Title

Integrated and Data-Driven Transportation Infrastructure Management through Consideration of Life Cycle Costs and Environmental Impacts

Author

Saboori, Arash

Publication Date

2020-11-01

Integrated and Data-Driven Transportation Infrastructure Management through Consideration of Life Cycle Costs and Environmental Impacts

By

ARASH SABOORI

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Professor John Harvey, Chair

Professor Alissa Kendall

Professor Miguel Jaller

Committee in Charge

2020

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346

To My Dearest Wife & Best Friend in Life,
Aida
For All Her Love, Patience,
Constructive Feedback, and Sacrifices

ABSTRACT

The main goal of this dissertation was to develop frameworks, quantitative models, and databases needed to support data-driven, informed, and integrated decision-making in managing the vast transportation infrastructure in California. Such a management system was envisioned to consider both costs and environmental impacts of management decisions, based on full life cycles of the infrastructure, and using reliable, high quality data that well represent local conditions in terms of materials and energy sources, production technologies, design methods, construction practices, and other critical parameters.

This PhD research consisted of three parts: 1) development of a comprehensive life cycle inventory (LCI) database for implementation of life cycle assessment (LCA) methodology in transportation infrastructure management in California. 2) Evaluation of current and potential sustainability actions at the state and local government levels through the development of frameworks, models, and datasets needed for objective and accurate quantification of the impacts of management decisions. 3) Assessment of recycling practices available for pavements at their end of life to quantify changes in environmental impacts compared to conventional methods, considering the effects of recycling through the use stage.

Through the first part of this research, the most comprehensive and up to date, as of 2019, life cycle inventory database, the UCPRC LCI Database, was developed for accurate quantification of transportation infrastructure management projects in the state of California. This database includes an extensive list of all the energy sources, materials, mixes, transportation modes, and construction processes used in the projects at state and local government levels.

In the UCPRC LCI Database, the electricity grid mix and other energy sources used in various life cycle stages are modified to represent the state's local conditions. Mix designs are defined based on specifications enforced by Caltrans and also cover designs used by local governments. Construction practices are closely simulated based on data collected from local contractors and experts in addition to the collection of primary data from a few field projects. The LCI database developed and presented in this chapter has been verified by a third party according to ISO recommendations.

In the second part of this research, multiple studies were also carried out to develop decision-making frameworks, models, and tools for local governments and state agencies to assess their policies and alternative decision choices in meeting their sustainability goals. The frameworks in each case laid the roadmap in terms of what needs to be included in the study and what models are needed for quantifying the environmental impacts. The UCPRC LCI Database was then utilized to develop the required models in each case, which were then assembled in tools that can calculate life cycle costs and environmental impacts of different alternatives.

The first project in part two compared urban street designs from a widely used complete street design guide and conventional street designs. The comparison used LCA to consider the full life cycle environmental impacts of conversion of several types of conventional streets to complete streets. The full system impacts of complete streets on environmental impact indicators, considering materials,

construction, and traffic changes, are driven by changes in reduction in VMT and changes in the operation of the vehicles with regard to speed and drive cycle changes caused by congestion, if it occurs. An LCA comparison of complete street implementation revealed the importance of considering speed and drive cycle changes caused by congestion where it occurs.

The initial results indicate that application of the complete streets networks to streets where there is little negative impact on vehicle drive cycles from speed change will have the most likelihood of causing overall net reductions in environmental impacts. The results also indicate that there is a range of potential VMT changes to which environmental impacts are more sensitive than they are to the effects of the materials and construction stages, and that changes in vehicle speed have different effects on environmental impacts depending on the context of their implementation, including the street type.

This second study in part two focused on comparing multiple pathways (scenarios) for Caltrans to transition their fleet from vehicles with internal combustion engines burning fossil fuels to alternative fleet vehicles (AFVs.) Four scenarios were considered based on AFV adoption rate including business as usual (BAU), All-at-Once, a scenario based on the Department of General Services (DGS) recommendations, and a Worst-Case scenario (do nothing, keep the current mix.) The project compared the life cycle greenhouse gas (GHG) emissions, fuel consumption, and costs of vehicle purchase and maintenance between 2018 and 2050.

The results showed a total life cycle costs of 2.4 billion dollars for the BAU case with 7.4 and 3.3 percent increases versus BAU for the DGS and All-at-Once cases, and a 16.9 percent decrease for the Worst-Case Scenario. Total GHG emissions during the analysis period of 2018 to 2050 reached close to 1.46 million metric tonnes (MMT) of CO_2e for the BAU case while the results for the DGS, All-at-Once show savings of 2 and 9 percent in total GHG emissions versus BAU for the DGS and All-at-Once scenarios. The Worst-Case Scenario results show that consequences of inaction in the adopting AFVs by Caltrans and maintaining the current mix of vehicle technology and fuel will result in 54 percent increase in the GHG footprint of their fleet between now and the year 2050.

The third chapter in part two focused on quantifying savings in greenhouse gases (GHG), energy, material consumption, and costs that might be possible through increased use of recycled asphalt pavements (RAP) in construction projects in California. The material production impacts of hot mix asphalt (HMA) in Caltrans construction projects throughout the state during the entire analysis period of 33 years (2018 to 2050) results in close to 11.5 MMT of CO_2e for the baseline scenario.

Increasing the RAP content in HMA from the baseline of the 11.5 percent can result in up to a 6 percent of GHG savings with 30.5 percent RAP content during the 33-year analysis period, when using aromatic BTX rejuvenating agents (RAs.) These reductions are equivalent to 0.7, 5.2, 6.2 percent reductions in GHG emissions compared to the baseline. The potential saving can be as high as 9 percent when bio-based RA is used.

The last segment of this research focused on end-of-life (EOL) of flexible pavements and developed the required models for full life cycle comparison of alternatives. Cradle-to-laid impacts of conventional alternatives and new in-place recycling options were first calculated followed by development of performance prediction models that are needed to identify future performance during the use stage.

This first study in the last part was conducted to benchmark the cradle-to-laid environmental impacts of several EOL treatments used in California for flexible pavements at their end of service life. The results show that the material production stage is dominant in all impact categories for all treatments. The results also show that the total amount of stabilizer added (which depends on percent stabilizer and the layer thickness) has a significant impact on the total impacts. HMA overlay and HMA mill-and-fill have lower impacts compared to all the full-depth reclamation (FDR)options with stabilizers across all impact categories. Binder and stabilizer production caused more than 90 percent of the total impacts of the material production across all cases.

The last study was focused on development of crack progression and roughness models for cold in-place recycling (CIR) and FDR sections. Such models, which did not exist up to this point, allow a fair comparison of EOL alternatives for flexible pavements by providing the means necessary for quantifying the use stage impacts and including them in the analysis. As always, there is no EOL solution that fits all cases, and the optimal decision is context sensitive. The selection of one treatment among all available alternatives depends on circumstances (traffic levels, climate, and structural design), agency goals (only considering costs or both costs and environmental impacts), project scope and analysis period (initial costs and impacts versus full life cycle), and potential limitations (in terms of budget, available technologies, and more).

ACKNOWLEDGEMENT

This research was mainly funded by the California Department of Transportation, Division of Research and Innovation. It was partly supported by a PhD grant from the U.S. Department of Transportation, which was awarded by the National Center of Sustainable Transportation (NCST) at UC Davis Institute of Transportation Studies.

I want to thank my advisor, Prof. John Harvey, for his continued support and insight throughout my PhD years, without which I would not be able to finish this work. I am also grateful to my dissertation committee members, Professor Alissa Kendall and Professor Miguel Jaller, for their support and guidance on my dissertation. I would also like to thank Professor Boulanger and Professor Novan for serving as my qualifying examination committee members. Great thanks go to Dr. Jeremy Lee, Dr. Ting Wang, and Dr. Hui Li and my classmates, Dr. Yuan He, and Dr. Shawn Hung, for their help and support throughout my PhD, especially in the first few quarters that I was adjusting to the new environment. I would also like to thank all the UCPRC members that have helped and supported my research pursuits here.

I am incredibly grateful to my wife, Aida, for all her support and sacrifices. I would not be able to finish this work without her continuous love and support. I am also in great debt to my parents and both my brothers, Anooshiravan and Ashkan, for maintaining the magnificent support system that they have provided me with throughout my life, especially during this chapter.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

Acronym	Stands for
AB	Assembly Bill
AC	Air Conditioning
ADR	Assembly, Disposal, and Recycling
AE	Asphalt Emulsion
AEO	Annual Energy Outlook
AFDC	Alternative Fuel Data Center
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
AFV	Alternative Fuel Vehicle
ANL	Argonne National Laboratory
APCS	Automated Pavement Condition Survey
ARRA	Asphalt Recycling and Reclaiming Association
ASTM	American Society for Testing and Materials
AVMT	Annual Vehicle Miles Travelled
BAU	Business-As-Usual
BCOA	Bonded Concrete Overlay on Asphalt
BPA	Bisphenol A
BTX	Benzene, Toluene and Xylene
CA	California
CARB	California Air Resources Board
CBA	Cost-Benefit Analysis
CCDB	Contract Cost Data Book
CEC	California Energy Commission
CFC	Chlorofluorocarbon
CI	Carbon Intensity
CIDI	Compression-Ignition Direct-Injection
CIR	Cold In-Place
CMU	Concrete Masonry Unit
CNG	Compressed Natural Gas
CPUC	California Public Utilities Commission
CRA	Crumb Rubber Asphalt
CRM	Crumb Rubber Modifier
CS	Charge Sustaining (PHEV)
CSA	Calcium Sulfo-Aluminate Cement
CSS	Cationic Slow Setting
DB	Database
DE	Deutschland (Germany)
DG	Design Guide
DGE	Diesel Gallon Equivalent
DGS	Department of General Services
DMV	Department of Motor Vehicles
DOE	Department of Energy
DQR	Data Quality Requirements
DSL	Diesel
EA	Environmental Analysis
EE	Engineered Emulsion
EFC	Excess Fuel Consumption
EIA	Energy Information Administration

Acronym	Stands for
EIO	Economic Input-Output
ELEC	Electricity
EMFAC	EMission FACtors
EO	Executive Order
EOL	End-Of-Life
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
ESAL	Equivalent Single Axle Load
EU	Europe
EV	Electric Vehicle
FA	Foamed Asphalt
FCV	Fuel-Cell Vehicle
FDR	Full Depth Reclamation
FE	Fuel Efficiency
FFV	Flex Fuel Vehicle (Generally E85)
FHWA	Federal Highway Administration
GAS	Gasoline
GGE	Gallon of Gasoline Equivalent
GHG	Greenhouse Gas
GLO	Global
GREET	GHG, Regulated Emissions, and Energy Use in Transportation
GVWR	Gross Vehicle Weight Rating
GWP	Global Warming Potential
HD	Heavy-Duty
HDM	Highway Development and Management Model
HEV	Hybrid Electric Vehicle
HFC	Hydrofluorocarbon
HFO	Heavy Fuel Oil
HIR	Hot In-Place Recycling
HMA	Hot Mix Asphalt
HPR	High Performance Renewable (Diesel)
HVS	Heavy Vehicle Simulator
HYD	Hydrogen
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IL	Illinois
IOA	Input-Output Analysis
IPCC	United Nations Intergovernmental Panel on Climate Change
IPDI	Isophorone di-isocyanate
IPR	In-Place Recycling
IRI	International Roughness Index
ISO	International Organization for Standardization
LA	Los Angeles
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life Cycle Cost Analysis
LCFS	Low Carbon Fuel Standard
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSF	Low Carbon Fuel Standard

Acronym	Stands for
LD	Light-Duty
LDA	Light Duty Automobiles
LDV	Light-Duty Vehicle
LNG	Liquefied Natural Gas
LPG	Liquified Petroleum Gas (also Propane)
LWP	Left Wheelpath
MAC	Materials and Construction
MD	Medium-Duty
MDI	Methylene di-isocyanate
MFA	Material Flow Accounting
MJ	Mega Joules
MMT	Million Metric Tonnes
MOVES	MOtor Vehicle Emission Simulator
MPD	Mean Profile Depth
MPG	Miles per Gallon
MTAG	Maintenance Technical Advisory Guide
NACTO	National Association of City Transportation Officials
NCHRP	National Cooperative Highway Research Program
NG	Natural Gas
NHTSA	National Highway Traffic Safety Administration
NPV	Net Present Value
NR	Non-Renewable
NREL	National Renewable Energy Laboratory
NS	No Stabilization
NZEV	Near Zero Emission Vehicle
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PC	Portland Cement
PCA	Portland Cement Association
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PCS	Pavement Condition Survey
PED	Primary Energy Demand
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matters
PMS	Pavement Management System
POCP	Photochemical Ozone Creation Potential
PTW	Pump-to-Wheel
PUT	Pick-Up Truck
PV	Photovoltaic
PVI	Pavement Vehicle Interaction
RA	Rejuvenating Agent
RAP	Reclaimed Asphalt Pavement
RCA	Recycled Concrete Aggregate
RCM	Reclaimed Concrete Materials
RDII	Renewable Diesel
RHMA	Rubberized Hot Mix Asphalt
RNA	Region North America
RPS	Renewable Portfolio Standard
RWP	Right Wheelpath
SAC	Sacramento
SBR	Styrene Butadiene Rubber

Acronym	Stands for
SCM	Supplemental Cementitious Material
SEA	Strategic Environmental Assessment
SEEA	System of Economic and Environmental Accounting
SFA	Substance Flow Analysis
SI	Spark-Ignition
SS	Slow Setting
STA	Swedish Transportation Administration
SUV	Sport Utility Vehicle
TAED	Tetraacetyl ethylenediamine
TMAH	Tetramethyl-ammonium hydroxide
TRACI	Tool for Reduction and Assessment of Chemicals and other environmental Impacts
UC	University of California
UCPRC	University of California Pavement Research Center
UP	Unsaturated Polyester
USEPA	US Environmental Protection Agency
USLCI	US Life Cycle Inventory
VIN	Vehicle Identification Number
VMT	Vehicle Miles Traveled
WMA	Warm Mix Asphalt
WPC	Wheelpath Cracking
WRF	Weather Research and Forecasting
WTP	Well-to-Pump
WTW	Well-to-Wheels
ZEV	Zero Emission Vehicle

CHAPTER 1. Introduction

Sustainable development is a topic that the State of California is culturally dedicated to, historically a pioneer in, and legally bound to strive for through state legislation and regulation, and other state and local initiatives. The goal of sustainability legislation in California is to drastically reduce the state's environmental impacts and natural resource consumption while maintaining its economic excellence. Sustainability considerations are pressing issues in all aspects of the state's vast economic landscape. The research presented in this dissertation is aimed at addressing some of the challenges that exist in improving the transportation infrastructure management system. This research strives to achieve its objectives by providing frameworks, models, and databases needed for incorporating objective and data-driven lifecycle thinking into decision making at all levels: network level to project level for both state agencies and local governments.

Figure 1.1 shows the scope of the research presented in this dissertation. There are three main categories: 1) development of a comprehensive life cycle inventory (LCI) database for implementation of life cycle assessment (LCA) methodology in transportation infrastructure management in California. Such a database should cover all the construction materials, transportation modes, construction activities used in transportation projects in the state and should represent local conditions in terms of energy sources, transport distance, mix design, and construction methodology. 2) Evaluation of current and potential sustainability actions at the state and local government levels through the development of frameworks, models, and datasets needed for objective and accurate quantification of the impacts of management decisions. Several different abatement strategies are evaluated in detail. 3) Assessment of recycling practices available for pavements at their end of life to quantify changes in environmental impacts compared to conventional methods, considering the effects of recycling through the use stage. This approach help avoid unintended consequences in cases where extra impacts during the use stage of new options compared to conventional ones offset the improvements in the material production and construction stages.

Following this introductory chapter, Chapter Two presents a review of the available information and literature to identify the gaps in knowledge and the significance of the challenges that need to be addressed in the field of sustainability of transportation infrastructure. This is followed by description of the research objectives of this dissertation, and the tasks to address the challenges and achieve its objectives.

The reliability of an LCA study is dependent on the quality and repeatability of the data used for quantification of the impacts at each life cycle stage. Chapter Three presents all the assumptions and modeling details for developing a comprehensive LCI database for transportation infrastructure management in California. This chapter also includes a section on data quality assessment, which was conducted under a third-party critical review process according to International Standards Organization (ISO) standards. The LCI database presented in this chapter will be used in eLCAP, a web-based tool for conducting LCA for decision-making at network and project levels in transportation infrastructure management.

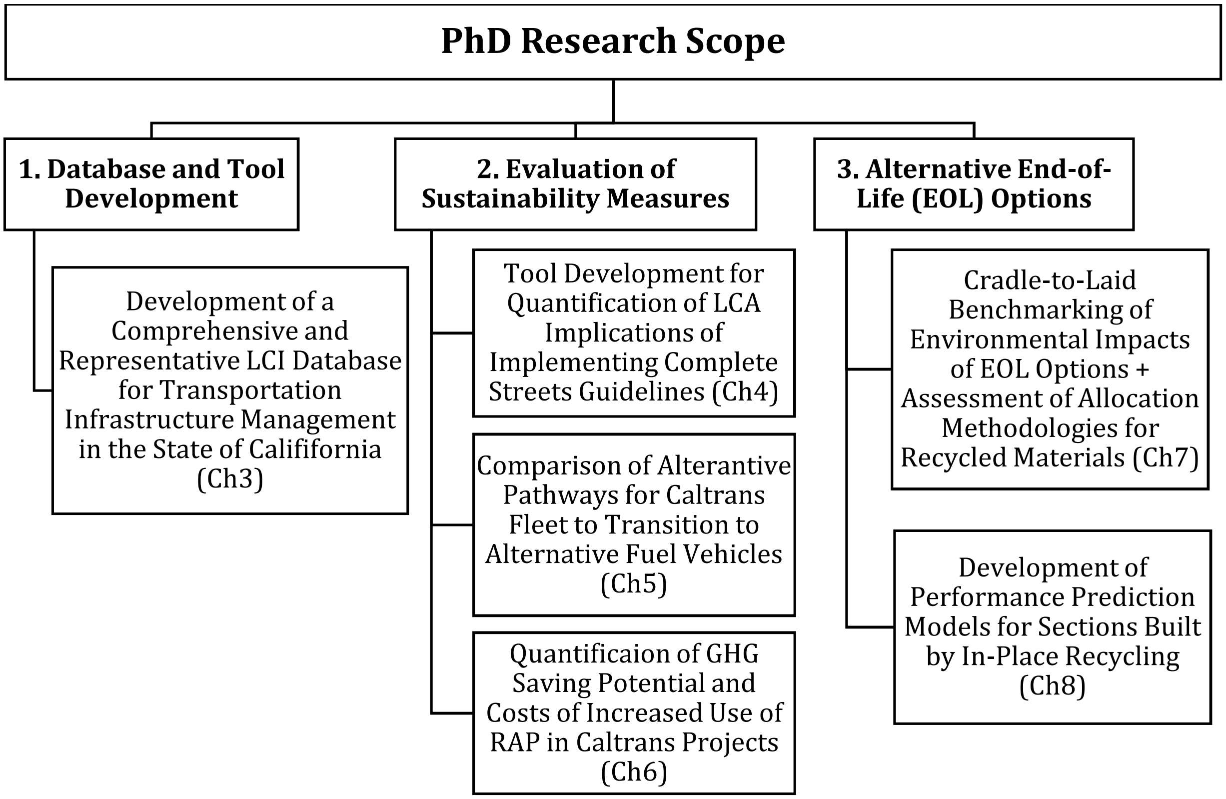


Figure 1.1: Research scope, main topics and projects covered under each topic

The next several chapters are focused on current and potential greenhouse gas (GHG) mitigation strategies at state and local government levels in California. Chapter Four presents the framework and the model that was developed to evaluate complete streets design strategies for reducing GHG emissions in urban areas. Complete streets design philosophies focus on facilitating active modes of transportation, reduction of vehicle miles travelled, and enhancement of local communities. SB375, the sustainable communities bill, mandates GHG reduction targets for urban areas in California. Implementing complete streets is one of the main land use strategies used by local governments to meet such GHG reduction mandates. To quantify the resulting changes in GHG emissions due to complete street designs versus conventional design methodologies, the LCI database presented in Chapter Three was used to develop an Excel-based model. The new model allows local governments to compare changes in the GHG emissions and energy consumption of the construction and maintenance of street right of ways designed using conventional and new design philosophies. The model also enables consideration of ranges of change in vehicle miles traveled (VMT) and traffic speed for different street types and calculation of the consequential changes in emission and energy consumption.

Caltrans and other state agencies have fleets of considerable size. Replacement of conventional state vehicles with alternative fuel vehicles (AFVs) can result in significant reductions in GHG emissions, fossil fuel consumption, and possibly life cycle costs of the fleet. Chapter Five provides comprehensive data collected from reliable national data sources that are used to develop a highly customizable and comprehensive model to evaluate various fleet transformation pathways. The model developed through this chapter is capable of quantifying the costs, fuel consumption, and environmental impacts of the Caltrans fleet considering an analysis period of 30 years. The chapter compares four different strategies in terms of the potential reduction in GHG emissions, changes in life cycle costs, and the average cost of GHG abatement compared to the business as usual case.

In Chapter Six, the increased use of reclaimed asphalt pavement (RAP) in construction projects that are annually handled by Caltrans is investigated. The goal of this chapter is to determine the potential reduction in GHG emissions over a 30-year analysis period by assuming various levels of increase in RAP content of asphalt mixtures in pavement projects in the whole state. Life cycle costs are also included in the analysis, and the abatement cost is compared across different alternatives.

Use of recycled materials has always been encouraged and considered as a more sustainable approach compared to conventional methods of using virgin materials and transferring old materials to landfills. The last portion of this dissertation is focused on quantifying the actual impacts of various recycling techniques currently available for pavements so that actual changes in impacts can be better understood. This task is undertaken in Chapter Seven.

The performance during the use stage of sections built using recycled materials can be significantly different from those sections built using conventional methods. Chapter Eight addresses this question by developing predictive performance models for sections built using in-place recycled materials. The models were developed by collecting data from Caltrans pavement management system and conducting various statistical methods for analyzing empirical methods.

