver placement	350	7.2	10	0.183	5.47	1	39.37	
Permeable Asphalt Concrete	Base layer lay-down	350	7.2	25	0.457	2.19	1	15.75	192.8
	Base layer compaction	150	8.1	25	0.457	2.19	1	17.72	
	HMA placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	

Permeable Portland Cement Concrete	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	49.9
	Base layer lay-down	350	7.2	25	0.457	2.19	1	15.75	
	Base layer compaction	150	8.1	25	0.457	2.19	1	17.72	
	HMA placement	90	3	10	0.183	5.47	1	16.4	
Portland Cement Concrete (slab replacement)	Saw/break/remove	275	5	10	0.183	5.47	1	27.34	44.8
	Sweeping	80	2	100	1.829	0.55	1	1.09	
	Concrete placement	90	3	10	0.183	5.47	1	16.4	
Portland Cement Concrete with SCM (Overlay)	Grinder	275	5	10	0.183	5.47	1	27.34	44.8
	Sweeping	80	2	100	1.829	0.55	1	1.09	
	Paver (Concrete)	90	3	10	0.183	5.47	1	16.4	
Reflective Coatings	Sweeping	80	2	100	1.829	0.55	1	1.09	16.8
	Reflective coating application	350	7.2	25	0.457	2.19	1	15.75	
Rubberized Asphalt Concrete (Mill-and-Fill)	Milling[a]	700	20	10	0.183	5.47	1	109.36	284.5
	Tack coat application	350	7.2	25	0.457	2.19	1	15.75	
	HMA Placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
Rubberized Asphalt Concrete (Overlay)	Tack coat application	350	7.2	25	0.457	2.19	1	15.75	175.1
	HMA Placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
Sand Seal	Sweeping	80	2	100	1.829	0.55	2	2.19	66.9
	Emulsion application	350	7.2	25	0.457	2.19	1	15.75	
	Sand application	350	7.2	25	0.457	2.19	1	15.75	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Sweeping	80	2	100	1.829	0.55	1	1.09	
Slurry Seal	Sweeping	80	2	100	1.829	0.55	1	1.09	56.4
	HMA Placement	250	10.6	25	0.457	2.19	1	23.18	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	

Note: Modeled based on Caltrans specifications, consultations with local experts, and the literature.

[a] Caltrans specifies milling by area along with the thickness. Milling is used as an area for equipment use time and user defines number of passes needed to mill the layer.

[b] Equation used to calculate fuel use of construction equipment: [hourly fuel use (gal./hr)] / [speed (km/hr] * number of passes per lane. Number of passes are based on the thickness of the layer.

Table E.9: Construction Process for EOL Treatments

Case	Equipment/Activity	Engine power (hp)	Hourly Fuel Consumption (gal./hr)	Speed (ft./min)	Speed (km/h)	Time (hr) for 1 pass over 1 lane-km	Number of Passes	Fuel Used (gal.)	Total Fuel Use
CIR (mechanical stabilization) with 1 in. [2.5 cm] HMA OL	Milling	700	20	10	0.183	5.47	1	109.36	373.1
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
	Tack coat application	350	7.2	25	0.457	2.19	1	15.75	
	HMA placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
CIR (mechanical stabilization) with chip seal	Milling	700	20	10	0.183	5.47	1	109.36	295.9
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	
	Emulsion application	350	7.2	25	0.457	2.19	1	15.75	
	Aggregate application	350	7.2	25	0.457	2.19	1	15.75	
	Rolling (pneumatic)	120	4.9	25	0.457	2.19	3	32.15	
	Sweeping	80	2	100	1.829	0.55	2	2.19	
FDR (+ additives) with overlay	Milling (with application of additives)	1,000	28.57	10	0.183	5.47	1	156.23	455.37
	Rolling (padfoot)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (vibratory)	120	4.9	25	0.457	2.19	3	32.15	
	Surface-leveling with grader	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (rubber-tired)	150	8.1	25	0.457	2.19	3	53.15	
	Tack coat application	350	7.2	25	0.457	2.19	1	15.75	
	HMA placement	250	10.6	15	0.274	3.65	1	38.64	
	Rolling (vibratory)	150	8.1	25	0.457	2.19	2	35.43	
	Rolling (static)	150	8.1	25	0.457	2.19	3	53.15	

Note: These construction processes are applicable for typical CIR (now called partial-depth recycling [PDR]) and FDR construction, regardless of stabilizer type.

Summary of Cradle-to-Lay Impacts (Material Production, Transportation, and Construction) for Various Surface Treatments

Table E.10 summarizes the main LCI and LCIA categories of interest for the treatments with the 2012 California electricity grid mix. Table E.11 shows the EOL treatments summary.