CHAPTER 2. Background, Problem Statement, and Research Objectives

The public roads in the USA consist of more than 4 million lane-miles of roads of which 2.63 million lane-miles are paved. This network supports close to three trillion vehicle-miles traveled each year (BTS webpage on Roadway Lane-Miles) which is responsible for 84 percent of the USA annual petroleum consumption of more than 203 billion gallons (Davis et al., 2015.) The maintenance and expansion of such a vast infrastructure requires nearly 320 million tonnes of raw materials each year and costs more than 150 billion dollars (Santero, 2009.) These numbers show the tremendous cost of the transportation network and the significant impacts it has on the environment. Reliable quantification of such costs and impacts is critical in the effective management of transportation infrastructure. There are several environmental analysis tools available for quantification of the environmental impacts.

Finnveden and Moberg (2005) conducted a comparison of the available methods for environmental analysis and categorized them based on four characteristics:

- Procedural or analytical: procedural methods focus on the procedures based on the decision context while analytical methods are concerned with the technical aspects of the analysis. The analytical tools can be part of the procedural ones.
- The type of impacts considered: natural resource consumption or environmental impacts or both.
- The object of the study, which can be: 1) policies, plans, programs, and projects, 2) regions or nations, 3) organizations or companies, 4) products and services, 5) substances
- If the tool is used in a descriptive (accounting, attributional) or change-oriented (consequential) study. As their names suggest, descriptive studies are used for describing a product or system in terms of its environmental impacts or natural resource consumption while change-oriented studies are used to identify the consequences of a system or policy outside its system boundaries.

Table 2.1 shows Finnveden's classification of analysis tools based on the type and object of the study followed by Table 2.2 that provides a brief explanation for each of the tools. As shown in the table, life cycle assessment (LCA) is a suitable tool for evaluating environmental impacts of products and services both in attributional and consequential studies and, therefore, has gained popularity in assessment of environmental impacts of transportation infrastructure.

Table 2.1. Classification of environmental analysis tools based on the type and object of the study (Finnveden and Moberg, 2005). Acronyms are defined in Table 2.2

Objects	Type of Study (acronyms explained in Table 2.2	
	Descriptive (Accounting, Attributional)	Change-Oriented (Consequential)
Policies, plans, programs, and projects	-	SEA, EIA, CBA
Regions or nations	IOA, SEEA	Economic policy models with input from SEEA
Organizations or companies	Environmental Auditing	
Products and services	LCA	LCA
Substances	SFA	SFA

Table 2.2. Description of different environmental analysis tools

Tool	Description
CBA: Cost-Benefit Analysis	An analytical tool for assessing the total costs and benefits of a project. All benefits and costs including environmental costs should be monetized and included.
EIA: Environmental Impact Assessment	A change-oriented procedural tool established mainly for assessing environmental impacts of projects. Generally, a site-specific tool.
IOA: Input-Output Analysis	An analytical tool within economics and systems of national accounts that comprise of matrixes that describe trades between sectors. Economic trades between the sectors are the basis used to divide the whole market environmental impacts between all the sectors.
LCA: Life Cycle Assessment	A tool for assessing environmental impacts and resource consumption through product's whole life cycle, from material acquisition through use stage and disposal., Used mainly as an analytical tool.
SEA: Strategic Environmental Assessment	Similar to EIA but intended to be used at an earlier stage in decision making and on a more strategic level. More used for policies, plans, and programs.
SEEA: System of Economic and Environmental Accounting	A system for organizing statistical data to monitor the interactions between the economy and the environment. Economic activities within a nation are the primary objects, physical measures (inputs and outputs of resources and emissions) plus monetary values are stored in such systems. In some cases, this is used to monetize the environmental impacts using different valuation methods.
SFA: Substance Flow Analysis	A Material Flow Accounting (MFA) method which focuses on specific substances either within a region or from cradle-to-grave of a product.

Life cycle assessment is a technique that can be used for analyzing and quantifying the environmental impacts of a product, system, or process. LCA provides a comprehensive approach to evaluating the total environmental burden of a product or process by examining all of the inputs and outputs over the life cycle, from raw material production to end-of-life. A generic model of a product system life cycle stages is shown in Figure 2.1. This systematic approach identifies where the most relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs. The process and rules for conducting an LCA are generally defined by the International Organization for Standardization (ISO) in its 14040 family of standards (ISO, 2006.)

Figure 2.2 shows the general framework for conducting LCA studies as defined by ISO (2006) which consists of four major steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

The process begins with defining the goal of the study which determines the system boundary and scope of study, duration of the study and a suitable functional unit. The next step is the life cycle inventory phase where all the inputs and outputs to the system boundary within the life cycle are quantified. The inputs are normally in the form of input flows of raw materials and energy and output flows of waste and pollution (depending on the system boundary), emissions to air, water, and soil as well as the flow of product output. In the LCIA phase, the LCI results are classified and categorized into several environmental impact categories such as global warming, acidification, eutrophication, primary energy consumption, ozone layer depletion and more. The final step is the interpretation of the results to answer the questions posed by the stated goals of the study.

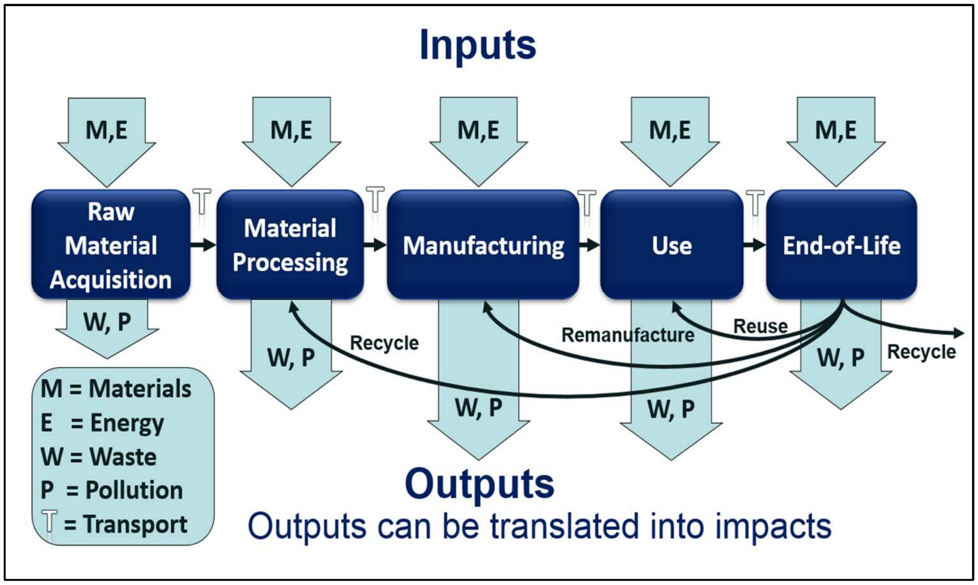


Figure 2.1: General life cycle of a production system (Kendall, 2012.)

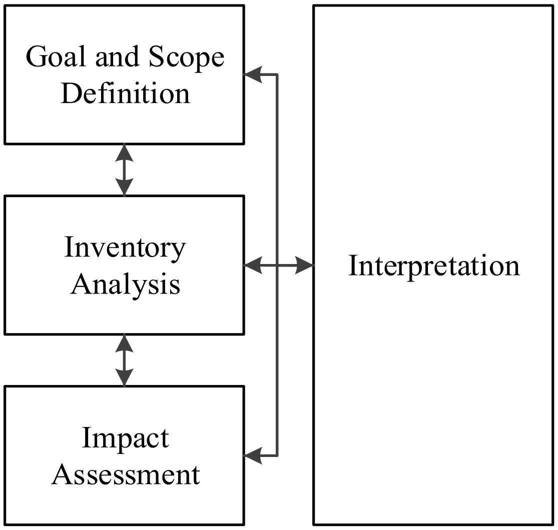


Figure 2.2: General life cycle assessment framework according to ISO (2006.)

LCA can be used for a variety of purposes, including (Harvey et al., 2015a):

- Identifying opportunities to improve the environmental performance of products at various points in their life cycles.
- Informing and guiding decision-makers in industry, government, and non-governmental organizations for number of purposes, including strategic planning, setting priorities, product or process design selection, and redesign.
- Selecting relevant indicators of environmental performance from a system-wide perspective.

- Quantifying information concerning the environmental performance of a product or system (e.g., to implement an eco-labeling scheme, make an environmental claim, or produce an Environmental Product Declaration (EPD) statement.)

2.1. Pavement LCA

The earliest applications of LCA to pavements were in the 1990s (Horvath et al., 1998; Stripple, 2001) and since then, it has continuously gained more attention for evaluating the environmental performance of pavements. In Europe, LCA is now widely used in the construction industry and some countries such as France (Jullien et al., 2015) and the Netherlands (van Leest et al., 2008) have regulations in place for the use of LCA in the procurement of pavement projects. In North America, use of LCA in the pavement industry was introduced to a wider audience at a Pavement LCA Workshop held in Davis, California in May 2010 and founding of the Concrete Sustainability Hub at the Massachusetts Institute of Technology at about the same time. It was introduced more comprehensively to the Federal Highway Administration (FHWA) and a wider audience at a subsequent meeting of the FHWA Sustainable Pavement Task Group in April 2012, also held in Davis. Other early studies on application of LCA in pavements in the United States were carried out at several universities including Carnegie Mellon University (Horvath et al., 1998), with the work continued at UC Berkeley (Horvath et al., 2003), the University of Michigan, Ann Arbor (Keoleian et al., 2005, Kendall, 2007, Zhang 2009), the University of California Davis (Santero, 2009; Li, 2012; and Wang, 2013), and the University of Illinois (Aurangzeb et al., 2014; Yang, 2014)

Santero et al., (2011) conducted a critical review of the LCA studies on pavements and concluded that even though the existing literature at that time provided a foundational framework for quantifying environmental impacts of pavements, it failed to deliver conclusions regarding material selection, maintenance strategies, design methodologies, and other best practice policies for achieving sustainability goals. Their recommendation for comprehensive quantification of environmental impacts of pavements and achieving sustainability goals was to standardize the functional units, expanding the system boundaries, improving data quality and reliability, and broadening scopes.

To address these shortcomings and to provide a general framework for conducting pavement LCA in the USA, University of California Pavement Research Center (UCPRC) developed the *UCPRC general framework for pavement LCA* and presented it at the three-day symposium in Davis in 2010 (Harvey et al., 2010.) Domestic and international researchers and professionals in pavement sustainability including representatives from academia, asphalt and cement industry, employees of a number of state departments of transportation, and FHWA were invited to attend and learn about LCA from European practitioners and North American researchers and critique the framework in breakout sessions. UCPRC used the results of the breakout discussion sessions to further develop the framework and then published it, as shown in Figure 2.3. The life cycle of any pavement can be divided into four main stages: 1) material production, 2) construction, maintenance, and rehabilitation, 3) use, and 4) end-of-life (EOL.)

Follow-up symposiums were held in Nantes (Nantes 2012 LCA Conference webpage), Davis (Pavement LCA 2014 Conference webpage), and Urbana/Champaign (Pavement LCA 2017 webpage) to share new findings, discuss areas which still needed further research, and transfer knowledge to other regions of the world (Harvey et al., 2015b.)

The Federal Highway Administration has also been working towards implementing sustainability and life cycle thinking into transportation infrastructure management. Their activities include, but are not limited to, developing management roadmaps, forming a technical writing group and a webpage for public education, and providing access to quality materials related to the topic. The sustainable pavement technical writing group at FHWA have so far published a reference document for improving the sustainability of pavement organized around a life cycle thinking (Van Dam et al., 2015) and a framework for application of LCA to pavements (Harvey et al., 2016) and number of tech briefs.

2.1.1. Material Production

The material production stage of a pavement LCA considers each material used in the life cycle. Each material must be characterized by a cradle-to-gate LCI. Cradle-to-gate refers to the process of raw material acquisition from the ground; transportation to, from and within processing or manufacturing sites; processing and manufacturing of materials; and mixing processes to the point at which the product is ready to leave the last processing site to begin transportation to its point of use. There are several LCI databases available for materials used in pavements. App-Table 1 in Appendix I shows some of the main databases used in pavement LCA and their popularity based on a recent literature survey by FHWA (FHWA 2014.) App-Table 2 lists the major models and tools used for conducting pavement LCA.

Reliability of any LCA study is directly affected by the data used for the LCI phase. The data should be representative of the local technology and practice in the material production. In California, The *Pavement Life Cycle Assessment Tool for Environmental and Economic Effects* (PaLATE), developed by Horvath (PaLATE webpage), is one of the first datasets developed in the USA for pavement LCA. PaLATE uses the economic input-output LCA (EIO-LCA) methodology for determining the LCI of raw materials. EIO-LCA is an approach based on economic input-output models to identify the flows of goods and services between distinct sectors of the economy and uses it to estimate the direct and indirect inputs to a product based on market demands. The main issue with PaLATE is that the database is outdated and does not represent the local conditions in California as it is based on national data. EIO-LCA is less accurate compared to process-based models that closely model each step of the material production.

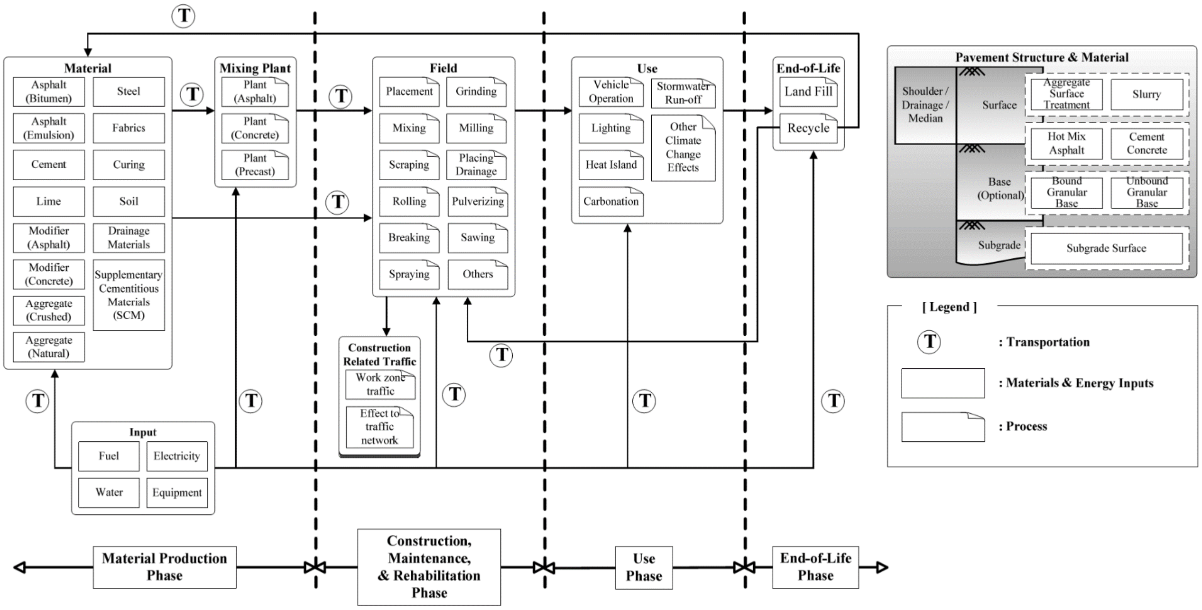


Figure 2.3: Life cycle stages of a pavement (Harvey et al., 2010.)

There are datasets that are highly cited in the literature such as Stripple (2001), and early versions of the Athena Institute database (2006), which are not the best options as they are outdated and may no longer represent the technologies used today in producing the materials. The Athena Institute databases have since been continuously updated, especially for cement and concrete materials. Even with the newer datasets, local practices and sources of plant energy and electricity grid mix are different for different regions, making the development of regionally representative datasets a necessity.

To address these issues, Wang et al., (2012) developed material production datasets in GaBi software in 2011 for the main materials and mixes used in California pavement projects and calibrated the models to represent the California electricity grid mix, plant fuels, and local mix designs. Although the dataset developed by Wang et al., was the most representative of material production in California at the time, it did not include a comprehensive and exhaustive list of all the materials and mixes used in Caltrans' projects and it was not developed by collecting primary data from the plants in California. Therefore, the first improvement for Wang's dataset is to develop models for the missing materials and mixes and the next, and ideal, step is to collect primary data by contacting the material production plants in order to closely model actual processes.

2.1.2. Construction, Maintenance, and Rehabilitation

There are five major types of pavement projects in California: 1) New construction, 2) Widening 3) Pavement preservation, 4) Rehabilitation, and 5) Reconstruction (Caltrans, 2015.) The definition for each of these items is provided in Appendix I. The following stages are recommended to be considered for modeling the construction stage and capturing all the energy consumption and environmental impacts in pavement LCA studies (Harvey et al., 2010):

- Equipment mobilization and demobilization.
- Equipment use at the site.

- Transport of materials to the site, including water; transport of materials from the site (for final disposal, reuse, or recycling.)
- Other use of energy used on site (e.g., for lighting if construction occurs at night.)
- Changes to traffic flow, including work zone speed changes and delay and diversions where applicable.

Most studies exclude capital investment and construction of the production plants and manufacturing of the equipment; however, this should be explicitly stated when describing the scope of analysis. In addition, while maintenance and rehabilitation happen at different times in the life cycle of a pavement, because the nature of the activities and processes are the same, they are all considered as recurring elements of the construction stage. The frequencies and types of maintenance and rehabilitation activities during the life cycle depend on the performance of the pavement in terms of roughness and cracking indices and the agency's decision tree and trigger values for such indices. This will be discussed in the next chapter, the use stage, as performance models are discussed there.

Figure 2.4 shows the items that need to be considered when developing the LCI of a construction process. A survey of the literature shows that different sources are used for estimating the emissions of the construction equipment. EPA's NONROAD model is a common source in many studies conducted in the USA. The California Air Resources Board (CARB) has developed OFFROAD, a model for construction equipment emissions which was used in the study by Wang et al., (2012) to model construction of hot mix asphalt (HMA, rubberized and conventional) and portland cement concrete (PCC.)

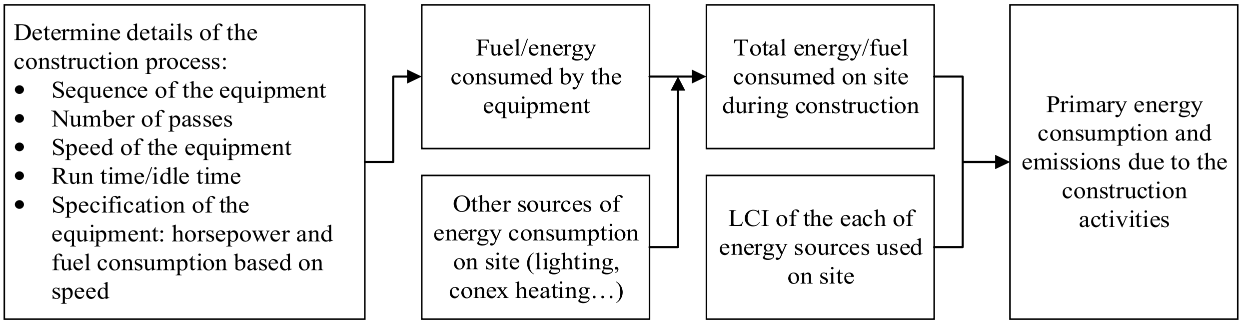


Figure 2.4: Flowchart for developing the construction stage LCI.

The same issues with the material production LCIs exist here: a comprehensive dataset for all possible surface treatments does not exist, and for those items for which a construction LCI is available in the literature, the data are either outdated or do not represent the current practice in California.

Construction activities not only cause environmental impacts directly through consumption of material and operation of equipment on site but also cause traffic flow changes which can translate into changes in emissions and energy consumption as the traffic is slowed down, stopped, or has to take detours around the construction work zone. The changes can result in increases or decreases in energy use and emissions depending on the baseline traffic speed. Figure 2.5 shows the flowchart that can be used in capturing the changes in emissions and energy consumption caused by traffic delay.

While a study on ranges of global warming potential of different life cycle stages of a pavement showed that traffic delay can potentially have a significant impact of the total impacts of a pavement (Santero and Horvath, 2009), a critical review of 15 pavement LCA studies conducted by Santero et al. (2011) showed only three studies considered traffic flow changes caused by the construction activities. Lepert and Brillet (2009) conducted a study to see the impacts of road works on the traffic flow and as their results show in Table 2.3, in most cases disrupting the traffic will result in more fuel consumption, although they have also added that there are special cases possible where road works can result in negative extra consumption due to limiting the speed limit and, therefore, improving fuel efficiency of the traffic. A recent LCA study conducted on the material production and construction stages of a two-lane reconstruction of an existing interstate in northern Illinois showed that GHG emissions and energy consumption caused by traffic delay are comparable to the impacts of the construction stages assuming a two-lane closure (Kang et al., 2014.)

The results of the studies mentioned above show the importance of considering the traffic delay to improve the accuracy of estimating the construction stage impacts, an issue which has not been considered in the pavement LCA case studies in California so far (Wang et al., 2012.)

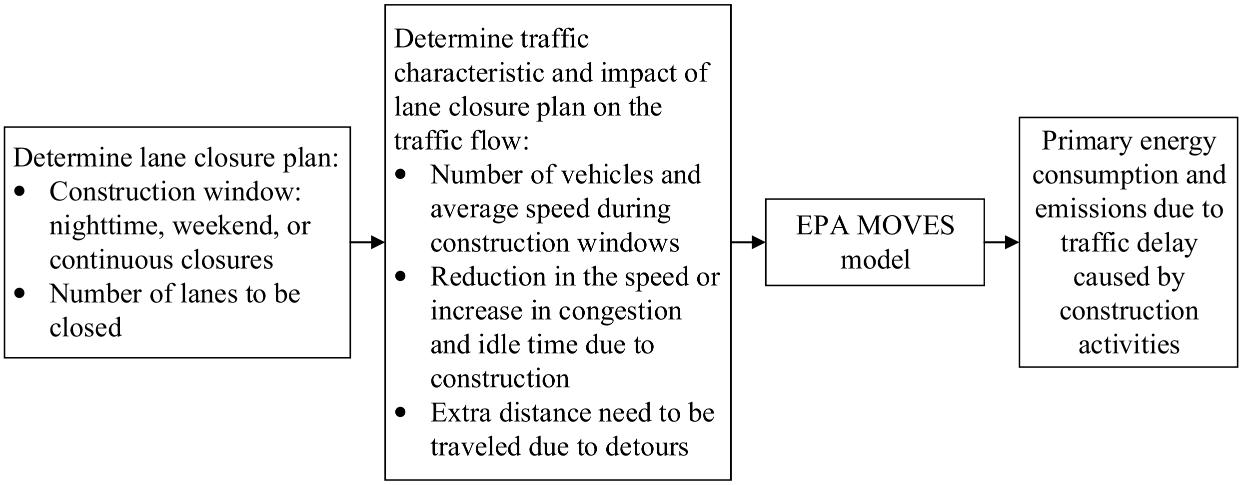


Figure 2.5: Flowchart for determining impacts of traffic delay caused by construction activities.

Table 2.3. Speed, acceleration, and fuel consumption in various traffic flow conditions for a Peugeot 406 sedan (Lepert and Brillet, 2009)

Parameter	Flow Condition			
	Free	Disturbed	Stop and Go	Congested
Mean speed (km/h)	90	74	46	4
Standard deviation on speed (km/h)	1.1	8.9	23	3.7
Mean acceleration (m/s2)	0	0	0	0
Standard deviation on acceleration (m/s2)	0.1	0.4	0.4	0.3
Mean consumption (1/100 km)	5.7	6.9	7.4	37.1
Mean extra consumption (% of free flow)	-	21%	70%	555%

2.1.3. Use

The pavement use stage can be broken into two types of processes: the travel of vehicles on the pavement; and the interaction of the pavement with the climate and the surrounding environment. Pavement characteristics directly affect the use stage impacts through different mechanisms such as roughness, surface texture and permeability, albedo, and more. Roughness, structural response under vehicle loads, and macrotexture affect vehicle fuel economy, and can collectively be labeled as “pavement rolling resistance” characteristics.

Figure 2.6, taken from Santero and Horvath (2009), shows the range of global warming potential for different life cycle stages of pavements. The bottom five categories are related to the use stage, and as the figure shows, impacts due to rolling resistance, which translate into fuel consumption in vehicles, are the main source of impacts during the use stage; this is dependent on the traffic level of the section though and might not be the case for low traffic volume roads.

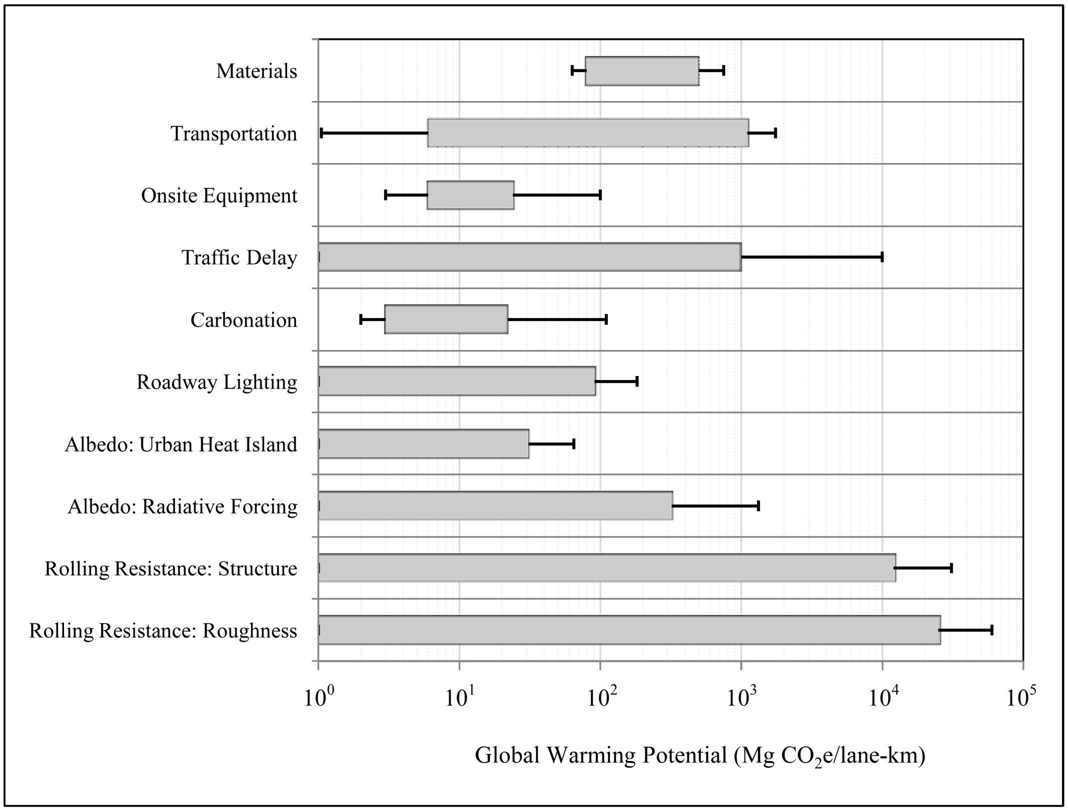


Figure 2.6: GWP impact ranges for pavement life cycle components (Santero and Horvath, 2009.)

Performance prediction models are required to estimate progression of rolling resistance of the pavement with time for determining vehicle fuel consumption during the use stage. Values of rolling resistance coupled with pavement-vehicle interaction models are used to calculate the fuel consumption of the vehicles. Models such as MOVES by EPA are then used to convert the fuel consumption into environmental impacts.

Mean Profile Depth (MPD) and International Roughness Index (IRI), are the major parameters measuring the effects of macrotexture and roughness, respectively, that contribute to the rolling resistance of flexible pavements (Wang et al., 2012.) Pavement roughness, influenced by pavement surface wavelengths between 0.5 and 50 m, is measured with IRI in units of in/mi or m/km and is defined as the ratio of the vehicle’s accumulated vertical movement and the vehicle distance traveled during the measurement. MPD is a measure of pavement macrotexture (unevenness with a wavelength between 0.5 mm to 50 mm) and can be measured using the methodology described in ASTM E1845-15. Conversion of the IRI and MPD into rolling resistance can be done through models such as HDM-4 developed by the International Road Federation and calibrated to the USA conditions (Chatti and Zaabar, 2012.)

While there are multiple studies that have considered rolling resistance in the use stage such as (Yu and Lu, 2012, Wang et al., 2012, and Zhang et al., 2010) and they have more or less used the same methodology explained above in estimating fuel consumption but the main gaps in the knowledge are lack of reliable roughness prediction models for different pavement surface treatments and for different climatic regions and also an updated pavement-vehicle interaction model.

Another issue that should be considered in the use stage is the frequency of maintenance and rehabilitation (M&R) activities. Frequency of M&R is typically determined using models for predicting cracking initiation and progression with time. The performance models are used to estimate when the cracking index will reach trigger values for doing maintenance and rehabilitation based on the agency's decision tree. For California, Tseng (2012) developed initial models for wheel-path crack initiation and progression by collecting pavement condition survey (PCS) data and using survival models to determine crack initiation and a mixed effect logit model to model crack progression. The shortcoming of the models developed by Tseng is that they do not cover all the surface treatments conducted in pavement projects in California, especially the ones related to the end-of-life stage of pavements such as CIR and FDR. Tseng's data also included the results of initial data mining of historic Caltrans pavement condition surveys and as-built records, which have been substantially improved in the succeeding five years.

2.1.4. End-of-Life

There are three different options available at the end of a pavement service life:

- Removal of materials and disposal in landfills,
- Continued use (also referred to as reuse) in place as an underlying layer in its state at the end of life of the pavement, or
- Pavement material recycling either:
    - In-place: mainly for flexible pavements through partial depth methods of cold in-place recycling (CIR) and hot in-place recycling (HIR), or full depth reclamation (FDR) of the pavement (discussed below.) For rigid pavements, in large projects, on-site recycling unit can be set up to process the old portland cement concrete by removing the steel reinforcement and breaking the concrete to the desired gradation and specification. The resulting material is called reclaimed concrete materials (RCM) and can be used as coarse aggregate, base materials, or for embankment.
    - At the recycling plant: used for both rigid and flexible pavements. Old asphalt concrete and portland cement concrete are pulverized and moved to a central plant for further processing. RCMs undergo the same processes as in an on-site recycling unit and have the same applications. The resulting recycled flexible pavement materials at the plant, called reclaimed asphalt pavement (RAP), can either be used directly as aggregate in base layers or be mixed with hot mix asphalt to take advantage of the aged binder that still

exists in RAP to replace the use of the virgin binder in asphalt mixes. PCC recycled at the plant is generally used as aggregate base.

Focusing on in-place strategies of flexible pavements, there are three strategies available: CIR, FDR, and HIR. CIR starts with milling and pulverizing the surface of the distressed pavement to a predetermined depth. The pulverized materials are then mixed with or without additives and are graded, placed, and compacted back in place providing an improved base layer and a wearing hot mix asphalt (HMA) overlay or a surface treatment is typically added on top. CIR and FDR are both cold recycling methods and the main difference is that CIR only pulverizes the materials in the HMA layer of the previous section and does not go through the layers underneath, while in FDR, all of the HMA layer and at least 2 in. (50 mm) of the base/sub-base materials are pulverized.

Therefore, CIR is mostly used for cases where the distresses and issues are only within the few top inches of the surface layer, but FDR is used when the pavement is heavily deteriorated. HIR construction process consists of four steps: (1) softening of asphalt pavement surface with heat, (2) scarification and mechanical removal of the surface material, (3) mixing with recycling agent, asphalt binder, or new mix, and (4) laydown and paving of the recycled mix. HIR is usually used for three applications: (1) surface recycling, (2) repaving, and (3) remixing and each application uses different sets of equipment and sequence of construction. HIR is not common in California and, therefore, will not be included in the scope of this study. Details of the construction process for CIR and FDR are later presented in Chapter Seven.

In-place recycling is gaining more popularity as it results in less consumption of virgin aggregates and less environmental impacts in hauling of the materials to the site. These reductions in material consumption and hauling expenses result in lower construction costs. Recycling has always been closely linked to environmental stewardship, this coupled with scarce resources of virgin materials in California, has led Caltrans to aggressively pursue recycling in their pavement projects. There is also legislation in this regard such as Assembly Bill 338, approved in 2005, which requires Caltrans to use crumb rubber asphalt (CRA) in its construction project with a minimum requirement of 20 percent of total asphalt weight used in projects to be from CRA by 2007, 25% by 2010 and 35% by 2013 (CA Legislature webpage on AB338.) Compared to recycling of the pavement, conventional EOL techniques for flexible pavements are reconstruction, mill-and-fill, or construction of an overlay on top of the existing pavement. EOL is the least considered life cycle stage in LCA studies identified across the world, as Table 2.4 taken from the FHWA review of the literature in 2014 shows.

Table 2.4. Inventory sources contributing to pavement life-cycle stages (FHWA, 2014)

Life-Cycle Stages	# of Studies
Material Acquisition	97
Construction	28
Maintenance and Rehabilitation	97
Use	27
End-of-life	19

A survey was conducted of recent LCA studies on EOL of pavements, and the summary is presented in App-Table 3. Within these studies, there is no reliable data set that closely models the local practice in California in terms of the construction activities, mix designs, and locally adjusted LCI for the materials used in each EOL alternative. As the table shows, there are still questions and issues to address:

- Reliable and locally representative quantification of the impacts of the options available at EOL.
- Allocation of the impacts between the upstream and downstream projects when using recycled materials (discussed below.)
- The performance of the sections built from recycled materials or built using in-place recycling compared to the conventional techniques. This should be investigated from two perspectives:
    - Surface roughness changes with time that directly affect vehicle fuel consumption.
    - Section cracking performance that affects future maintenance and rehabilitation (M&R) frequencies.

2.1.5. The Issue of Allocation in LCA Studies

ISO 14040 (2006) defines allocation as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems." Systems that produce co-products, by-products, or recycled materials are areas of concern for allocation. Co-products are two or more products that are produced in the same process, like the final products of a crude oil refinery plant. A by-product is the result of a production process that is primarily focused on another material, but the by-product can still be marketed and sold for value. What is left from a production process that has no economic value and no use in other industries is called waste. In the case of a refinery that processes crude oil and produces several refined products (co-products) how to allocate the total emissions and environmental impacts of the oil extraction, transportation and refinery processes between the co-products is an issue where they cannot be assigned exclusively to one product or another through thermodynamic or mechanical decomposition of the processes. . As another example, fly ash is a waste of coal combustion in power plants and can be used as a partial substitute for portland cement. Dividing the impacts of coal combustion between the electricity generated by the plant (the main product) and the fly ash (the waste) is an allocation issue.

Recycled materials are another area of concern. Recycling can be open-loop or closed-loop. In closed-loop recycling, the material is recycled back into the original product system, such as the case for aluminum cans or RAP back into HMA. In open-looped recycling, the material is recycled into other product systems with a substantial change in the inherent properties. Another issue to consider is the possible loss of quality during the recycling process and therefore the number of times recycling can be repeated in the future. Quality degradation during the recycling process might be significant enough that it would eventually lead to the disposal of the material as waste.

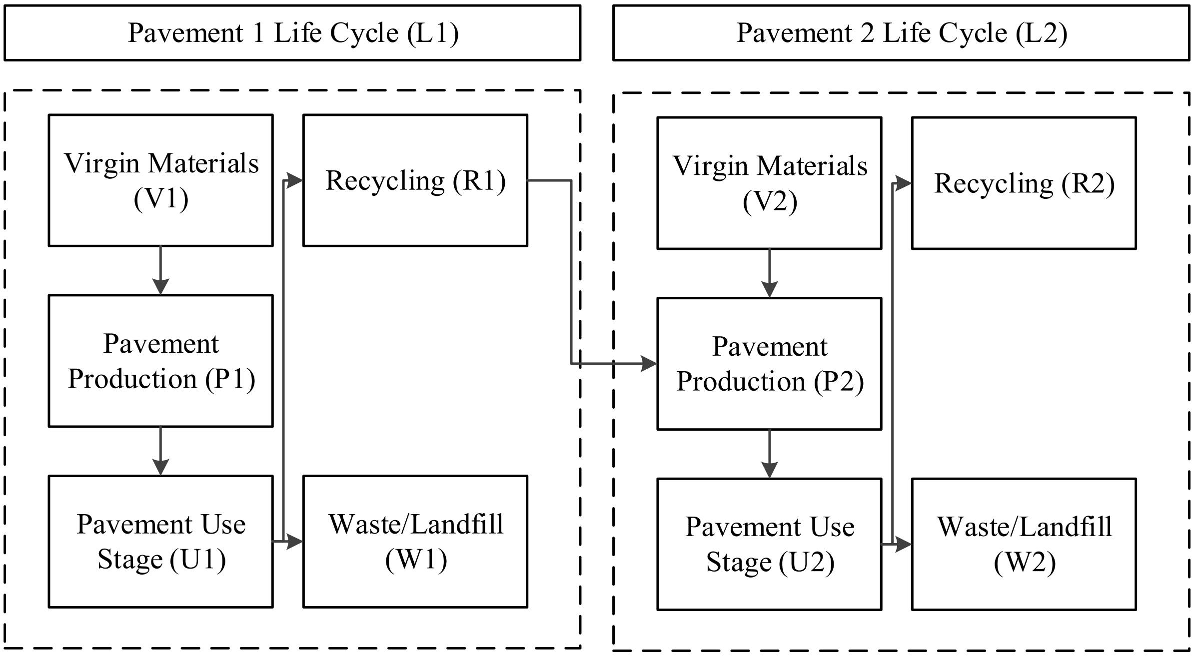
ISO 14040 recommends avoiding allocation, whenever possible, by: (1) Dividing the unit process into sub-processes and collecting inputs and outputs related to each, or (2) Expanding the system boundaries to include the additional functionalities related to the co-products. When the allocation is unavoidable, ISO recommends partitioning the impacts based on the underlying physical relationships between them such as mass proportions or energy content ratios. ISO also allows allocation based on economic value where appropriate. However, these methods can yield significantly different results depending on the physical property chosen for doing the allocation.

The issue of allocation is present in many aspects of pavement LCA studies such as environmental impacts of asphalt binder as a co-product of an oil refinery, or supplemental cementitious materials (SCMs) such as fly ash, slag cement, silica fume, and by-products of other industries. Another major area of concern is recycled materials such as RAP and RCA. While allocation of co-products and by-products in pavements have been considered by multiple studies (Sayagh, 2010; Huang, 2013; and Kang 2014), best practice for allocation of recycled materials, either in-place or at plant is still an area of debate.

Recycling pavement materials, either in-place or at a plant, will displace the use of finite resources such as virgin aggregates and sometimes virgin binders and therefore eliminate the impacts of producing virgin materials. This avoidance of using virgin materials can result in reductions in environmental impacts that should be allocated between the upstream project that provides the recycled materials and the downstream project that uses it. There are also emissions and energy consumptions, referred here as environmental burdens, for producing the recycled materials. These burdens for in-place recycling include pulverization, processing, further addition of stabilizing agents and virgin aggregate to achieve specified gradations and other specification limits for mix proportioning and properties. For plant recycling the burdens are caused by: demolition, transportation to the plant, processing done at the plant, and transportation of the recycled materials to the new construction site. The allocation of these environmental burdens between the upstream and downstream projects is not straight forward. There can also be plant recycling of materials produced at the plant but never transported to a construction site, for various reasons.

Allocation of recycled materials has been an area of discussion in all four international symposiums on pavement LCA (Davis, CA 2010; Nantes, France 2012; Davis, CA 2014; and Urbana-Champaign, IL 2017) and three different approaches have been suggested (Harvey et al., 2010; Van Dam et al., 2015), as explained in Figure 2.7:

- Cut-off method: benefits and burdens of recycling all goes to the downstream project (pavement 2 is responsible for R1, no reduction of environmental impacts allocated to pavement 1 for producing recycled materials)
- 50/50 method: half the impacts to the second pavement and half to the first pavement
- Substitution method: The first pavement is given the full benefits (the impacts that are avoided by substituting virgin materials in pavement 2)



V1: Environmental impacts of material production for pavement 1
V2: Environmental impacts of material production for pavement 2 (V1<V2 due to using recycled materials that replace virgin aggregate)
R1: Environmental impacts of the recycling processes
P1, P2: Environmental impacts of pavement construction
U1, U2: Environmental impacts of the use stage
W1, W2: Environmental impacts of waste management

Figure 2.7: EOL allocation rules potentially applicable for pavements (Van Dam et al., 2015.)

Not only there are no reliable models to quantify the environmental impacts of the in-place recycling and plant-recycling practices currently in use in California, but also, there is no consensus on a framework or methodology for handling the allocation. Some other questions that need to be addressed are:

- What is the damage to the recycled layers at the time that the surface fails, and how many times is the surface replaced before the underlying recycled layer(s) need to be treated?
- Is there a difference in recyclability of a new pavement at its EOL versus a section that is built using any of the conventional rehabilitation techniques?
- How many times can a recycling strategy be repeated, and do the materials and the construction activities change with subsequent recycling? If is the number of times recycling can be repeated is limited, which means the quality deteriorates with each recycling, how should the allocation of the impacts between the current and the future recycling be handled?
- Does consequent recycling have a detrimental impact on the pavement performance? Is the same performance model applicable to a section recycled once and a section that that has been recycled multiple times?
- Should the LCA consider repeated use of the same treatment or are there paths in the analysis period in which different alternatives should be considered?

2.1.6. Cost Effectiveness

Multiple studies have stated that in-place recycling practices cost less compared to conventional EOL of treatments such as mill-and-fill or total reconstruction. In-place recycling involves less consumption of virgin aggregate and potentially less binder, as well as less hauling of the materials to the site. However, a complete comparison should include all life cycle stages and requires life cycle cost analysis, as more frequent future M&R may offset the savings in the initial construction impacts. App-Table 4 in Appendix I shows a review of some of these studies with limitations identified in each. It should be noted though that due to high fluctuations in relative prices of asphalt and cement (BLS webpage on Producer Price Index; Caltrans webpage on Asphalt Price Index), most of the cost studies conducted in the past are not very useful nor applicable for now and do not provide an accurate picture of the relative costs of the current practices. This shows the need for updated cost estimates and sensitivity studies for each of the rehabilitation alternatives.

2.2. Implementation of Life Cycle Thinking in Local Roads Management in California

Most pavement LCA studies, either at the project level or network level, are conducted on pavement sections which are part of the state network and local roads have not been included as much. While in fact, as Figure 2.8 shows, local roads are more than 82 percent of the total statewide lane-miles in California, and as presented in Table 2.5, they support an estimated 54 percent of the statewide annual vehicle miles traveled.