Table E.10: Summary LCI and LCIA of Treatments for Default Thicknesses and a Functional Unit of 1 ln-km:

Item	Default Thickness (in.)	Life Cycle Stage	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Ren)[b] [MJ]	Feedstock Energy [MJ]
Bonded Concrete Overlay of Asphalt (BCOA) OP139SCM139	5	Material	6.28E+04	5.64E+03	3.71E+01	4.93E+05	4.61E+05	0.00E+00
		Transport	1.97E+04	5.29E+03	9.53E+00	2.74E+05	2.74E+05	0.00E+00
		Construction	1.54E+03	6.80E+02	1.21E+00	2.12E+04	2.12E+04	0.00E+00
		Total	8.40E+04	1.16E+04	4.78E+01	7.88E+05	7.41E+05	0.00E+00
Bonded Concrete Overlay of Asphalt (BCOA) OP267SCM71	5	Material	1.14E+05	9.78E+03	6.44E+01	8.67E+05	8.12E+05	0.00E+00
		Transport	1.52E+04	2.77E+03	5.30E+00	2.16E+05	2.16E+05	0.00E+00
		Construction	1.54E+03	6.80E+02	1.21E+00	2.12E+04	2.12E+04	0.00E+00
		Total	1.31E+05	1.32E+04	7.09E+01	1.10E+06	1.04E+06	0.00E+00
Bonded Concrete Overlay of Asphalt (BCOA) OP448SCM0	5	Material	1.89E+05	1.83E+04	1.07E+02	1.38E+06	1.29E+06	0.00E+00
		Transport	1.34E+04	2.13E+03	4.28E+00	1.92E+05	1.92E+05	0.00E+00
		Construction	1.54E+03	6.80E+02	1.21E+00	2.12E+04	2.12E+04	0.00E+00
		Total	2.04E+05	2.11E+04	1.13E+02	1.60E+06	1.50E+06	0.00E+00
Cape Seal	n/a	Material	5.03E+03	8.24E+02	4.03E+00	1.05E+05	1.00E+05	3.75E+05
		Transport	6.53E+02	1.04E+02	2.09E-01	9.35E+03	9.35E+03	0.00E+00
		Construction	1.49E+03	6.56E+02	1.17E+00	2.05E+04	2.05E+04	0.00E+00
		Total	7.17E+03	1.58E+03	5.40E+00	1.35E+05	1.30E+05	3.75E+05
Chip Seal	n/a	Material	3.64E+03	5.97E+02	2.91E+00	7.60E+04	7.23E+04	2.69E+05
		Transport	4.80E+02	7.65E+01	1.53E-01	6.87E+03	6.87E+03	0.00E+00
		Construction	8.12E+02	3.59E+02	6.37E-01	1.12E+04	1.12E+04	0.00E+00
		Total	4.93E+03	1.03E+03	3.70E+00	9.41E+04	9.04E+04	2.69E+05
Conventional Asphalt Concrete (Mill-and-Fill) Mix 1 (15% RAP)	2.4	Material	2.58E+04	2.41E+03	1.69E+01	4.20E+05	4.06E+05	8.95E+05
		Transport	3.32E+03	5.30E+02	1.06E+00	4.76E+04	4.76E+04	0.00E+00
		Construction	3.40E+03	1.50E+03	2.67E+00	4.68E+04	4.68E+04	0.00E+00
		Total	3.25E+04	4.44E+03	2.06E+01	5.14E+05	5.01E+05	8.95E+05
Conventional Asphalt Concrete (Overlay) Mix 1 (15% RAP)	2.4	Material	2.58E+04	2.41E+03	1.69E+01	4.20E+05	4.06E+05	8.95E+05
		Transport	3.32E+03	5.30E+02	1.06E+00	4.76E+04	4.76E+04	0.00E+00
		Construction	2.09E+03	9.23E+02	1.64E+00	2.88E+04	2.88E+04	0.00E+00
		Total	3.12E+04	3.86E+03	1.96E+01	4.96E+05	4.83E+05	8.95E+05
Conventional Asphalt Concrete (Mill-and-Fill) Mix 1 (No RAP)	2.4	Material	3.05E+04	3.22E+03	2.12E+01	5.56E+05	5.38E+05	1.29E+06
		Transport	1.85E+02	2.94E+01	5.90E-02	2.64E+03	2.64E+03	0.00E+00
		Construction	3.40E+03	1.50E+03	2.67E+00	4.68E+04	4.68E+04	0.00E+00
		Total	3.41E+04	4.75E+03	2.39E+01	6.05E+05	5.88E+05	1.29E+06
Conventional Asphalt Concrete (Overlay) Mix 2 (No RAP)	2.4	Material	3.05E+04	3.22E+03	2.12E+01	5.56E+05	5.38E+05	1.29E+06
		Transport	1.85E+02	2.94E+01	5.90E-02	2.64E+03	2.64E+03	0.00E+00
		Construction	2.09E+03	9.23E+02	1.64E+00	2.88E+04	2.88E+04	0.00E+00
		Total	3.28E+04	4.17E+03	2.29E+01	5.87E+05	5.70E+05	1.29E+06