Table 2.5. Maintained road miles and estimated annual vehicle miles of travel (AVMT) by jurisdiction (Caltrans, 2018a)

Jurisdiction	Lane-Miles	% of Statewide Total	AVMT (millions)	% of Total AVMT
City Streets	181,475	45.7%	118,466	34.4%
County Roads	146,128	36.8%	37,313	10.8%
State Highways	51,279	12.9%	187,164	54.4%
Federal Agencies	15,765	4.0%	964	0.3%
Other State Agencies	2,067	0.5%	396	0.1%
Statewide Total	**396,715**	**100.0%**	**344,304**	**100.0%**

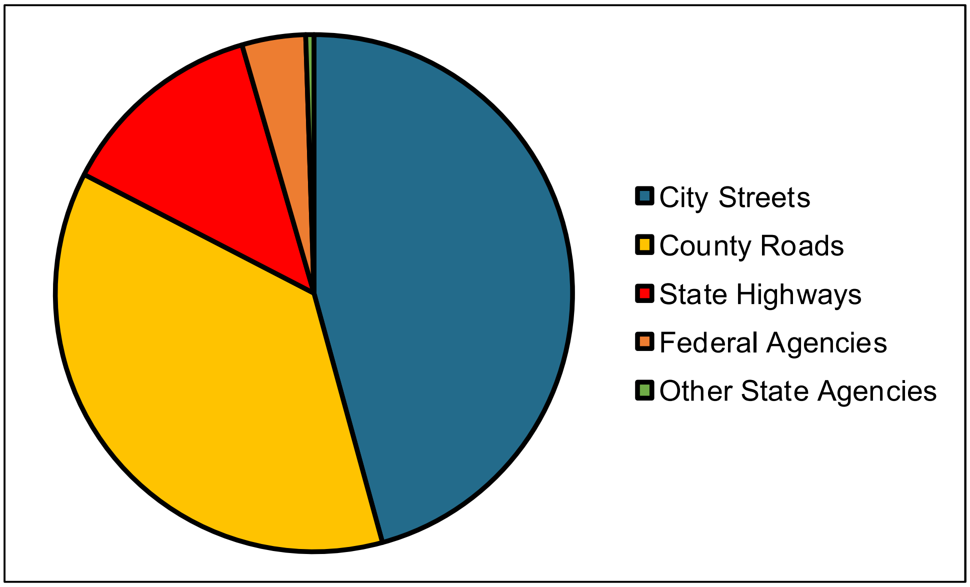


Figure 2.8: Breakdown of public road ownership in California based on lane-miles (Caltrans, 2018a).

There are several state GHG emission reduction policies in California, some of which directly target local agencies. The most important ones are Assembly Bill 32, the global warming solution act, which was enacted in 2006, requiring reduction of statewide GHG emissions to the 1990 level by 2020 and 50 percent reduction from that level by 2050 (CA Legislature webpage on AB32.) and Senate Bill 375 which mandates metropolitan planning organizations (MPOs) to create land use and transportation plans to meet the regional GHG reduction mandates set by Air Resources Board (CARB webpage on SB375.)

Another area of concern for local agencies is the cost of maintaining their networks. A statewide study of California's local street and road system conducted in 2014 reported that while existing funding levels were $1.657 billion/year, it was estimated that maintaining the current conditions required 3.328 billion/year (at its current Pavement Condition Index (PCI) of 66) and funding required to reach what the report considered optimal was $7.275 billion/year. It was assumed that by bringing the roads to optimal level, cities and counties will be able to maintain streets and roads at the most cost-effective level.

In April 2017, Senate Bill 1, the Road Repair and Accountability Act of 2017, was signed into law which invests $54 billion over the next decade to fix roads, freeways and bridges in communities across California. These funds through SB1 are equally split between state and local investments. SB1 has a dedicated webpage that reports how the funding is allocated and the status of projects funded by this bill (SB1 Overview webpage.)

Local agencies in northern California usually use modified Caltrans' guidelines for new pavements, and maintenance and rehabilitation of existing pavements. Similar specifications are used in southern California through the Greenbook. Local roads normally have lower traffic levels compared to the state network, and typically fail because of issues with utility cuts, traffic and construction quality that are different from the context of the state highway system. Currently, local governments do not have any tool to quantify the environmental impacts of their civil infrastructure decisions at network level management (to comply with SB375) nor compare alternatives at the project level.

What can help mitigate some of the challenges with the budget and reduce GHG emissions is to use Caltrans' type pavement structures where applicable, but to develop new designs for structures and M&R that recognize the differences between the state and local networks and that potentially use less material, cost less, and have less environmental impacts considering the whole life cycle of the option. This requires new section designs, and estimates of the construction costs, service life, and GHG emissions in each of the life cycle stages for them and to compare with conventional designs. There is no such model available for local agencies at this point. Recent work at UCPRC (Jones et al., 2016) points towards the potential of greater use of recycled materials, designs that are easier to maintain when utilities are present and the potential benefits of more frequent preservation treatments as opposed to less frequent, but more expensive rehabilitation treatments

2.3. Problem Statement and Gaps in the Knowledge

Based on the previous discussion presented in this proposal, the current gaps in the knowledge are:

- There are LCI datasets available for materials, surface treatments, and construction activities, but these datasets generally: a) do not include a comprehensive list of all available options, b) are outdated, and c) are not representative of the local conditions in terms of processes, mix designs, and energy sources.
- Frameworks and models that can help local governments quantify the life cycle costs and environmental impacts of their decisions in transportation infrastructure management do not exist at this point. Such frameworks and data models are critical to help local governments evaluate their strategies and decision making. Asset management through such frameworks and tools would allow local governments and state agencies to find the most efficient solutions to meet their goals at minimum cost. Such an approach would help managers avoid less optimal solutions or even worse, cases where unintended consequences offset the whole benefits realized through a novel approach.
- There are limited and unreliable data for quantifying the environmental impacts of EOL strategies for flexible pavements; these strategies include conventional methods (such as reconstruction, mill-and-fill, and overlays) and recycling strategies (either in-place or plant-recycling.)
- There are no reliable performance prediction models for pavements built from recycled materials. Therefore, it is unclear whether such sections perform better, equally, or worse compared to conventional strategies. If the performance is worse, it is possible that the potential savings in environmental impacts due to recycling are offset by the need for more frequent maintenance and rehabilitation in the future compared to conventional strategies.
- The surface roughness is going to affect vehicle fuel consumption during the use stage. Roughness performance models for sections built using in-place recycling are also unknown at this point.
- There is no consensus on the methodology on how to allocate the reduction in environmental impacts due to recycling between the upstream project that is at its EOL and the downstream project that is going to use the recycled materials.

2.4. Research Objectives

The main objectives of this research are to:

- Complete the LCI database for the materials and surface treatments used by Caltrans and local governments on their pavement projects.
- Develop frameworks and models as a decision-making approach and tool for local and state agencies, consisting of modules for LCA and Life Cycle Cost Analysis (LCCA.) The data to be fed into the models will be taken from the UCPRC LCI database which is the deliverable of the first objective in this list. The frameworks and tool will allow decision makers to quantify the costs and environmental impacts of multiple alternatives during analysis period and within the scope and system boundary set by the decision maker. The alternatives are a list of the conventional treatments used by local agencies and new section designs that will be developed as part of this project that are expected to use less materials and cost less in the initial construction stage and over the life cycle. The cost estimates coupled with estimates of the service life of the options and the future M&R frequencies will be used to compare the life cycle cost (LCC) of the alternatives. LCC and LCA results can provide the decision maker with all the information needed to select among available alternatives. The decision support approach and tool will be mindful of the limitations of data, time, and expertise typically available to local government agencies.
- Develop models to quantify the environmental impacts of EOL alternatives for flexible pavements, using the practice in California as the case study.
- Investigate and recommend a methodology for handling allocation of the EOL impacts and provide understanding on how it can affect the decision making in terms of selecting the treatments based on their environmental impacts.
- Develop performance prediction models for recycled sections to understand how their roughness and cracking change with time and therefore, allow fair comparison of recycling and conventional methods throughout their life cycle.

CHAPTER 3. Comprehensive Life Cycle Inventory for Transportation Infrastructure Projects, Calibrated to the Energy Mix, Technologies, and State-of-Practice in California

3.1. Introduction

This chapter 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 pavement projects in California, as well as some impacts from building heating, cooling, and lighting. The UCPRC LCI database presented in this chapter is mostly the result of two LCA studies by the UCPRC completed for the California Air Resources Board (CARB) and the California Department of Transportation (Caltrans.) The goal and scope of each of those studies is defined in Section 3.2.1. and Section 3.2.2. , respectively, in order to contextualize how they will use the LCI data and to specify how the data will be applied within the scope of each study.

The data presented in this chapter are intended as background LCI 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 provided in this chapter do not include background information for any use stage elements other than building energy consumption (e.g., pavement vehicle interaction [PVI], lighting, carbonation, albedo effects due to radiative forcing.) Foreground data are “from the system of primary concern to the analyst” and background data “include energy and materials that are delivered to the foreground system as aggregated data sets in which individual plants and operations are not identified” (EPA webpage on LCA Glossary.)

These LCI have been incorporated into the LCA software called *eLCAP* (environmental Life Cycle Assessment for Pavement.) These inventories will continue to be updated in the future as part of the ongoing development of *eLCAP* and will be subjected to periodic outside critical review.

The models and inventories were either developed by the author or are modified versions of models available in commercial software. In either case, the main goal in 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 LCI for other locations around the world.

The main commercial source used in the development of these LCIs was the PE Profession Database available in the software program *GaBi* (GaBi webpage). Other database sources were also used, including *ecoinvent* (ecoinvent webpage) and the US Life Cycle Inventory (USLCI) which is hosted at the NREL website (NREL webpage on USCLI.) The energy sources and materials for which LCIs were developed and included in the UCPRC LCI database are listed in Table 3.2, and the composite materials and transportation mode inventories are listed in Table 3.3. These LCIs combine the results of both studies and not all the items were used in both; the items included in each study are detailed in Section 3.2.1. and Section 3.2.2. .

The UCPRC decided that a third-party verification of the database was needed to verify the accuracy and reliability of data sources, modeling assumptions, and the LCI results. The three-member review committee selected to conduct the verification according to ISO 14040 requirements is listed in Table 3.1.

Table 3.1. The third-party review committee members

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

The original version of the remainder of this chapter, written by the author, served as the UCPRC report to the review committee, and the version included in this chapter now includes the results of responding to their comments A few additional concrete mix design inventories were added after the critical review, as noted in this chapter, and the naming of the existing concrete mix designs was changed to more specifically identify the type of mix and its intended use. These additional inventories are for:

- Portland Cement Type III
- Calcium Sulfo-Aluminate Cement (CSA)
- Concrete mix designs for state highway lane replacement, local streets, and minor concrete
- Concrete mix designs for slab replacement with Type III and CSA cement
- Bonded Concrete Overlay of Asphalt concrete mix designs from the Cool Pavement project with three levels of supplementary cementitious materials

Table 3.2. Energy sources and materials included in the UCPRC LCI database

Item	Type
Electricity	Energy Sources
Diesel Burned in Equipment	Energy Sources
Natural Gas Combusted in Industrial Equipment	Energy Sources
Aggregate (Crushed)	Materials
Aggregate (Natural)	Materials
Bitumen	Materials
Bitumen Emulsion	Materials
Crumb Rubber Modifier (CRM)	Materials
Dowel	Materials
Limestone	Materials
Paraffin (Wax)	Materials
Portland Cement Type I	Materials
Portland Cement with 19% SCM	Materials

Item	Type
Portland Cement with 50% SCM	Materials
Portland Cement Admixtures (Accelerator)	Materials
Portland Cement Admixtures (Air Entraining)	Materials
Portland Cement Admixtures (Plasticizer)	Materials
Portland Cement Admixtures (Retarder)	Materials
Portland Cement Admixtures (Superplasticizer)	Materials
Portland Cement Admixtures (Waterproofing)	Materials
Quicklime	Materials
Reclaimed Asphalt Pavement (RAP)	Materials
Reflective Coating (BPA)	Materials
Reflective Coating (Polyester Styrene)	Materials
Reflective Coating (Polyurethane)	Materials
Reflective Coating (Styrene Acrylate)	Materials
Styrene Butadiene Rubber (SBR)	Materials
Tie Bar	Materials

* SCM: Supplementary Cementitious Materials

Table 3.3. Pavement composite surface materials and treatments, and transportation modes included in the database

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

A downloadable *Excel* file for each item discussed in this chapter is available in a supplementary data folder available over the internet (UCPRC LCI DB Shared Folder on Box), this folder will be referred to as the Supplementary Data throughout this chapter. Each file contains two tabs: one is the full LCI of the item and the other is the life cycle impact assessment (LCIA) results from different impact assessment methodologies. It should be noted that the impacts calculated using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 (Bare, 2012) results are the only impact calculations that were subjected to critical review.

In general, the system boundary of the LCIs developed included: (a) extraction of raw material from the ground, (b) transportation of raw materials to the plant, and (c) the processes conducted in the plant to prepare the final product to be shipped to the construction site, which is referred to as a "cradle-to-gate" LCIs. Delivery of the product to the construction site and the impacts associated with the transportation are not included in a cradle-to-gate LCI. Transportation is included in the LCIs as a separate item, with different inventories for each mode of transportation shown in Table 3.3. Section in Chapter 2 describe the specific system boundary for each item in more detail.

3.2. Goal and Scope Assumptions Used to Develop Inventories

3.2.1. Goal and Scope of CARB/Caltrans Lawrence Berkeley National Laboratory Heat Island Study

This project was a collaborative effort between the Lawrence Berkeley National Laboratory (LBNL) as lead, the UCPRC, the University of Southern California, and thinkstep, and was jointly funded by CARB and Caltrans. The study 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 (tool summarized in (Levinson et al., 2017), study results summarized in (Gilbert et al., 2017) Urban areas generally have higher temperatures compared to the undeveloped land around them, as they are covered with pavement and buildings that absorb heat from solar irradiance, and have multiple sources of heating including building and motor vehicles. This phenomenon is referred to as an urban heat island.

Cool pavements have higher albedo (reflectivity) compared to conventional pavements which can contribute to reducing urban heat island effects by reflecting more solar irradiance than conventional pavements. The objective of this study was to conduct a full life cycle analysis so that the environmental impacts of the full life cycle stage considering materials, construction, transportation, year-round building energy use, and end of life could be fully accounted for, not just the reduction of urban heat island and consequent impacts from summer-time building energy use during the use stage which was the system boundary of previous LBNL studies. The analysis period was defined as 50 years for the various surface treatments compared in the study.

Table 3.4 shows the parameters that were calculated in the study to allow objective comparison of alternative cool pavement strategies considering the full life cycle of pavement materials and energy consumption in buildings. The surface treatments considered in this project consisted of a comprehensive list of conventional and alternative approaches that can potentially be applied to urban public pavements. The list of treatment types considered in the study is shown in Table 3.5 which includes covering pavement surfaces with reflective coatings instead of conventional asphalt-based slurry seals, even though reflective coatings were still not generally available in the market at the time of this study. The study's geographic scope was limited to the state of California and its temporal scope was assumed to be begin between the years 2012 (then current electrical energy production) and 2020 (under the California Renewables Portfolio Standard (RPS.)

Table 3.4. Parameters of interest in the cool pavement study

Pavement Side	Climate Side	Building Side
Energy Consumption and Environmental Impacts due to: - Material Production - Transportation - Construction -Total Cradle to Laid Calculated Using LCA	Changes in Urban temperature due to changes in pavement albedo. Calculated using a climate model considering: - percent of public roads changed each year - albedo of the specific type of surface treatment selected - changes in albedo with age of pavement	Changes in Energy consumption in buildings due to changes in urban temperature caused by changing pavement albedo - Cooling in summers - Heating in winters

Table 3.5. List of surface treatments considered in the cool pavements study

Surface Treatment
Bonded Concrete Overlay on Asphalt (BCOA) with three levels of SCM*
Seals (Cape, Chip, Fog, Sand, Slurry)
Conventional Asphalt Concrete, (mill and fill; overlay)
Conventional Interlocking Concrete Pavement (Pavers)
Permeable Asphalt Concrete
Permeable Portland Cement Concrete
Permeable Rubberized Asphalt Concrete
Portland Cement Concrete (PCC) with three levels of SCM
Reflective Coating (with four different coating)
Rubberized Asphalt Concrete (mill and fill; overlay)

* SCM: Supplementary Cementitious Materials

The material production stage included extraction of raw materials from the ground, transportation to processing plants, and the processing conducted in 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. Processes for construction activities on site were modeled for each surface treatment according to Caltrans specifications and correspondence with local contractors. During the use stage, energy use in buildings was quantified with consideration of changes in urban temperatures according to the albedo of the surface treatment applied calculated using the WRF model by the University of Southern California, and also considering the percentage of the urban public pavements treated, and 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 the journal article describing the total study, including a summary of the LCA (Gilbert et al., 2017.) Changes in the surface roughness and its resulting impact on vehicle fuel consumption during the use stage was also not included in the study scope and system boundary. The service life for each surface treatment was considered based on previous experience and consultation with local agencies, however, maintenance activities during the use stage were excluded from the system boundary. Changes in traffic during the construction periods and construction work zone congestion were also excluded from the system boundary.

The intended audience of the study included local governments, pavement researchers and practitioners, and construction contractors. The functional unit selected for the study was *1 lane-mile of pavement surface.* To enable investigation of the impact of the cleaner electricity grid mix mandated by California Renewable Portfolio Standard, the LCI for the study was developed under two assumptions, one based on the year 2012 electricity grid mix and one based on the grid mix anticipated for the year 2020. The tool developed was named *pLCA (pavement LCA)* and Figure 3.1 shows the system boundary defined for this project. Coding of pLCA was outside the scope of this dissertation and was done by LBNL.

3.2.2. eLCAP

UCPRC has developed a web based LCA tool, *eLCAP*, for pavement designers to quantify the environmental impacts of their pavement design decisions, both at planning and project design stages of project development. *eLCAP* will include the inventories developed in the cool pavement project as well as complementary items needed to quantify all the impacts occurring across the full life cycle of pavements under management of public agencies. At this time the inventories in *eLCAP* are focused on California. Figure 3.2 shows the items that can be included in the system boundary of studies conducted in *eLCAP*.

3.3. Allocation

Allocation is the assigning of proportions of total single process impacts to multiple products of the process where the impacts cannot be separated based on sub-division of the process into the parts each product is responsible for based on physical sub-processes. The two pavement material products that required allocation for their inventories in this study are bitumen, which comes from the refining of oil into bitumen and many other products, and reclaimed asphalt pavement (RAP) which involves the creation of the original asphalt pavement and the additional processes of reclaiming it at the end of its life. Details of allocation assumptions and corresponding results can be found in each of the respective sections for these products later in this chapter. Table 3.6 lists the pavement materials for which allocation of the LCI data was needed and the potential allocation methods that could be used for each.

Table 3.6. Possible allocation methods to be used for selected pavement materials in the database

Item	Applicable Allocation Methods
Bitumen	Mass-based, energy-based, and value-based (economic)
Reclaimed asphalt pavement (RAP)	Cut-off and 50/50

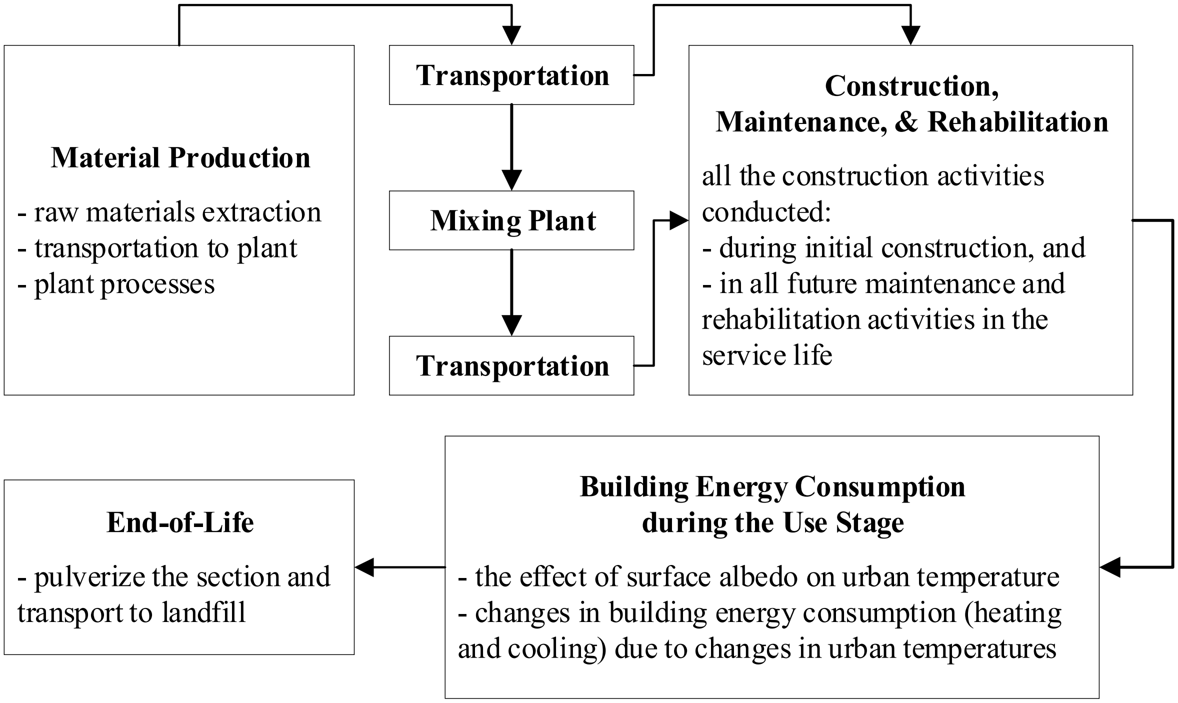


Figure 3.1: Scope of the *pLCA* tool.

3.4. Life Cycle Impact Assessment

TRACI 2.1 (Bare, 2012) 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 study:

- Global warming potential (GWP)
- Photochemical ozone creation (smog) potential (POCP)
    - Smog emission, unlike global warming, is a local issue and therefore the location of the emission matters. However, this study did not specify the location nor timing of the emission of these ozone precursors. Instead this 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.)
    - Similar to smog potential, particulate emissions occur on a local scale and are emitted at various locations as part of 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 nonrenewable resources (net calorific value excluding feedstock energy)
- Primary energy used as a material from nonrenewable resources (feedstock energy)

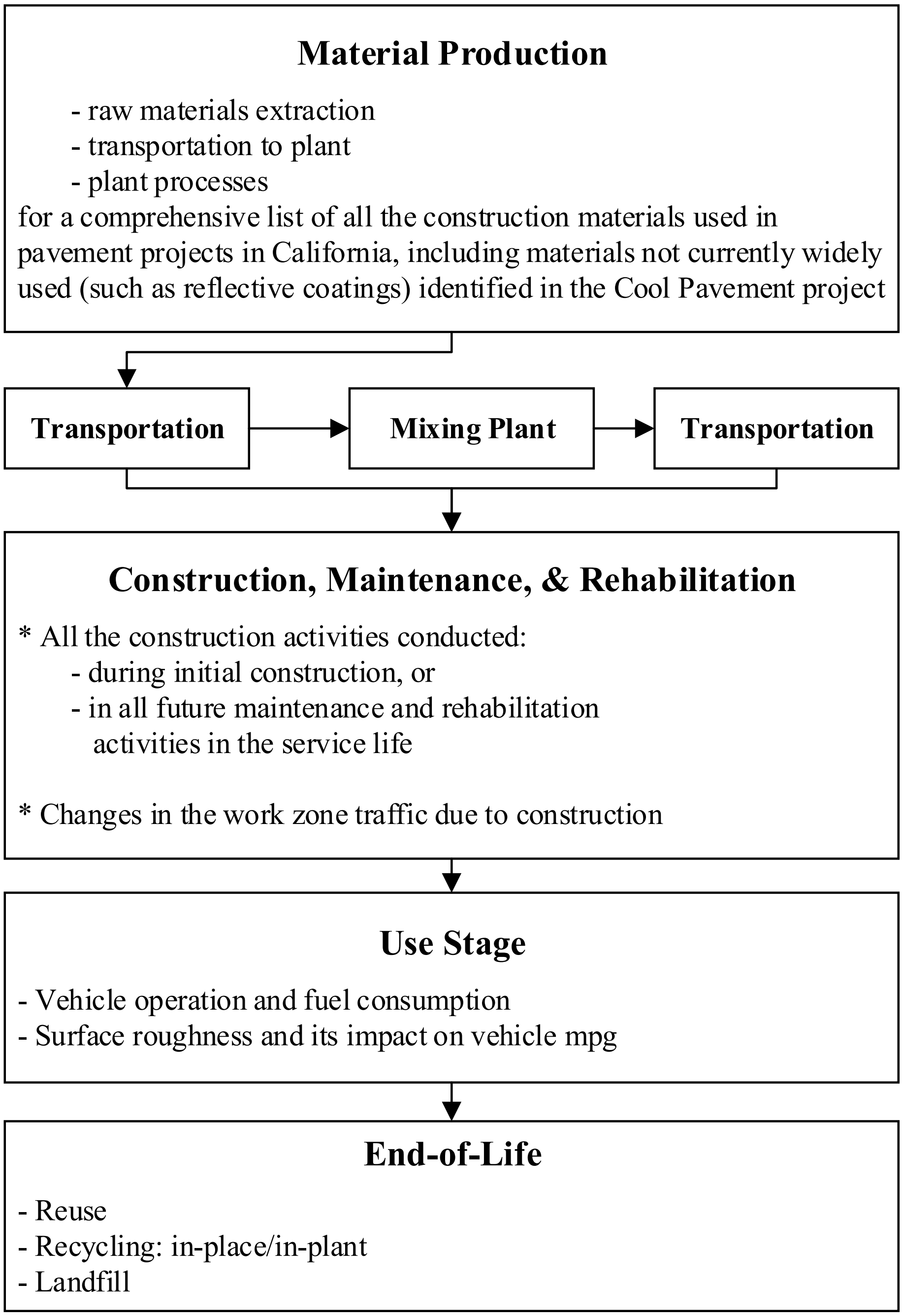


Figure 3.2: Scope of the eLCAP software.

Initial LCA studies conducted for Caltrans (Wang et al., 2012) primarily focused on global warming potential, primary energy demand used as fuel (renewable and nonrenewable), and primary energy used as a material from nonrenewable resources (feedstock energy.) More recent studies, such as the benchmarking of EOL practices (Saboori et al., 2017), also include smog and particulate matter. The *eLCAP* software has been developed with the intention that it will report all the impact categories identified by the EPA and two main inventory items, primary energy and feedstock energy, as shown in Table 3.7. The full LCIA results of the UCPRC LCI dataset are included in the supplementary data available for download, as noted earlier.

Table 3.7. TRACI 2.1 impact categories and selected inventory items to be used in the UCPRC eLCAP software

Life of Impact Categories in the USEPA TRACI 2.1 Impact Assessment Methodology
Acidification [kg SO2-e*]
Ecotoxicity [CTUe]
Eutrophication [kg N-e]
Global Warming Air, Excluding Biogenic Carbon [kg CO2-e]
Global Warming Air, Including Biogenic Carbon [kg CO2-e]
Human Health Particulate Air [kg PM2.5-e]
Human Toxicity, Cancer [CTUh]
Human Toxicity, [ds: spell as “non-cancer”?] [as: fixed] Non-Cancer [CTUh]
Ozone Depletion Air [kg CFC 11-e]
Primary Energy Demand Use as Fuel from Renewable and Nonrenewable Resources (Net Calorific Value) [MJ]
Primary Energy Demand Used as Raw Materials (Feedstock Energy) [MJ]
Resources, Fossil Fuels [MJ Surplus Energy]
Smog Air [kg O3-e]

* equivalent

The data sources used to model each item in the inventory described in this chapter were chosen after the available options were examined to see which were most up to date and representative of the regional conditions in California. Details are available in the discussion of each item below and also in Chapter Three, Data Quality Requirements and Data Validation. As noted earlier, although an *Excel* file for each of the items in this chapter is available in the Supplementary Data (UCPRC LCI DB Shared Folder on Box) on the web with full LCI and LCIA, the LCIA results are provided below for reference. 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 there were no better available datasets.

3.5. Energy Sources

3.5.1. Electricity

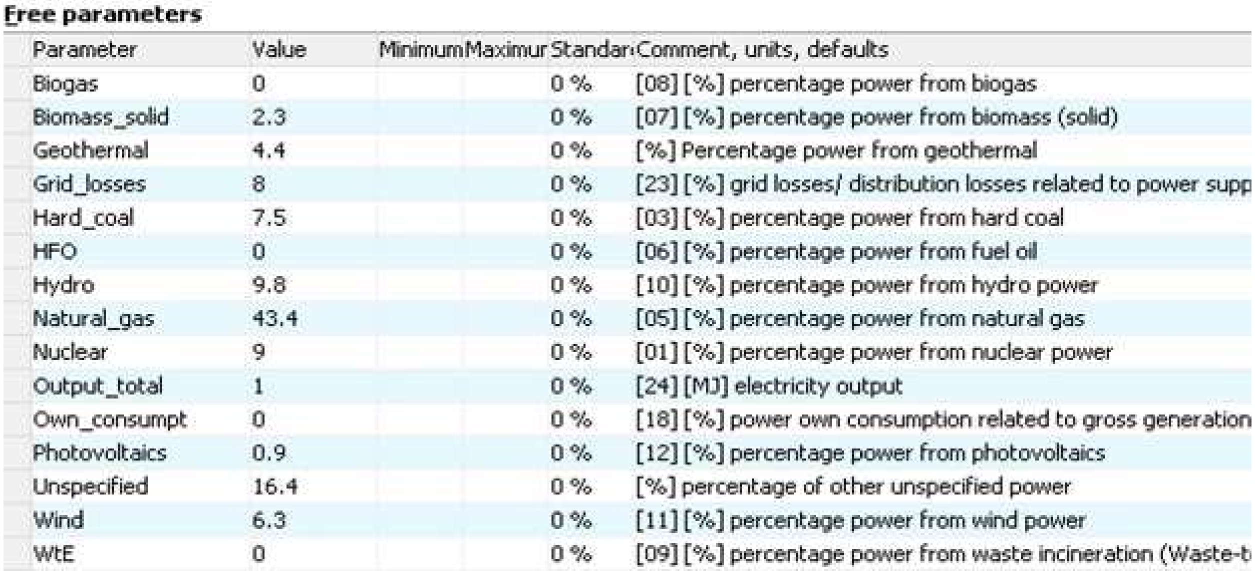
The electricity grid mix for California was taken from *The California Energy Almanac* webpage, and the table for 2012 is reproduced here as Table 3.8. Figure 3.3 and Figure 3.4 show the other parameters used in the model definition and Figure 3.5 shows the model developed using the software program *GaBi,*. The average Western US grid process (based on the EPA’s Emissions & Generation Resource Integrated Database [eGRID]) that is included in GaBi was used in the model to account for the unspecified portion of the grid mix. As noted in Section 3.2.1. , the electricity LCI was developed under two different grid mix scenarios, one based on the year 2012 and one based on the year 2020. Including the latter will allow analysts to investigate the impact of a cleaner energy mix on the results of the study. As noted, the use of the 2020 renewables portfolio was specifically requested by the California Air Resources Board assuming that implementation of cool pavement strategies will happen after 2020.

Table 3.8. Electricity generation mix in CA
(a) In year 2012 (CA Energy Almanac webpage)

Fuel Type	Percent in CA Grid Mix
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%**

(b) In year 2020 (CA Renewable Portfolio Standard [RPS])

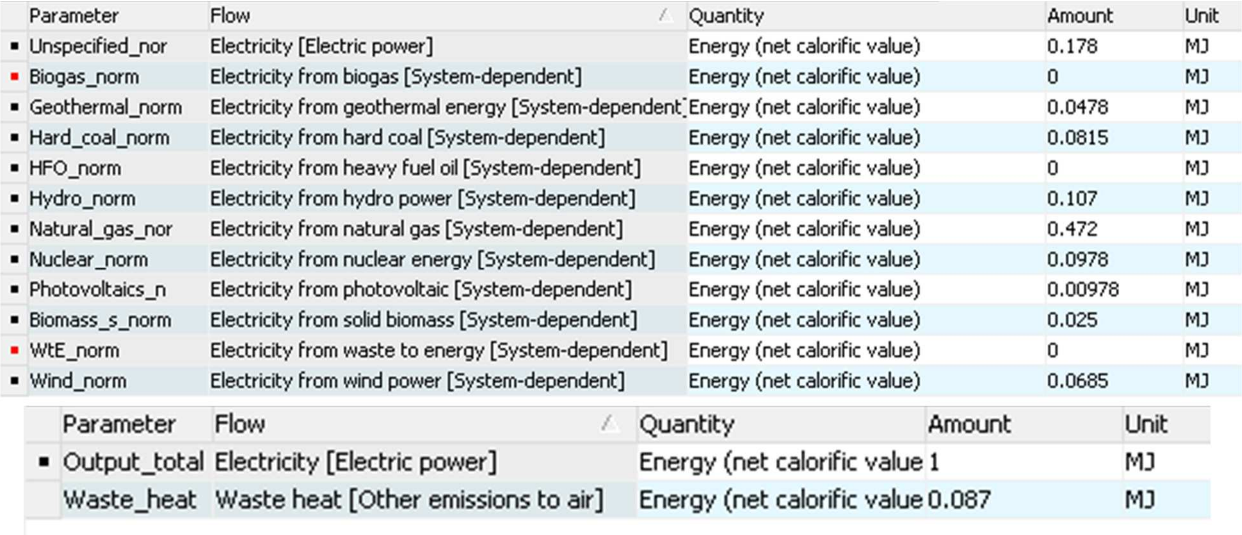
Fuel Type	Percent in CA Grid Mix
Total Renewables	28.20%
Biomass	1.20%
Landfill Gas	0.30%
Geothermal	2.90%
Small Hydro	1.60%
Solar PV	10.90%
Solar Thermal	2.30%
Wind	9.00%
Total Non-Renewables	71.80%
Hard Coal	6.40%
Hydro Large	7.00%
Natural Gas	36.80%
Nuclear	7.60%
Unspecified	13.90%
Total	**100%**



Free parameters

Parameter	Value	Minimum	Maximur	Standar	Comment, units, defaults
Biogas	0			0 %	[08] [%] percentage power from biogas
Biomass_solid	2.3			0 %	[07] [%] percentage power from biomass (solid)
Geothermal	4.4			0 %	[%] Percentage power from geothermal
Grid_losses	8			0 %	[23] [%] grid losses/ distribution losses related to power supp
Hard_coal	7.5			0 %	[03] [%] percentage power from hard coal
HFO	0			0 %	[06] [%] percentage power from fuel oil
Hydro	9.8			0 %	[10] [%] percentage power from hydro power
Natural_gas	43.4			0 %	[05] [%] percentage power from natural gas
Nuclear	9			0 %	[01] [%] percentage power from nuclear power
Output_total	1			0 %	[24] [MJ] electricity output
Own_consumpt	0			0 %	[18] [%] power own consumption related to gross generation
Photovoltaics	0.9			0 %	[12] [%] percentage power from photovoltaics
Unspecified	16.4			0 %	[%] percentage of other unspecified power
Wind	6.3			0 %	[11] [%] percentage power from wind power
WtE	0			0 %	[09] [%] percentage power from waste incineration (Waste-t

Figure 3.3: Parameters used in the electricity model.



	Parameter	Flow	Quantity	Amount	Unit
▪	Unspecified_nor	Electricity [Electric power]	Energy (net calorific value)	0.178	MJ
▪	Biogas_norm	Electricity from biogas [System-dependent]	Energy (net calorific value)	0	MJ
▪	Geothermal_norm	Electricity from geothermal energy [System-dependent	Energy (net calorific value)	0.0478	MJ
▪	Hard_coal_norm	Electricity from hard coal [System-dependent]	Energy (net calorific value)	0.0815	MJ
▪	HFO_norm	Electricity from heavy fuel oil [System-dependent]	Energy (net calorific value)	0	MJ
▪	Hydro_norm	Electricity from hydro power [System-dependent]	Energy (net calorific value)	0.107	MJ
▪	Natural_gas_nor	Electricity from natural gas [System-dependent]	Energy (net calorific value)	0.472	MJ
▪	Nuclear_norm	Electricity from nuclear energy [System-dependent]	Energy (net calorific value)	0.0978	MJ
▪	Photovoltaics_n	Electricity from photovoltaic [System-dependent]	Energy (net calorific value)	0.00978	MJ
▪	Biomass_s_norm	Electricity from solid biomass [System-dependent]	Energy (net calorific value)	0.025	MJ
▪	WtE_norm	Electricity from waste to energy [System-dependent]	Energy (net calorific value)	0	MJ
▪	Wind_norm	Electricity from wind power [System-dependent]	Energy (net calorific value)	0.0685	MJ

	Parameter	Flow	Quantity	Amount	Unit
▪	Output_total	Electricity [Electric power]	Energy (net calorific value	1	MJ
	Waste_heat	Waste heat [Other emissions to air]	Energy (net calorific value	0.087	MJ

Figure 3.4: The inputs and outputs of the electricity model.

Figure 3.5: The model developed for the California electricity grid mix.

3.5.2. Diesel Combusted in Industrial Equipment

The data for diesel combusted in industrial equipment were directly taken from the *GaBi* database. Figure 3.6 and Figure 3.7 show the model and its inputs and outputs in *GaBi*.

3.5.3. Natural Gas Combusted in Industrial Equipment

The data for natural gas combusted in industrial equipment were directly taken from the *GaBi* database. Figure 3.8 and Figure 3.9 show the model and its inputs and outputs in *GaBi*.

3.5.4. Summary of Energy Sources

Table 3.9 shows a summary of selected LCI and LCIA results for the energy sources studied.

Table 3.9. Summary of selected LCI and LCIA results for energy sources (based on the 2012 CA electricity grid mix)

Item	Func-tional Unit	GWP [a] [kg CO_2e]	POCP [b] [kg O_3e]	PM2.5 [c] [kg]	PED (Total) [d] [MJ]	PED (Non-Ren) [e] [MJ]	FE [f] [MJ]
Electricity (2012 grid mix)	1 MJ	1.32E-01	4.28E-03	2.54E-05	3.09E+00	2.92E+00	0.00E+00
Electricity (2020 grid mix)	1 MJ	1.07E-01	3.53E-03	2.23E-05	2.92E+00	2.23E+00	0.00E+00
Diesel, combusted	1 liter	4.50E+01	1.99E+01	3.55E-02	6.25E+02	6.25E+02	0.00E+00
Natural gas, combusted	1 m3	2.42E+00	5.30E-02	1.31E-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 matters 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.

e PED (non-ren): Total primary energy demand from non-renewable resources. The same note as PED (Total) applies to this category as well.

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

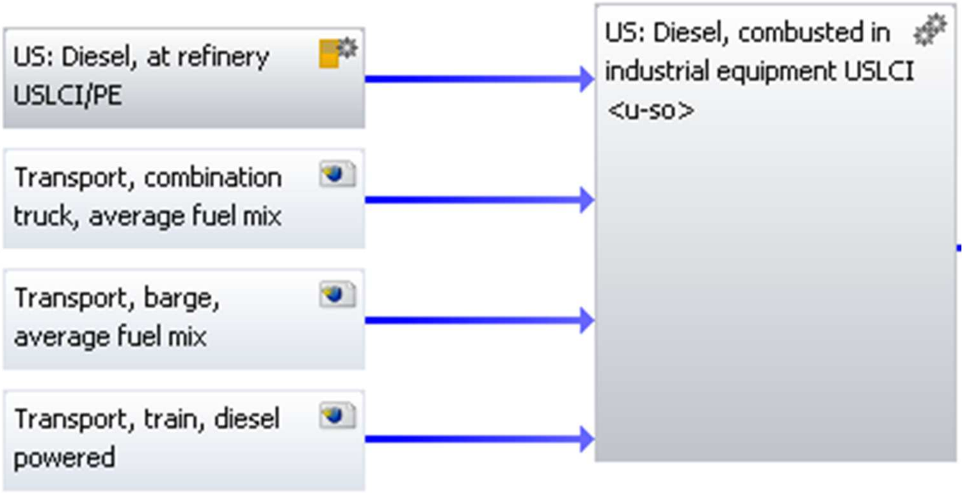
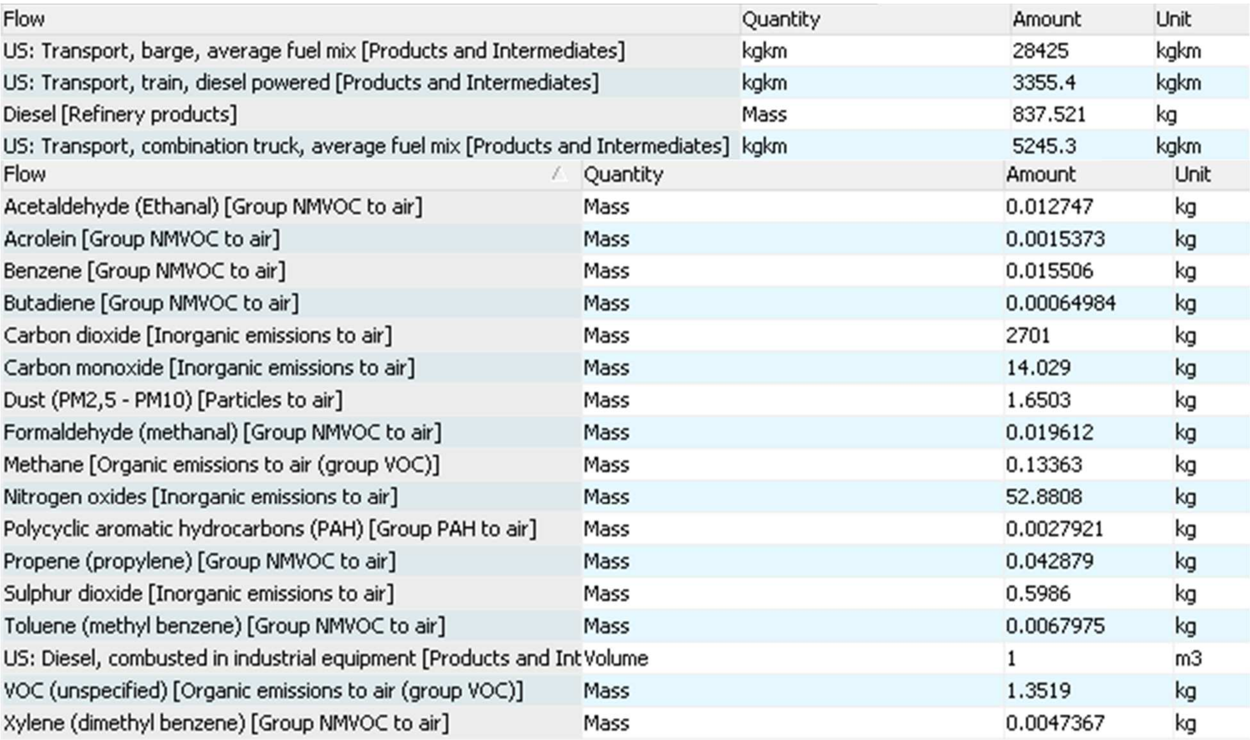


Figure 3.6: Diesel combusted in industrial equipment.



Flow	Quantity	Amount	Unit
US: Transport, barge, average fuel mix [Products and Intermediates]	kgkm	28425	kgkm
US: Transport, train, diesel powered [Products and Intermediates]	kgkm	3355.4	kgkm
Diesel [Refinery products]	Mass	837.521	kg
US: Transport, combination truck, average fuel mix [Products and Intermediates]	kgkm	5245.3	kgkm

Flow	Quantity	Amount	Unit
Acetaldehyde (Ethanal) [Group NMVOC to air]	Mass	0.012747	kg
Acrolein [Group NMVOC to air]	Mass	0.0015373	kg
Benzene [Group NMVOC to air]	Mass	0.015506	kg
Butadiene [Group NMVOC to air]	Mass	0.00064984	kg
Carbon dioxide [Inorganic emissions to air]	Mass	2701	kg
Carbon monoxide [Inorganic emissions to air]	Mass	14.029	kg
Dust (PM2,5 - PM10) [Particles to air]	Mass	1.6503	kg
Formaldehyde (methanal) [Group NMVOC to air]	Mass	0.019612	kg
Methane [Organic emissions to air (group VOC)]	Mass	0.13363	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	52.8808	kg
Polycyclic aromatic hydrocarbons (PAH) [Group PAH to air]	Mass	0.0027921	kg
Propene (propylene) [Group NMVOC to air]	Mass	0.042879	kg
Sulphur dioxide [Inorganic emissions to air]	Mass	0.5986	kg
Toluene (methyl benzene) [Group NMVOC to air]	Mass	0.0067975	kg
US: Diesel, combusted in industrial equipment [Products and Int	Volume	1	m3
VOC (unspecified) [Organic emissions to air (group VOC)]	Mass	1.3519	kg
Xylene (dimethyl benzene) [Group NMVOC to air]	Mass	0.0047367	kg

Figure 3.7: Inputs and outputs of diesel combusted in industrial equipment.