Item	Default Thickness (in.)	Life Cycle Stage	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Ren)[b] [MJ]	Feedstock Energy [MJ]
Conventional Interlocking Concrete Pavement (Pavers)	n/a	Material	7.66E+04	7.84E+03	n/a	6.81E+05	n/a	n/a
		Transport	9.38E+03	1.50E+03	3.00E+00	1.34E+05	1.34E+05	0.00E+00
		Construction	6.82E+02	3.01E+02	5.35E-01	9.39E+03	9.39E+03	0.00E+00
		Total	8.67E+04	9.64E+03	3.53E+00	8.25E+05	1.44E+05	0.00E+00
Fog Seal	n/a	Material	1.06E+03	1.72E+02	8.73E-01	2.24E+04	2.14E+04	8.42E+04
		Transport	1.31E+01	2.08E+00	4.17E-03	1.87E+02	1.87E+02	0.00E+00
		Construction	2.14E+02	9.46E+01	1.68E-01	2.95E+03	2.95E+03	0.00E+00
		Total	1.29E+03	2.69E+02	1.05E+00	2.56E+04	2.46E+04	8.42E+04
Permeable Asphalt Concrete	6	Material	5.09E+04	5.25E+03	32.3	8.35E+05	799000	1.59E+06
		Transport	1.51E+04	2.40E+03	4.81E+00	2.15E+05	2.15E+05	0.00E+00
		Construction	2.30E+03	1.02E+03	1.81E+00	3.17E+04	3.17E+04	0.00E+00
		Total	6.83E+04	8.66E+03	3.90E+01	1.08E+06	1.05E+06	1.59E+06
Permeable Portland Cement Concrete	6	Material	2.70E+05	2.26E+04	1.42E+02	1.77E+06	1.65E+06	0.00E+00
		Transport	1.76E+04	2.80E+03	5.62E+00	2.52E+05	2.52E+05	0.00E+00
		Construction	5.95E+02	2.63E+02	4.67E-01	8.21E+03	8.21E+03	0.00E+00
		Total	2.88E+05	2.57E+04	1.48E+02	2.03E+06	1.91E+06	0.00E+00
Portland Cement Concrete (PC284 SCM50) for Lane Replacement	6.8	Material	1.65E+05	1.49E+04	9.40E+01	1.17E+06	1.10E+06	0.00E+00
		Transport	2.06E+04	3.64E+03	7.03E+00	2.94E+05	0.00E+00	0.00E+00
		Construction	1.84E+03	8.13E+02	1.44E+00	2.54E+04	0.00E+00	0.00E+00
		Total	1.88E+05	1.94E+04	1.02E+02	1.49E+06	1.10E+06	0.00E+00
Portland Cement Concrete (PC335 SCM0) for Minor Concrete	6.8	Material	1.93E+05	1.66E+04	1.10E+02	1.37E+06	1.28E+06	0.00E+00
		Transport	2.87E+04	7.70E+03	1.39E+01	3.99E+05	3.77E+05	0.00E+00
		Construction	1.84E+03	8.13E+02	1.44E+00	2.54E+04	2.54E+04	0.00E+00
		Total	2.24E+05	2.51E+04	1.25E+02	1.79E+06	1.69E+06	0.00E+00
Portland Cement Concrete (PC418 SCM0) for Local Streets	6.8	Material	2.44E+05	2.07E+04	1.38E+02	1.75E+06	1.65E+06	0.00E+00
		Transport	1.91E+04	3.05E+03	6.12E+00	2.74E+05	2.23E+03	0.00E+00
		Construction	1.84E+03	8.13E+02	1.44E+00	2.54E+04	8.32E+00	0.00E+00
		Total	2.65E+05	2.45E+04	1.45E+02	2.05E+06	1.65E+06	0.00E+00
Portland Cement Concrete (CSA390 SCM0) for Slab Replacement (CSA Cement) – One Slab	6.8	Material	8.65E+02	7.47E+01	4.72E-01	5.82E+03	5.47E+03	0.00E+00
		Transport	1.60E+02	4.30E+01	7.75E-02	2.23E+03	2.23E+03	0.00E+00
		Construction	8.42E+00	3.72E+00	6.61E-03	1.16E+02	3.80E-02	0.00E+00
		Total	3.39E+04	6.56E+03	2.93E+03	2.48E+05	2.34E+05	2.91E+03
Portland Cement Concrete (PCIII475 SCM0) for Slab Replacement (Type III) – One Slab	6.8	Material	1.81E+03	1.45E+02	9.41E-01	1.50E+04	1.42E+04	0.00E+00
		Transport	1.60E+02	4.30E+01	7.75E-02	2.23E+03	2.23E+03	0.00E+00
		Construction	8.42E+00	3.72E+00	6.61E-03	1.16E+02	3.80E-02	0.00E+00
		Total	6.13E+04	8.59E+03	2.94E+03	5.14E+05	4.88E+05	2.91E+03
Reflective Coating – BPA	n/a	Material	1.04E+04	4.46E+02	2.75E+00	2.52E+05	2.46E+05	n/a
		Transport	1.38E+02	2.21E+01	4.43E-02	1.98E+03	1.98E+03	n/a
		Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	n/a
		Total	1.07E+04	5.57E+02	2.95E+00	2.57E+05	2.51E+05	n/a
Reflective Coating – Polyester Styrene	n/a	Material	1.22E+04	5.77E+02	1.42E+01	2.55E+05	2.43E+05	n/a
		Transport	1.38E+02	2.21E+01	4.43E-02	1.98E+03	1.98E+03	n/a
		Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	n/a
		Total	1.25E+04	6.88E+02	1.44E+01	2.59E+05	2.47E+05	n/a

Item	Default Thickness (in.)	Life Cycle Stage	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Ren)[b] [MJ]	Feedstock Energy [MJ]
Reflective Coating – Polyurethane	n/a	Material	8.66E+03	3.78E+02	3.42E+00	1.91E+05	1.81E+05	n/a
		Transport	1.85E+02	2.94E+01	5.90E-02	2.64E+03	2.64E+03	n/a
		Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	n/a
		Total	9.05E+03	4.96E+02	3.63E+00	1.96E+05	1.87E+05	n/a
Reflective Coating – Styrene Acrylate	n/a	Material	5.76E+03	2.35E+02	1.82E+00	1.36E+05	1.31E+05	n/a
		Transport	1.85E+02	2.94E+01	5.90E-02	2.64E+03	2.64E+03	n/a
		Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	n/a
		Total	6.15E+03	3.53E+02	2.04E+00	1.41E+05	1.36E+05	n/a
Rubberized Asphalt Concrete (Mill-and-Fill)	2	Material	2.72E+04	2.71E+03	1.83E+01	2.43E+05	2.01E+05	1.34E+06
		Transport	2.77E+03	4.42E+02	8.85E-01	3.96E+04	3.96E+04	0.00E+00
		Construction	3.40E+03	1.50E+03	2.67E+00	4.68E+04	4.68E+04	0.00E+00
		Total	3.34E+04	4.65E+03	2.19E+01	3.29E+05	2.88E+05	1.34E+06
Rubberized Asphalt Concrete (Overlay)	2	Material	2.72E+04	2.71E+03	1.83E+01	2.43E+05	2.01E+05	1.34E+06
		Transport	2.77E+03	4.42E+02	8.85E-01	3.96E+04	3.96E+04	0.00E+00
		Construction	2.09E+03	9.23E+02	1.64E+00	2.88E+04	2.88E+04	0.00E+00
		Total	3.20E+04	4.07E+03	2.09E+01	3.11E+05	2.70E+05	1.34E+06
Sand Seal	n/a	Material	1.59E+03	2.59E+02	1.26E+00	3.33E+04	3.16E+04	1.18E+05
		Transport	2.88E+02	4.58E+01	9.19E-02	4.11E+03	4.11E+03	0.00E+00
		Construction	7.99E+02	3.53E+02	6.27E-01	1.10E+04	1.10E+04	0.00E+00
		Total	2.67E+03	6.57E+02	1.98E+00	4.84E+04	4.67E+04	1.18E+05
Slurry Seal	n/a	Material	1.39E+03	2.27E+02	1.12E+00	2.93E+04	2.79E+04	1.06E+05
		Transport	1.73E+02	2.76E+01	5.53E-02	2.48E+03	2.48E+03	0.00E+00
		Construction	6.74E+02	2.98E+02	5.29E-01	9.29E+03	9.29E+03	0.00E+00
		Total	2.24E+03	5.52E+02	1.71E+00	4.11E+04	3.97E+04	1.06E+05

[a] The total primary energy demand excluding the feedstock energy, where feedstock energy is available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[b] Same note as above applies to PED (Non-Renewable). PED from non-renewable resources (net calorific value).