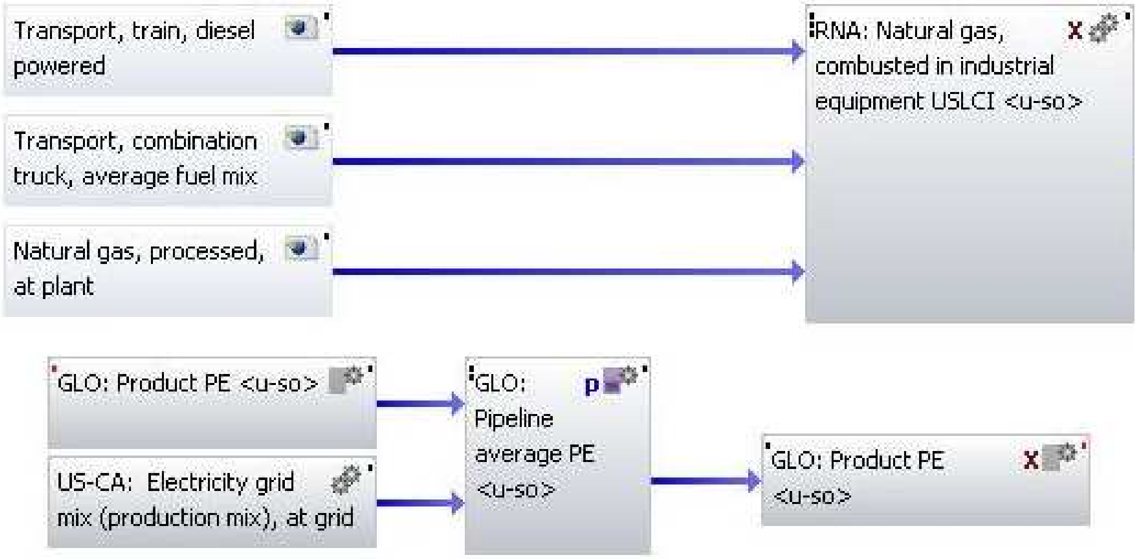
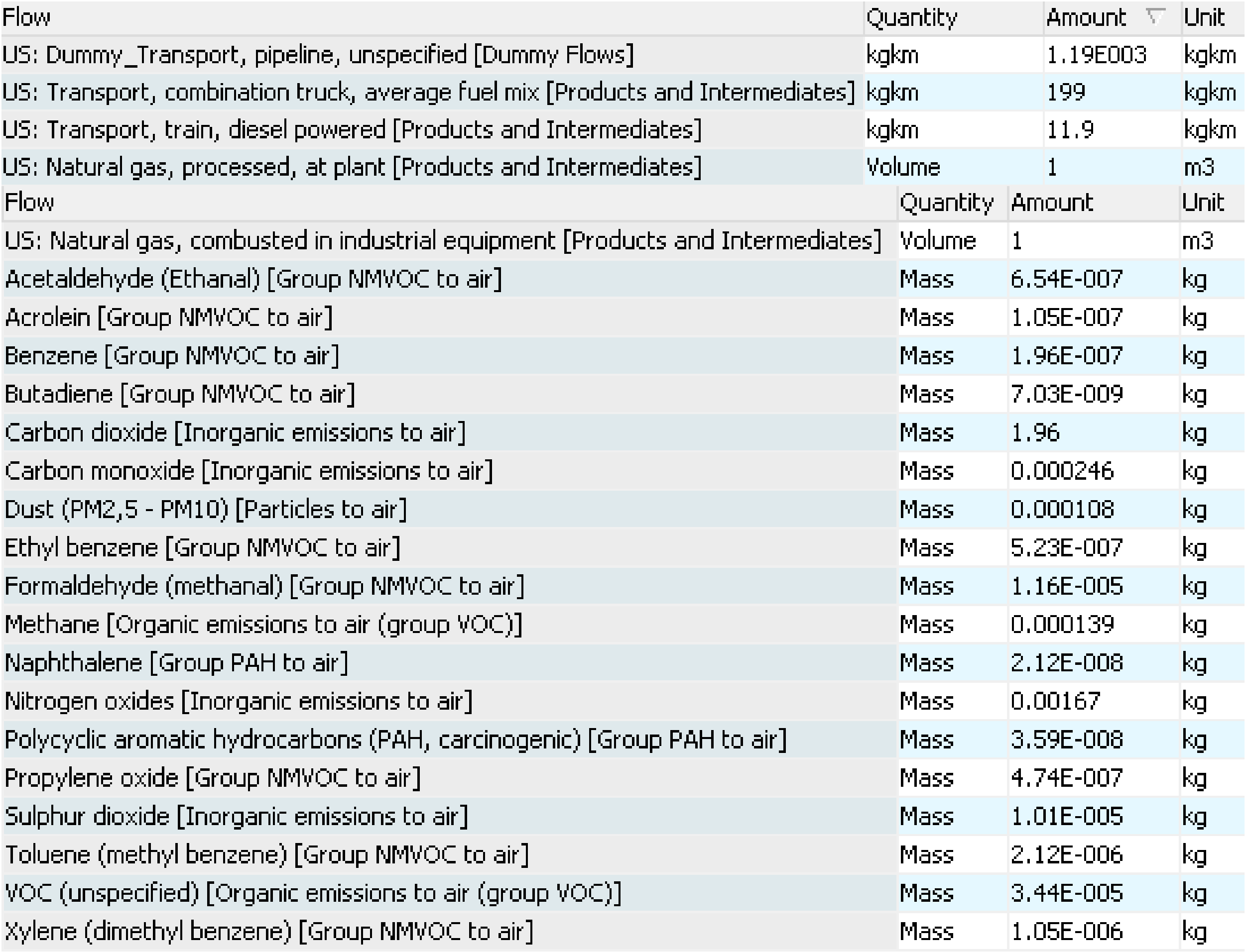


Figure 3.8: Natural gas combusted in industrial equipment



Flow	Quantity	Amount ▽	Unit
US: Dummy_Transport, pipeline, unspecified [Dummy Flows]	kgkm	1.19E003	kgkm
US: Transport, combination truck, average fuel mix [Products and Intermediates]	kgkm	199	kgkm
US: Transport, train, diesel powered [Products and Intermediates]	kgkm	11.9	kgkm
US: Natural gas, processed, at plant [Products and Intermediates]	Volume	1	m3

Flow	Quantity	Amount	Unit
US: Natural gas, combusted in industrial equipment [Products and Intermediates]	Volume	1	m3
Acetaldehyde (Ethanal) [Group NMVOC to air]	Mass	6.54E-007	kg
Acrolein [Group NMVOC to air]	Mass	1.05E-007	kg
Benzene [Group NMVOC to air]	Mass	1.96E-007	kg
Butadiene [Group NMVOC to air]	Mass	7.03E-009	kg
Carbon dioxide [Inorganic emissions to air]	Mass	1.96	kg
Carbon monoxide [Inorganic emissions to air]	Mass	0.000246	kg
Dust (PM2,5 - PM10) [Particles to air]	Mass	0.000108	kg
Ethyl benzene [Group NMVOC to air]	Mass	5.23E-007	kg
Formaldehyde (methanal) [Group NMVOC to air]	Mass	1.16E-005	kg
Methane [Organic emissions to air (group VOC)]	Mass	0.000139	kg
Naphthalene [Group PAH to air]	Mass	2.12E-008	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	0.00167	kg
Polycyclic aromatic hydrocarbons (PAH, carcinogenic) [Group PAH to air]	Mass	3.59E-008	kg
Propylene oxide [Group NMVOC to air]	Mass	4.74E-007	kg
Sulphur dioxide [Inorganic emissions to air]	Mass	1.01E-005	kg
Toluene (methyl benzene) [Group NMVOC to air]	Mass	2.12E-006	kg
VOC (unspecified) [Organic emissions to air (group VOC)]	Mass	3.44E-005	kg
Xylene (dimethyl benzene) [Group NMVOC to air]	Mass	1.05E-006	kg

Figure 3.9: Inputs and outputs of the natural gas model.

3.6. Material Production Stage for Conventional Materials

3.6.1. Aggregate (Crushed)

The data shown in Table 10 in Marceau (2007) were used to model plant production of crushed aggregate production. That table is reproduced here as Table 3.10(a.) Figure 3.10 shows the model developed in *GaBi* to calculate the LCI and the LCIA results, and Figure 3.11 shows the inputs and outputs of the model.

Before the data from Marceau (2007) could be modeled with GaBi, it was necessary to convert from the unit *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 3.10(b) (note that modeling of electricity did not require this conversion.)

Table 3.10. (a) Aggregate—crushed production in plant, reproduction of table 10 of Marceau (2007)

Item	Energy/ton Aggregate	Btu/ton	kJ/metric ton
Coal, ton	2.75E-05	577	670
Distillate (light) grade nos. 1, 2, 4, & light diesel fuel, gallon	9.32E-02	12,920	15,030

Item	**Energy/ton Aggregate**	**Btu/ton**	**kJ/metric ton**
Residual (heavy) grade nos. 5 & 6 and heavy diesel fuel, gallon	1.45E-02	2,167	2,520
Natural gas, 1000 cu ft	3.45E-03	3,543	4,120
Gasoline used as fuel, gallon	9.39E-03	1,174	1,370
Electricity, 1000 kWh	2.96E-03	10,088	11,730
Total	**—**	**30,470**	**35,440**

Table 3.10. (b) Conversion factors for items in Table 3.10 and Table 3.11 to adjust their units for modeling in *GaBi*

Energy Source	**kJ/ton of Agg***	**Energy Content**	**Unit**	**Value used in *GaBi***	**Unit**
Coal	670	4.10E-05	kJ/kg	2.75E-05	kg/kg of agg*
Distillate (light) grades 1, 2, 4, & light diesel fuel	15030	2.65E-08	kJ/m^3	3.98E-07	m^3/kg of agg
Residual (heavy) grades 5, 6, & heavy diesel fuel	2520	2.40E-08	kJ/m^3	6.05E-08	m^3/kg of agg
Natural gas	4120	2.62E-05	kJ/m^3	1.08E-04	m^3/kg of agg
Gasoline used as fuel, gallon	1370	2.86E-08	kJ/m^3	3.92E-08	m^3/kg of agg

* Agg: aggregate

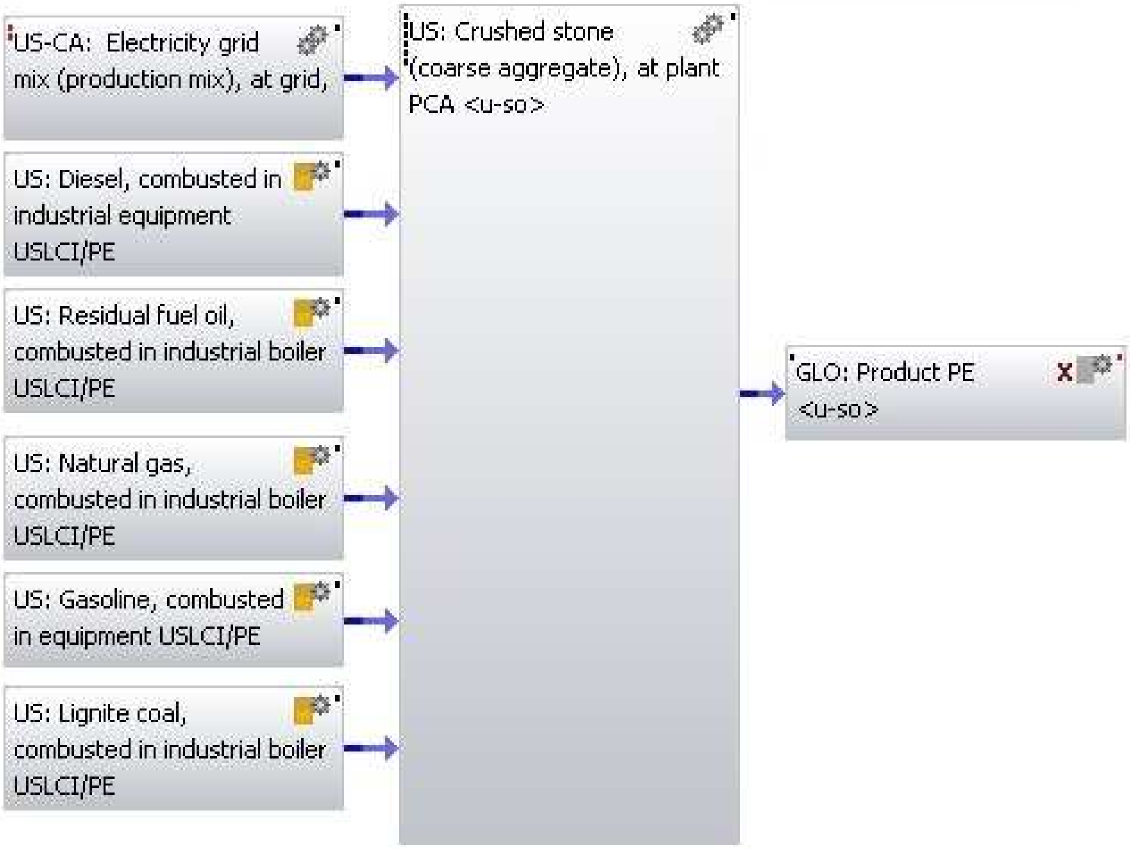
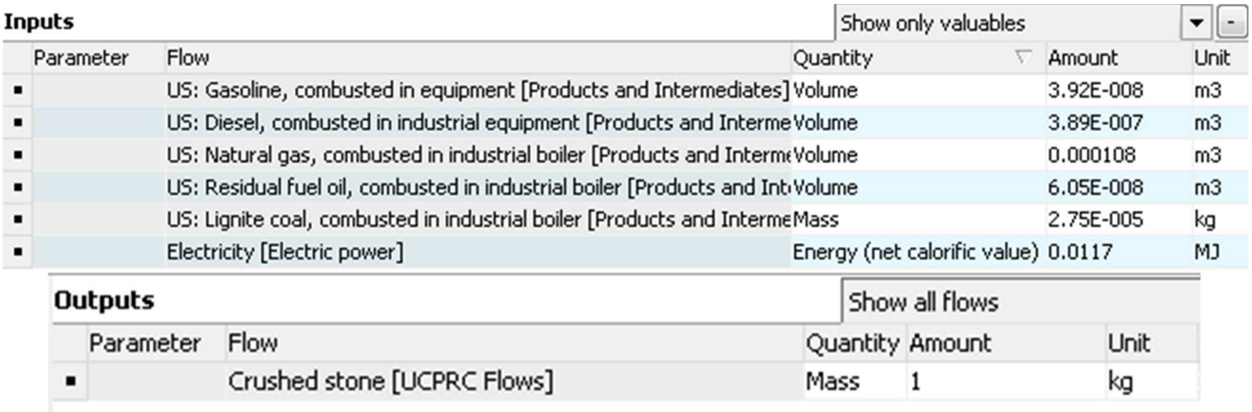


Figure 3.10: Model developed for crushed aggregate production.



	Parameter	Flow	Quantity	Amount	Unit
▪		US: Gasoline, combusted in equipment [Products and Intermediates]	Volume	3.92E-008	m3
▪		US: Diesel, combusted in industrial equipment [Products and Interme	Volume	3.89E-007	m3
▪		US: Natural gas, combusted in industrial boiler [Products and Interm	Volume	0.000108	m3
▪		US: Residual fuel oil, combusted in industrial boiler [Products and Int	Volume	6.05E-008	m3
▪		US: Lignite coal, combusted in industrial boiler [Products and Interme	Mass	2.75E-005	kg
▪		Electricity [Electric power]	Energy (net calorific value)	0.0117	MJ

	Parameter	Flow	Quantity	Amount	Unit
▪		Crushed stone [UCPRC Flows]	Mass	1	kg

Figure 3.11: Inputs and outputs of the crushed aggregate model.

3.6.2. Aggregate (Natural)

The data shown in Table 9 in Reference Marceau (2007) were used to model natural aggregate production in the plant. That table is reproduced here as Table 3.11. Figure 3.12 and Figure 3.13 show the model developed for natural aggregate and the model's inputs and outputs. Conversion of values from *kJ/ton of aggregate* to the values used in *GaBi* was done based on Table 3.10(b.)

Table 3.11. Aggregate—natural production in plant, reproduction of Table 9 of Marceau (2007)

Item	Energy/ton Aggregate	Btu/ton	kJ/metric ton
Coal, ton	5.62E-02	7,793	9,060
Distillate (light) grade nos. 1, 2, 4, & light diesel fuel, gallon	1.26E-02	1,888	2,200
Residual (heavy) grade nos. 5 & 6 and heavy diesel fuel, gallon	1.33E-03	1,370	1,590
Natural gas, 1000 cu ft	5.43E-03	679	790
Gasoline used as fuel, gallon	2.41E-03	8,210	9,550
Electricity, 1000 kWh	—	19,940	23,190
Total	**5.62E-02**	**7,793**	**9,060**

3.6.3. Bitumen

The model for bitumen in *GaBi* was based on the USLCI database developed by National Renewable Energy Lab (NREL webpage on USLCI) which represents an average refinery in the US. In this study, the electricity process in the *GaBi* model was modified to reflect the electricity grid mix in California. Figure 3.14 and Figure 3.15 show the models and the relevant inputs and outputs. A mass-based approach was used for the allocation of refinery plant impacts between the products, as shown in Table 3.6. This allocation approach was used because *GaBi* uses USLCI results that are mass-based, and it 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 be applied.

This study required the bitumen model to also be used as a sub model in several other models under development in *GaBi* by UCPRC, therefore, a decision was made to use mass-based allocations both for consistency and to aid in developing full LCIs. Because the FHWA framework for pavement LCA (Harvey et al., 2010) recommends reporting feedstock energy separately as this energy might be recovered in the future (if economically viable), the feedstock energy of bitumen (for bitumen and bitumen emulsion) was assumed to be 40.2 MJ per kg of residual bitumen (IPCC, 2006.)

It should also be noted that all the LCIs in this chapter are *cradle to gate* (including extraction of raw materials from the ground (cradle), transporting the raw materials to plant, and all the processes conducted in the plant to get the final material ready to ship at the gate of plant.) This is particularly important for bitumen and materials using bitumen, such as bitumen emulsion, 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; that potential future carbon emission if the material might be burned in the future is not included in the LCIs reported in this chapter. The source of the crude oil used for producing asphalt and the processes undertaken at the source for extraction can also impact the final results. Yang et al. (2016) conducted a study to calculate environmental impacts of refinery products in five different U.S. regions, considering changes in the crude oil extraction processes and the allocation methodology used. Their study showed that regional differences in extraction process caused an average 15 percent difference in the impacts of the asphalt mixture.

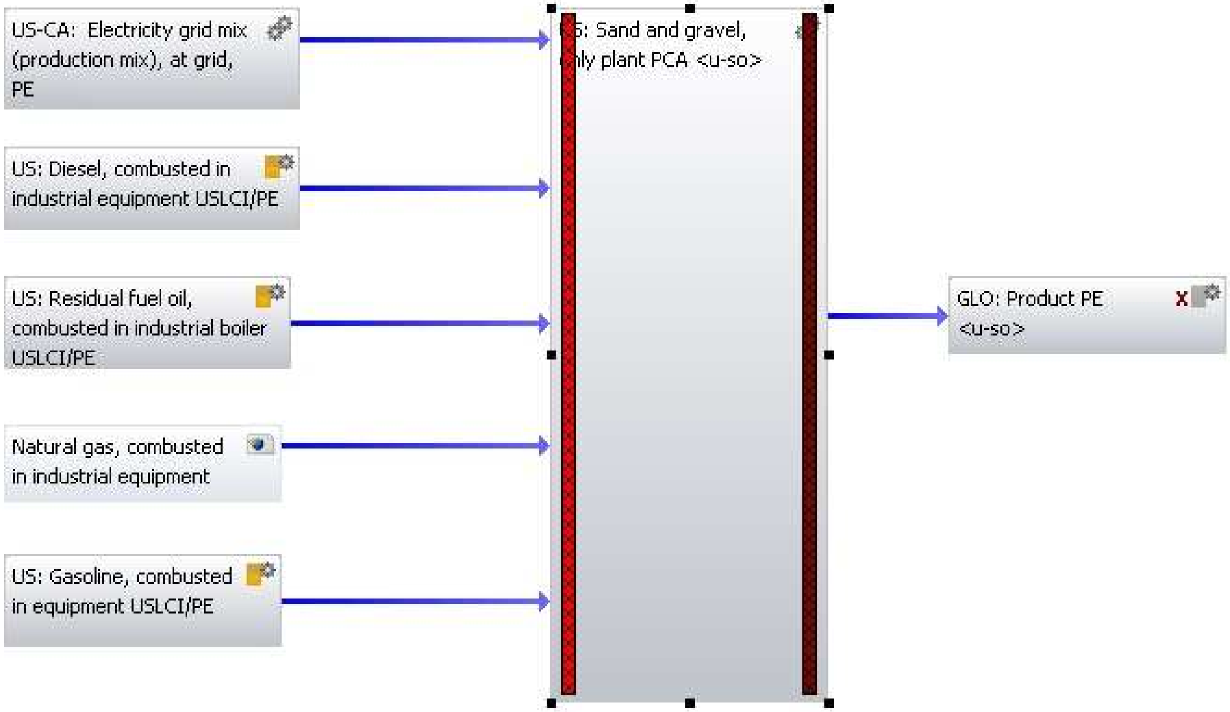
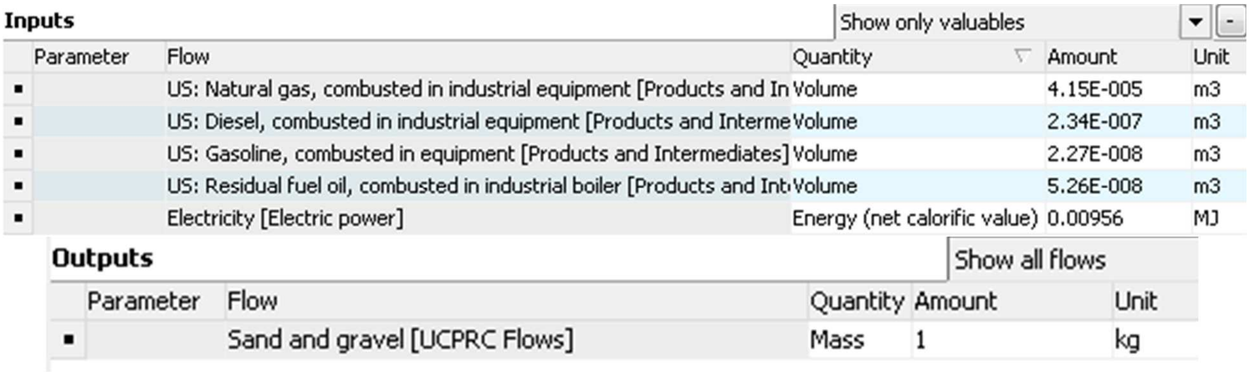


Figure 3.12: The *GaBi* model developed for natural aggregate.