Table E.11: Summary LCI and LCIA of EOL Treatments for a Functional Unit of 1 ln-km: 2012 California Electricity Grid Mix

Item	Life Cycle Stage	GWP [kg CO2-e]	POCP [kg O3-e]	PM2.5 [kg]	PED (Total)[a] [MJ]	PED (Non-Ren)[b] [MJ]
CIR (4 in. [10 cm] milled + mechanical stabilization) with 1 in. (2.5 cm) of HMA OL	Material	1.06E+04	9.65E+02	6.97E+00	5.45E+05	5.39E+05
	Transport	1.38E+03	2.21E+02	4.43E-01	1.98E+04	1.98E+04
	Construction	4.45E+03	1.97E+03	3.50E+00	6.14E+04	6.14E+04
	Total	1.64E+04	3.15E+03	1.09E+01	6.26E+05	6.20E+05
CIR (4 in. [10 cm] milled + mechanical stabilization) with Chip Seal	Material	3.64E+03	5.97E+02	2.91E+00	3.45E+05	3.42E+05
	Transport	4.80E+02	7.65E+01	1.53E-01	6.87E+03	6.87E+03
	Construction	3.53E+03	1.56E+03	2.77E+00	4.87E+04	4.87E+04
	Total	7.65E+03	2.23E+03	5.83E+00	4.01E+05	3.97E+05
FDR (10 in. [25 cm] milled + no stabilization) with 2.4 in. (6 cm) RHMA OL	Material	3.33E+04	3.27E+03	2.21E+01	1.88E+06	1.86E+06
	Transport	3.32E+03	5.30E+02	1.06E+00	4.76E+04	4.76E+04
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04
	Total	4.20E+04	6.20E+03	2.74E+01	2.01E+06	1.98E+06
FDR (10 in. [25 cm] milled + 4% AE + 1% PC) with 2.4 in. (6 cm) RHMA OL	Material	1.06E+05	4.22E+04	3.33E+04	4.69E+06	4.64E+06
	Transport	4.02E+03	6.40E+02	1.28E+00	5.75E+04	5.75E+04
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04
	Total	1.16E+05	4.52E+04	3.33E+04	4.82E+06	4.77E+06
FDR (10 in. [25 cm] milled + 3% FA + 1% PC) with 2.4 in. (6 cm) RHMA OL	Material	9.31E+04	4.03E+04	3.33E+04	3.47E+06	3.44E+06
	Transport	3.88E+03	6.18E+02	1.24E+00	5.55E+04	5.55E+04
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04
	Total	1.02E+05	4.33E+04	3.33E+04	3.60E+06	3.57E+06
FDR (10 in. [25 cm] milled + 2% PC) with 2.4 in. (6 cm) RHMA OL	Material	8.96E+04	6.50E+03	4.42E+01	2.15E+06	2.10E+06
	Transport	3.60E+03	5.74E+02	1.15E+00	5.15E+04	5.15E+04
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04
	Total	9.87E+04	9.48E+03	4.96E+01	2.27E+06	2.23E+06
FDR (10 in. [25 cm] milled + 4% PC) with 2.4 in. (6 cm) RHMA OL	Material	1.46E+05	9.74E+03	6.64E+01	2.41E+06	2.35E+06
	Transport	3.88E+03	6.18E+02	1.24E+00	5.55E+04	5.55E+04
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04
	Total	1.55E+05	1.28E+04	7.19E+01	2.54E+06	2.48E+06
FDR (10 in. [25 cm] milled + 6% PC) with 2.4 in. (6 cm) RHMA OL	Material	2.02E+05	1.30E+04	8.85E+01	2.67E+06	2.60E+06
	Transport	4.15E+03	6.62E+02	1.33E+00	5.95E+04	5.95E+04
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04
	Total	2.12E+05	1.60E+04	9.41E+01	2.81E+06	2.73E+06

[a] The total primary energy demand excluding the feedstock energy, where feedstock energy is available and shown in the table. Otherwise, PED (Total) is the total primary energy demand including the unknown feedstock energy. PED from renewable and non-renewable resources (net calorific value).

[b] Same note as above applies to PED (Non-Renewable). PED from non-renewable resources (net calorific value).