Inputs — Show only valuables

	Parameter	Flow	Quantity	Amount	Unit
▪		US: Natural gas, combusted in industrial equipment [Products and In	Volume	4.15E-005	m3
▪		US: Diesel, combusted in industrial equipment [Products and Interme	Volume	2.34E-007	m3
▪		US: Gasoline, combusted in equipment [Products and Intermediates]	Volume	2.27E-008	m3
▪		US: Residual fuel oil, combusted in industrial boiler [Products and Int	Volume	5.26E-008	m3
▪		Electricity [Electric power]	Energy (net calorific value)	0.00956	MJ

Outputs — Show all flows

	Parameter	Flow	Quantity	Amount	Unit
▪		Sand and gravel [UCPRC Flows]	Mass	1	kg

Figure 3.13: Inputs and outputs of the natural aggregate model.

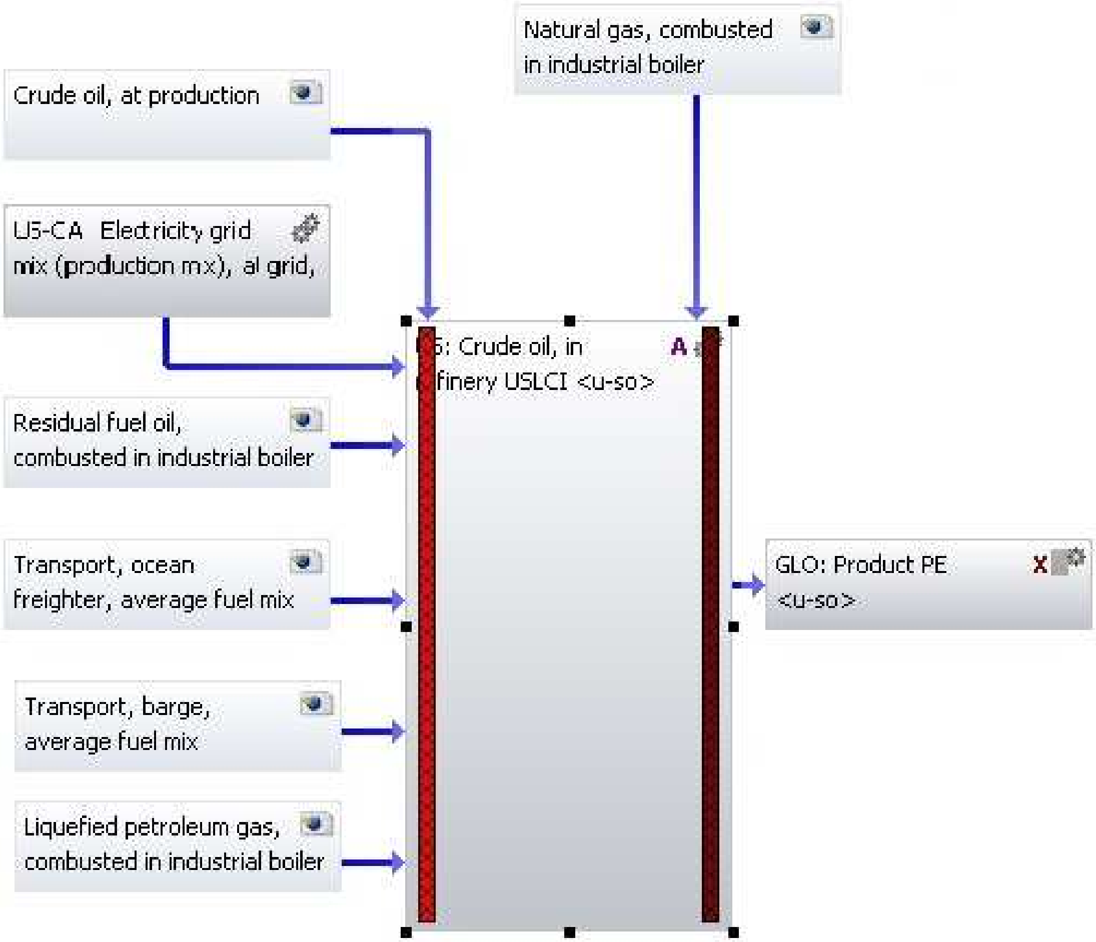
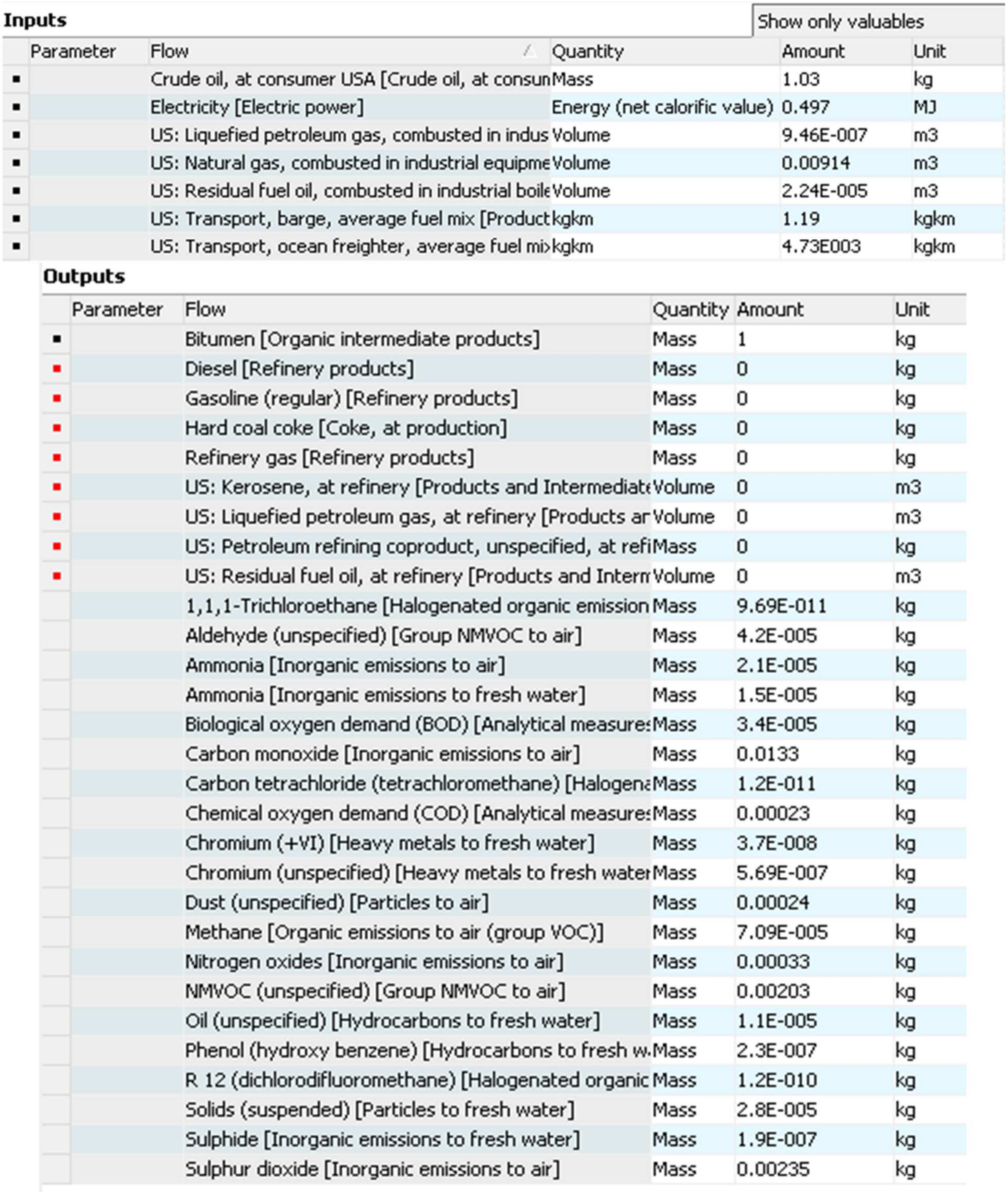


Figure 3.14: *GaBi* model developed for bitumen.



Inputs

	Parameter	Flow	Quantity	Amount	Unit
■		Crude oil, at consumer USA [Crude oil, at consun	Mass	1.03	kg
■		Electricity [Electric power]	Energy (net calorific value)	0.497	MJ
■		US: Liquefied petroleum gas, combusted in indus	Volume	9.46E-007	m3
■		US: Natural gas, combusted in industrial equipme	Volume	0.00914	m3
■		US: Residual fuel oil, combusted in industrial boile	Volume	2.24E-005	m3
■		US: Transport, barge, average fuel mix [Product	kgkm	1.19	kgkm
■		US: Transport, ocean freighter, average fuel mi›	kgkm	4.73E003	kgkm

Outputs

	Parameter	Flow	Quantity	Amount	Unit
■		Bitumen [Organic intermediate products]	Mass	1	kg
🟥		Diesel [Refinery products]	Mass	0	kg
🟥		Gasoline (regular) [Refinery products]	Mass	0	kg
🟥		Hard coal coke [Coke, at production]	Mass	0	kg
🟥		Refinery gas [Refinery products]	Mass	0	kg
🟥		US: Kerosene, at refinery [Products and Intermediate	Volume	0	m3
🟥		US: Liquefied petroleum gas, at refinery [Products ar	Volume	0	m3
🟥		US: Petroleum refining coproduct, unspecified, at refi	Mass	0	kg
🟥		US: Residual fuel oil, at refinery [Products and Interr	Volume	0	m3
		1,1,1-Trichloroethane [Halogenated organic emission	Mass	9.69E-011	kg
		Aldehyde (unspecified) [Group NMVOC to air]	Mass	4.2E-005	kg
		Ammonia [Inorganic emissions to air]	Mass	2.1E-005	kg
		Ammonia [Inorganic emissions to fresh water]	Mass	1.5E-005	kg
		Biological oxygen demand (BOD) [Analytical measures	Mass	3.4E-005	kg
		Carbon monoxide [Inorganic emissions to air]	Mass	0.0133	kg
		Carbon tetrachloride (tetrachloromethane) [Halogena	Mass	1.2E-011	kg
		Chemical oxygen demand (COD) [Analytical measures	Mass	0.00023	kg
		Chromium (+VI) [Heavy metals to fresh water]	Mass	3.7E-008	kg
		Chromium (unspecified) [Heavy metals to fresh water	Mass	5.69E-007	kg
		Dust (unspecified) [Particles to air]	Mass	0.00024	kg
		Methane [Organic emissions to air (group VOC)]	Mass	7.09E-005	kg
		Nitrogen oxides [Inorganic emissions to air]	Mass	0.00033	kg
		NMVOC (unspecified) [Group NMVOC to air]	Mass	0.00203	kg
		Oil (unspecified) [Hydrocarbons to fresh water]	Mass	1.1E-005	kg
		Phenol (hydroxy benzene) [Hydrocarbons to fresh w.	Mass	2.3E-007	kg
		R 12 (dichlorodifluoromethane) [Halogenated organic	Mass	1.2E-010	kg
		Solids (suspended) [Particles to fresh water]	Mass	2.8E-005	kg
		Sulphide [Inorganic emissions to fresh water]	Mass	1.9E-007	kg
		Sulphur dioxide [Inorganic emissions to air]	Mass	0.00235	kg

Figure 3.15: Inputs and outputs of the bitumen model.

3.6.4. Bitumen Emulsion

LCI data for bitumen from Section 6.4 of the Eurobitume LCI report (Eurobitume, 2012), were used and are reproduced here as Table 3.12. Figure 3.22 and Figure 3.23 show the models developed and the inputs and outputs. The Eurobitume report was also used to determine the other flow numbers used in modeling the process in *GaBi* (Figure 3.23) as there were no other sources available at the time.

Table 3.12. Energy and material requirements for bitumen emulsion production in plant (one tonne of residual bitumen), data from section 6.4 of the Eurobitume report (Eurobitume, 2012)

Category	Item	Unit	Bitumen	Emulsifier	HCl	Hot Water	Emulsion Milling	Total
Raw Material	Bitumen at Refinery	kg	1.00E+3	1.10E+0	-	-	-	1.00E+3
Energy Resources	Natural Gas	kg	2.01E+1	2.20E-1	3.40E-1	8.00E-2	1.21E+0	2.19E+1
	Crude Oil	kg	4.09E+1	1.40E+0	4.00E-1	1.80E+0	4.00E-1	4.49E+1
	Coal	kg	1.03E+0	3.00E-1	6.70E-1	7.00E-2	3.25E+0	5.32E+0
	Uranium	kg	6.00E-5	2.00E-5	4.00E-5	0.00E+0	2.30E-4	4.00E-4

3.6.5. Cement

Two methods for producing cement were considered: precalciner and preheater. The general model developed includes both methods and allows the user to define what percentage of the final product is made with each method (this enables a user to closely represent average local conditions.) The LCI model for portland cement was developed based on the PCA report (Marceau, 2007), with the electricity component modified to represent the California grid mix. Although the process CO_2 was overestimated in the USLCI database due to double counting the emissions from energy production, this was corrected by changing the process CO_2 using Xu et al., (2016.)

The general model is pictured in Figure 3.16 and Figure 3.17 shows the inputs and outputs of the model. Figure 3.18 and Figure 3.19 show the details of the models for each of the production methods, precalciner and preheater. In developing this LCI it was assumed that all the cement used in California is produced in-state. Based on correspondence with the California Nevada Cement Association, it is likely that at least 95 percent of the cement used in California is produced in precalciner plants. Therefore, for the results reported in this chapter, it was assumed that 100 percent of the cement was produced by precalciner plants, as shown in Figure 3.17.

There are different types of cement used for various applications. The main types included in the UCPRC database are:

- portland cement type I/II, used for most pavement construction where high early strength in overnight closures is not needed
- portland cement type III (rapid setting for slab replacement)
- calcium sulfo-aluminate cement (CSA, rapid setting for slab replacement)
- portland cement with supplementary cementitious materials (SCM), made of type I/II and SCMs such as fly ash and blast furnace slag.

For many materials, fuel and electricity consumption are the major two sources of CO_2 emissions during the material production stage. However, for cement production, calcination of limestone at the pyroprocessing step is a nearly equal source of CO_2 emissions to fuel and electricity consumption. Limestone and other raw feeds undergo a series of mineral phase transitions when heated, and calcium carbonate ($CaCO_3$, the primary mineral compound in limestone) is converted to calcium oxide (CaO) by driving CO_2 out of the compound in a process called calcination.

The amount of CO_2 released during the pyroprocessing step can also be calculated based on the composition of the mineral phases of the clinker. The composition of the mineral phases of a clinker differ for every product. Portland cement (PC) and CSA cement have different mineral phase compositions, and this chapter uses numbers from Quillin (2007) which are shown in Table 3.13. The main components of portland cement are alite and belite and the main components of CSA cement are belite and calcium sulfo-aluminate. The amount of CO_2 released from calcination during the formation of 1 kg of each mineral phase is also listed in Table 3.13, showing 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.

Table 3.13. Mineral stage composition of portland cement (type I/II & III) and Calcium Sulfo-aluminate cement

Mineral Stages of Clinker	Alite	Belite	Aluminate	Ferrite	Calcium Sulfo-aluminate
Portland cement	64%	16.50%	3.50%	9.50%	0%
CSA cement	0%	38%	0%	8%	35%
CO2 release	579	512	489	362	216

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

The mineral phase compositions of Type I and Type III portland cement are similar, however the Type III PC is more finely ground. While Type I is ground to a surface area of 330 to 380 m^2/kg, Type III is ground to 400 to 450 m^2/kg. It was assumed that the difference between Type I and Type III only exists in the surface area, and therefore the only differences in the LCI are from the grinding process. The grinding is usually performed in a ball mill, which is operated by electricity. The surface areas of Type I and Type III were assumed to be 330 m^2/kg and 400 m^2/kg, respectively, and it was assumed that electricity consumption is linearly related to the surface area. For CSA cement, both heating processes in the plant and the CO_2 released were corrected based on data provided in the previous paragraph.

For portland cement with SCM, LCI for portland cement with 19 percent slag and 50 percent slag were 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 are based on the technology and manufacturing processes in Switzerland and were developed in 1997. The summary table at the end of this chapter includes the LCI and LCIAs of 1 kg of portland cement produced using the precalciner method (as an example.)

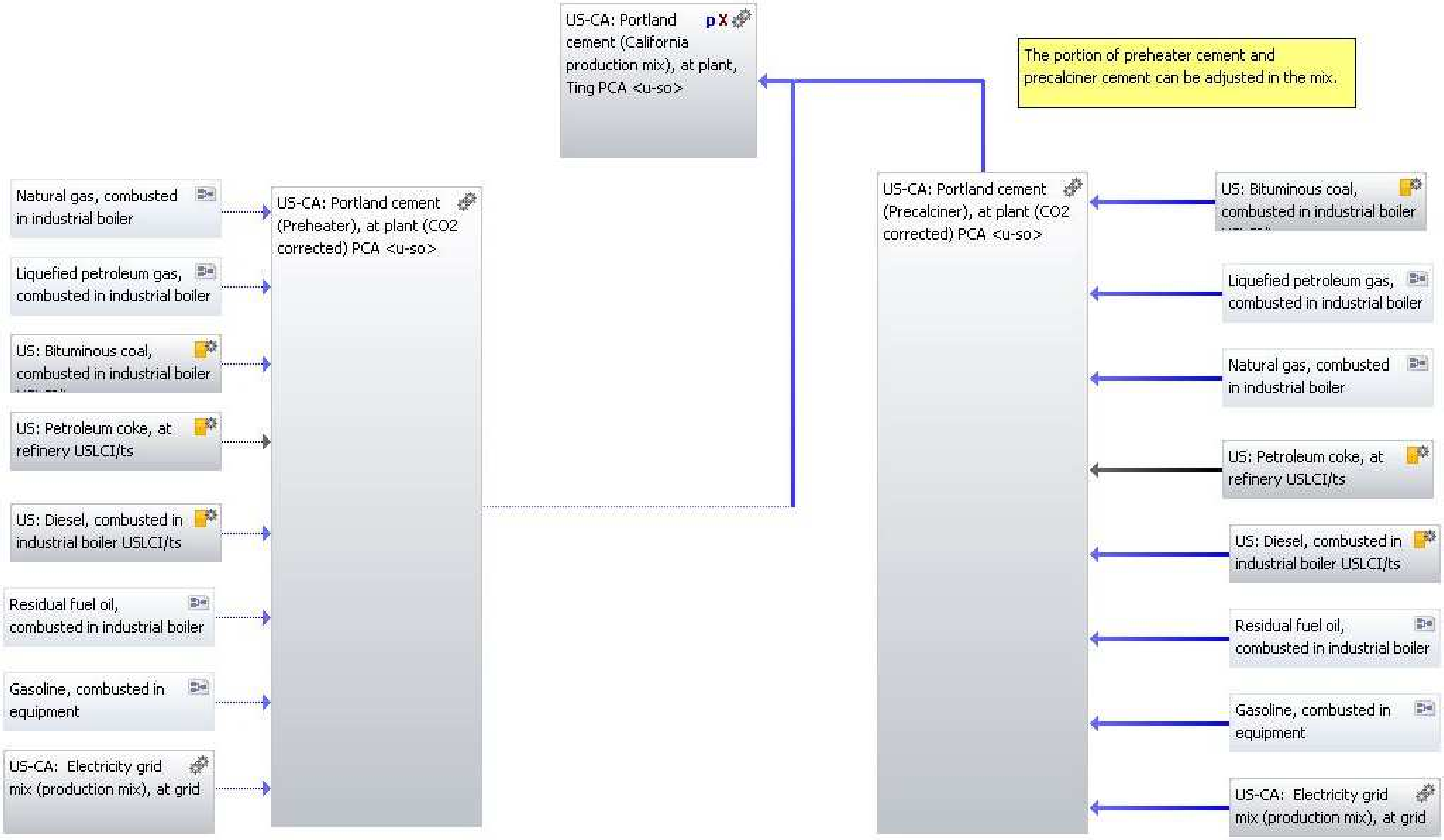
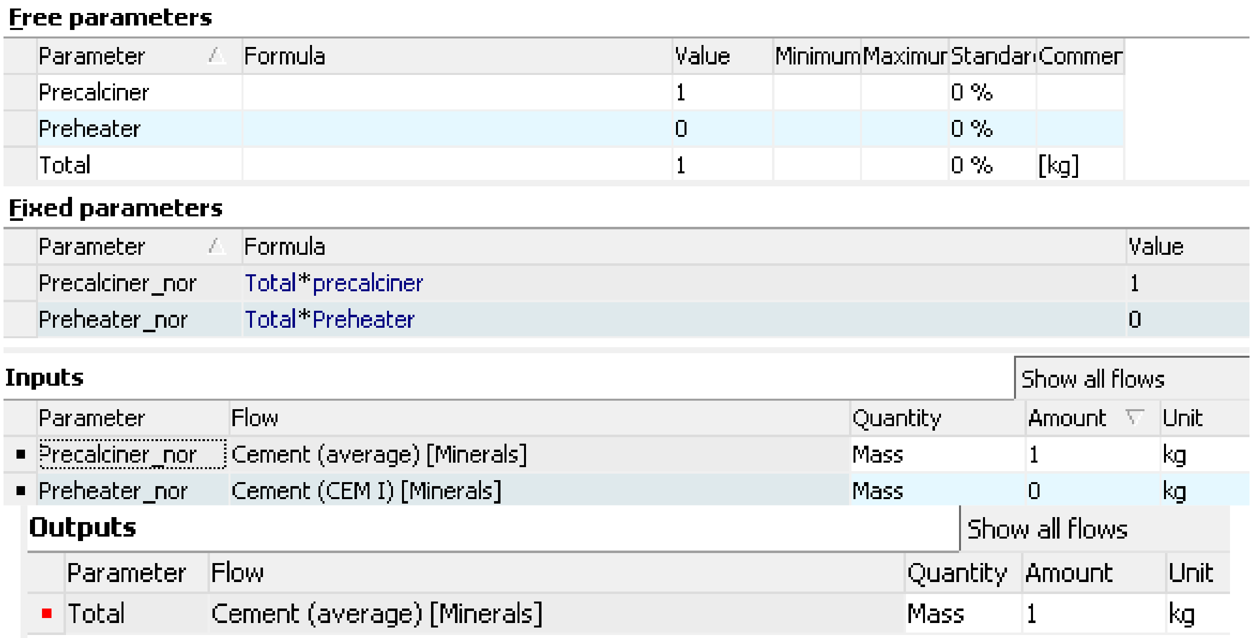


Figure 3.16: The model developed for cement (general.)



Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Precalciner		1			0 %	
Preheater		0			0 %	
Total		1			0 %	[kg]

Fixed parameters

Parameter	Formula	Value
Precalciner_nor	Total*precalciner	1
Preheater_nor	Total*Preheater	0

Inputs

Show all flows

	Parameter	Flow	Quantity	Amount	Unit
■	Precalciner_nor	Cement (average) [Minerals]	Mass	1	kg
■	Preheater_nor	Cement (CEM I) [Minerals]	Mass	0	kg

Outputs

Show all flows

	Parameter	Flow	Quantity	Amount	Unit
■	Total	Cement (average) [Minerals]	Mass	1	kg

Figure 3.17: Inputs and outputs of the general model for cement that can be modified by a user.

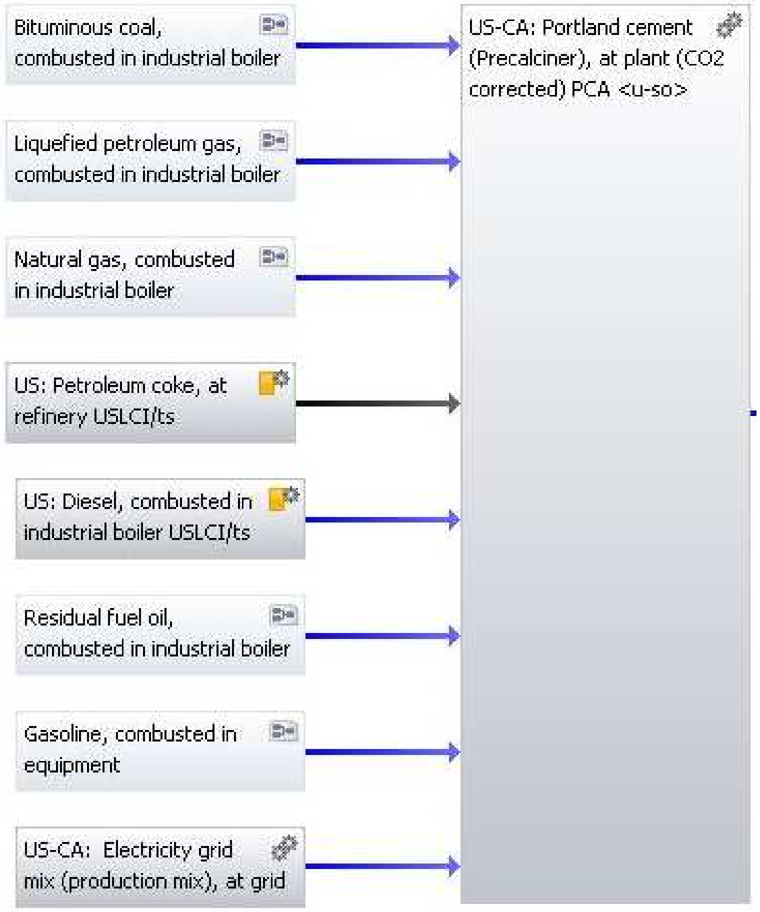


Figure 3.18: The model developed for cement production (precalciner method + CA electricity mix.)

Flow	Quantity	Amount	Unit
Electricity [Electric power]	Energy (net calo	0.515	MJ
US: Bituminous coal, combusted in industrial boiler [Products	Mass	0.101	kg
Hard coal coke [Coke, at production]	Mass	0.0134	kg
US: Natural gas, combusted in industrial boiler [Products anc	Volume	0.00725	m3
US: Dummy_Waste, miscellaneous, combusted in industrial b	Mass	0.0037	kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.00137	kg
Water [Water]	Mass	0.000841	kg
Gypsum (natural gypsum) [Non renewable resources]	Mass	6.15E-005	kg
Clay [Non renewable resources]	Mass	5.97E-005	kg
Shale [Non renewable resources]	Mass	5.22E-005	kg
Sand [Non renewable resources]	Mass	4.05E-005	kg
US: Dummy_Disposal, cement kiln dust, in residual material la	Mass	3.73E-005	kg
Raw material, unspecified [Material resources]	Mass	2.64E-005	kg
US: Dummy_Slag, at blast furnace [Dummy Flows]	Mass	1.98E-005	kg
Iron ore (56,86%) [Non renewable resources]	Mass	1.35E-005	kg
US: Dummy_Fly ash, unspecified origin [Dummy Flows]	Mass	1.35E-005	kg
US: Dummy_Bottom ash, unspecified origin [Dummy Flows]	Mass	1.01E-005	kg
US: Dummy_Recycling, cement kiln dust [Dummy Flows]	Mass	9.65E-006	kg
US: Dummy_Waste, solvents, combusted in industrial boiler [	Mass	8.81E-006	kg
US: Dummy_Foundry sand, at mine [Dummy Flows]	Mass	3.82E-006	kg
US: Dummy_Waste, tire derived, combusted in industrial boil	Mass	3.37E-006	kg
US: Diesel, combusted in industrial boiler [Products and Inter	Volume	1.36E-006	m3
Slate [Non renewable resources]	Mass	1.13E-006	kg
US: Dummy_Waste, other solid, combusted in industrial boile	Mass	9.34E-007	kg
US: Dummy_Cement bags, at plant [Dummy Flows]	Mass	6.8E-007	kg
US: Dummy_Refractory material, unspecified, at plant [Dumi	Mass	6.47E-007	kg
US: Dummy_Grinding aids, at plant [Dummy Flows]	Mass	3.6E-007	kg
US: Dummy_Explosives, at plant [Dummy Flows]	Mass	2.95E-007	kg
US: Dummy_Grinding media, at plant [Dummy Flows]	Mass	1.4E-007	kg
US: Dummy_Oil and grease, at plant [Dummy Flows]	Mass	1.3E-007	kg
US: Gasoline, combusted in equipment [Products and Interm	Volume	9.7E-008	m3
US: Residual fuel oil, combusted in industrial boiler [Products	Volume	6.24E-008	m3
US: Dummy_Chains, at plant [Dummy Flows]	Mass	2.01E-008	kg
US: Dummy_Filter bags, at plant [Dummy Flows]	Mass	1.92E-008	kg
US: Liquefied petroleum gas, combusted in industrial boiler [F	Volume	1.48E-008	m3
US: Dummy_Middle distillates, combusted in industrial boiler [	Volume	1.07E-009	m3
US: Dummy_Waste, oil, combusted in industrial boiler [Dumm	Volume	4.87E-010	m3

Flow	Quantity	Amount	Unit
Carbon dioxide [Inorganic emissions to air]	Mass	0.48	kg
Carbon monoxide [Inorganic emissions to air]	Mass	0.00184	kg
Cement (average) [Minerals]	Mass	1	kg
Methane [Organic emissions to air (group VOC)]	Mass	5.25E-005	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	0.0021	kg
NMVOC (unspecified) [Group NMVOC to air]	Mass	6.48E-005	kg
Sulphur dioxide [Inorganic emissions to air]	Mass	0.000541	kg
Ammonia [Inorganic emissions to air]	Mass	4.76E-006	kg
Dioxins (unspec.) [Halogenated organic emissions to air]	Mass	6.7E-014	kg
Dust (PM10) [Particles to air]	Mass	0.000299	kg
Hydrochloric acid (100%) [Inorganic intermediate products]	Mass	6.5E-005	kg
Mercury [Heavy metals to air]	Mass	6.94E-008	kg

Figure 3.19: Inputs and outputs of the precalciner method for production of portland cement.

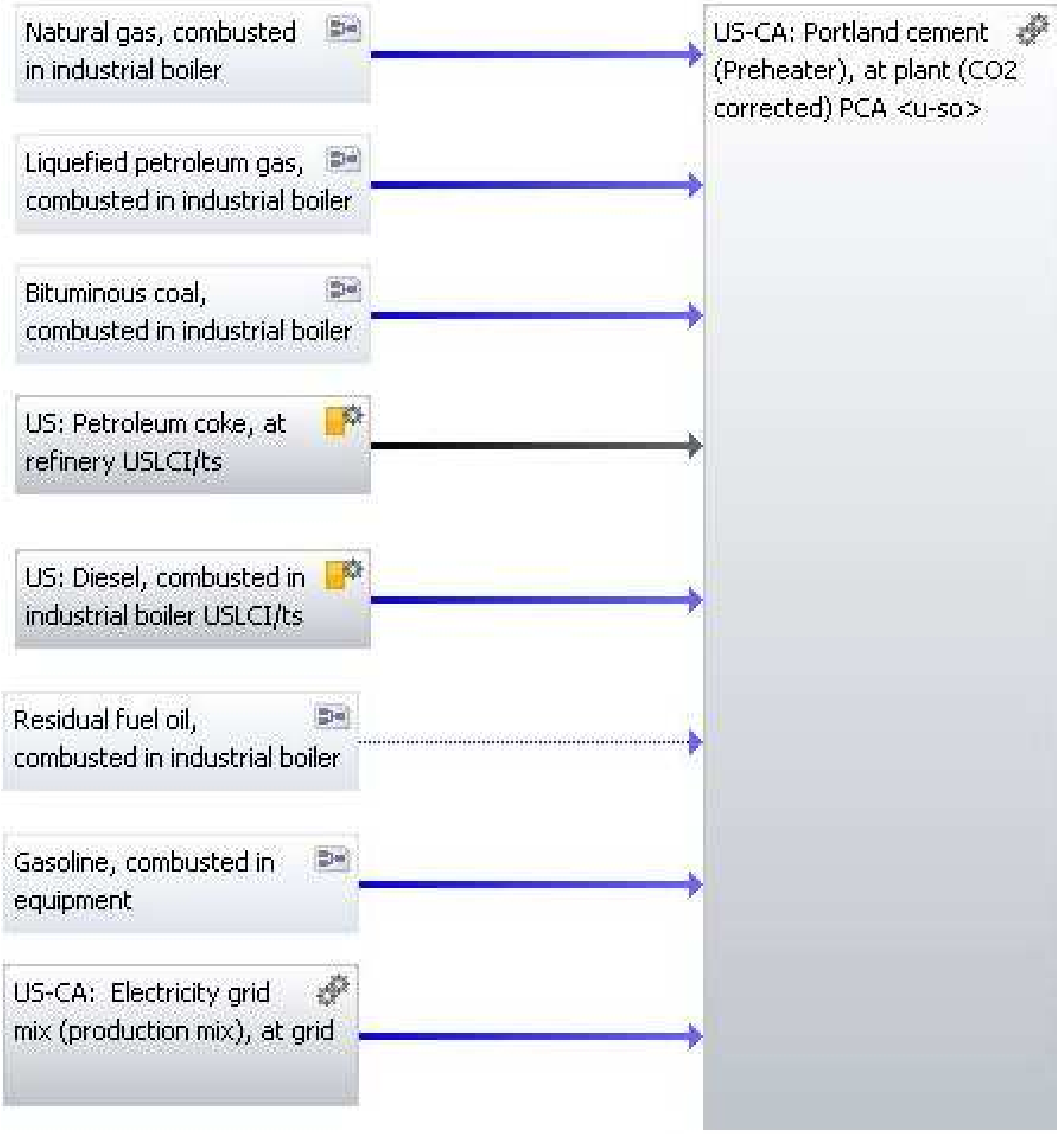
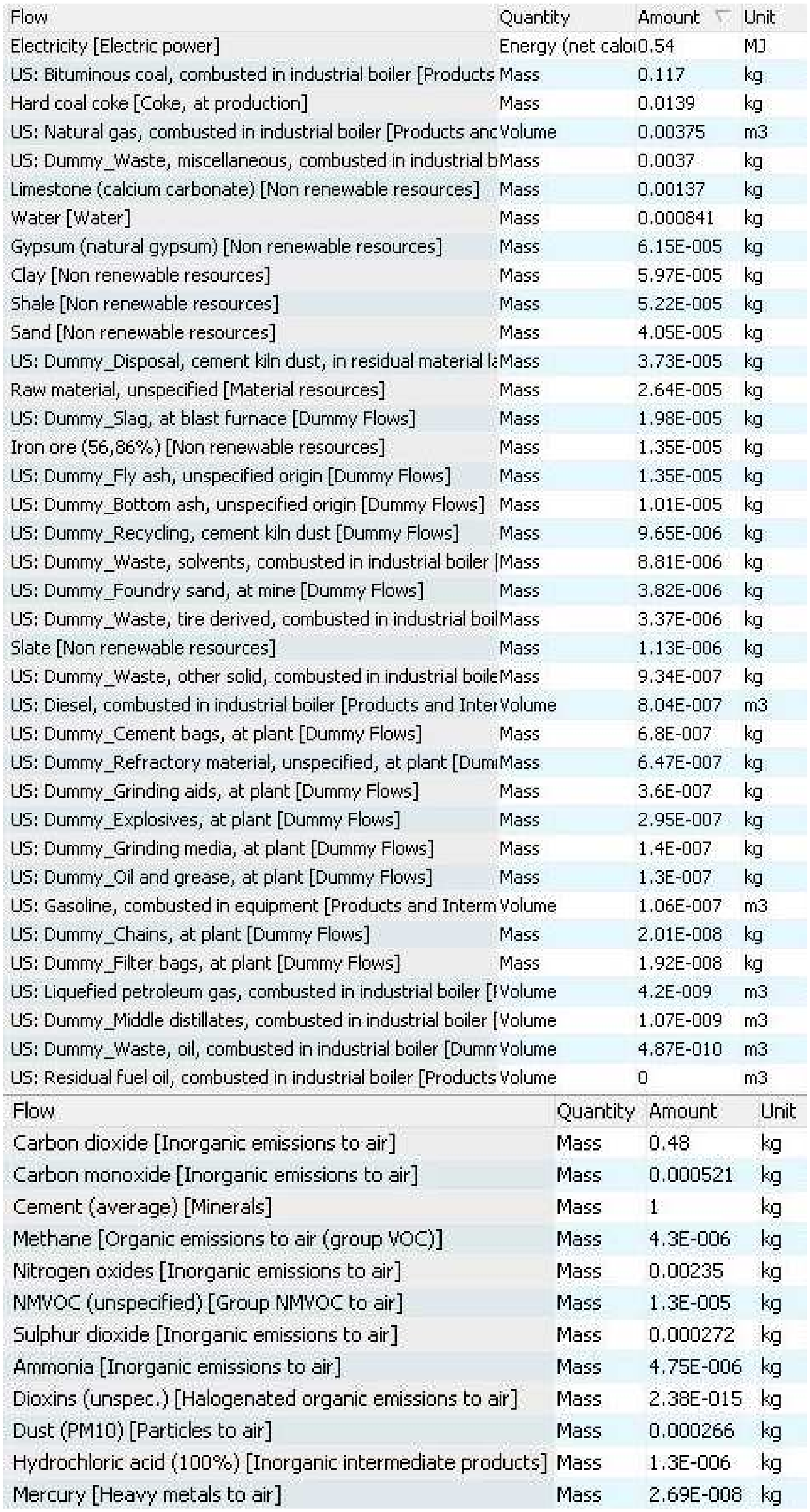


Figure 3.20: The model for cement production (preheater method + CA electricity mix.)



Flow	Quantity	Amount	Unit
Electricity [Electric power]	Energy (net calo	0.54	MJ
US: Bituminous coal, combusted in industrial boiler [Products	Mass	0.117	kg
Hard coal coke [Coke, at production]	Mass	0.0139	kg
US: Natural gas, combusted in industrial boiler [Products anc	Volume	0.00375	m3
US: Dummy_Waste, miscellaneous, combusted in industrial b	Mass	0.0037	kg
Limestone (calcium carbonate) [Non renewable resources]	Mass	0.00137	kg
Water [Water]	Mass	0.000841	kg
Gypsum (natural gypsum) [Non renewable resources]	Mass	6.15E-005	kg
Clay [Non renewable resources]	Mass	5.97E-005	kg
Shale [Non renewable resources]	Mass	5.22E-005	kg
Sand [Non renewable resources]	Mass	4.05E-005	kg
US: Dummy_Disposal, cement kiln dust, in residual material la	Mass	3.73E-005	kg
Raw material, unspecified [Material resources]	Mass	2.64E-005	kg
US: Dummy_Slag, at blast furnace [Dummy Flows]	Mass	1.98E-005	kg
Iron ore (56,86%) [Non renewable resources]	Mass	1.35E-005	kg
US: Dummy_Fly ash, unspecified origin [Dummy Flows]	Mass	1.35E-005	kg
US: Dummy_Bottom ash, unspecified origin [Dummy Flows]	Mass	1.01E-005	kg
US: Dummy_Recycling, cement kiln dust [Dummy Flows]	Mass	9.65E-006	kg
US: Dummy_Waste, solvents, combusted in industrial boiler		Mass	8.81E-006	kg
US: Dummy_Foundry sand, at mine [Dummy Flows]	Mass	3.82E-006	kg
US: Dummy_Waste, tire derived, combusted in industrial boil	Mass	3.37E-006	kg
Slate [Non renewable resources]	Mass	1.13E-006	kg
US: Dummy_Waste, other solid, combusted in industrial boile	Mass	9.34E-007	kg
US: Diesel, combusted in industrial boiler [Products and Inte	Volume	8.04E-007	m3
US: Dummy_Cement bags, at plant [Dummy Flows]	Mass	6.8E-007	kg
US: Dummy_Refractory material, unspecified, at plant [Dum	Mass	6.47E-007	kg
US: Dummy_Grinding aids, at plant [Dummy Flows]	Mass	3.6E-007	kg
US: Dummy_Explosives, at plant [Dummy Flows]	Mass	2.95E-007	kg
US: Dummy_Grinding media, at plant [Dummy Flows]	Mass	1.4E-007	kg
US: Dummy_Oil and grease, at plant [Dummy Flows]	Mass	1.3E-007	kg
US: Gasoline, combusted in equipment [Products and Interm	Volume	1.06E-007	m3
US: Dummy_Chains, at plant [Dummy Flows]	Mass	2.01E-008	kg
US: Dummy_Filter bags, at plant [Dummy Flows]	Mass	1.92E-008	kg
US: Liquefied petroleum gas, combusted in industrial boiler [	Volume	4.2E-009	m3
US: Dummy_Middle distillates, combusted in industrial boiler [	Volume	1.07E-009	m3
US: Dummy_Waste, oil, combusted in industrial boiler [Dumm	Volume	4.87E-010	m3
US: Residual fuel oil, combusted in industrial boiler [Products	Volume	0	m3

Flow	Quantity	Amount	Unit
Carbon dioxide [Inorganic emissions to air]	Mass	0.48	kg
Carbon monoxide [Inorganic emissions to air]	Mass	0.000521	kg
Cement (average) [Minerals]	Mass	1	kg
Methane [Organic emissions to air (group VOC)]	Mass	4.3E-006	kg
Nitrogen oxides [Inorganic emissions to air]	Mass	0.00235	kg
NMVOC (unspecified) [Group NMVOC to air]	Mass	1.3E-005	kg
Sulphur dioxide [Inorganic emissions to air]	Mass	0.000272	kg
Ammonia [Inorganic emissions to air]	Mass	4.75E-006	kg
Dioxins (unspec.) [Halogenated organic emissions to air]	Mass	2.38E-015	kg
Dust (PM10) [Particles to air]	Mass	0.000266	kg
Hydrochloric acid (100%) [Inorganic intermediate products]	Mass	1.3E-006	kg
Mercury [Heavy metals to air]	Mass	2.69E-008	kg

Figure 3.21: Inputs and outputs of the preheater method for production of portland cement.

3.6.6. *Cement Admixtures*

Cement admixtures are added to improve the constructability or performance of portland cement concrete. The following admixtures were taken directly from *GaBi:* accelerator, air entraining, plasticizer, retarder, and superplasticizer. Refer to the Supplementary Data for more information.

3.6.7. *Crumb Rubber Modifier*

A new GaBi-based model for crumb rubber modifier (CRM) was developed based on Reference. The model is presented in Figure 3.24, and its inputs and outputs are presented in Figure 3.26, Figure 3.27, and Figure 3.28. The latter three figures show the inputs and outputs of each of the model's main processes: crushing, grinding, and pulverization (Corti and Lombardi, 2004.) The cut-off method was used as the allocation method for crumb rubber modifier, with all the impacts of producing and using the initial material, the tire, assumed to be allocated to the upstream processes and the recycling process impacts to produce CRM were assumed to be allocated to the CRM (see Table 3.6.)

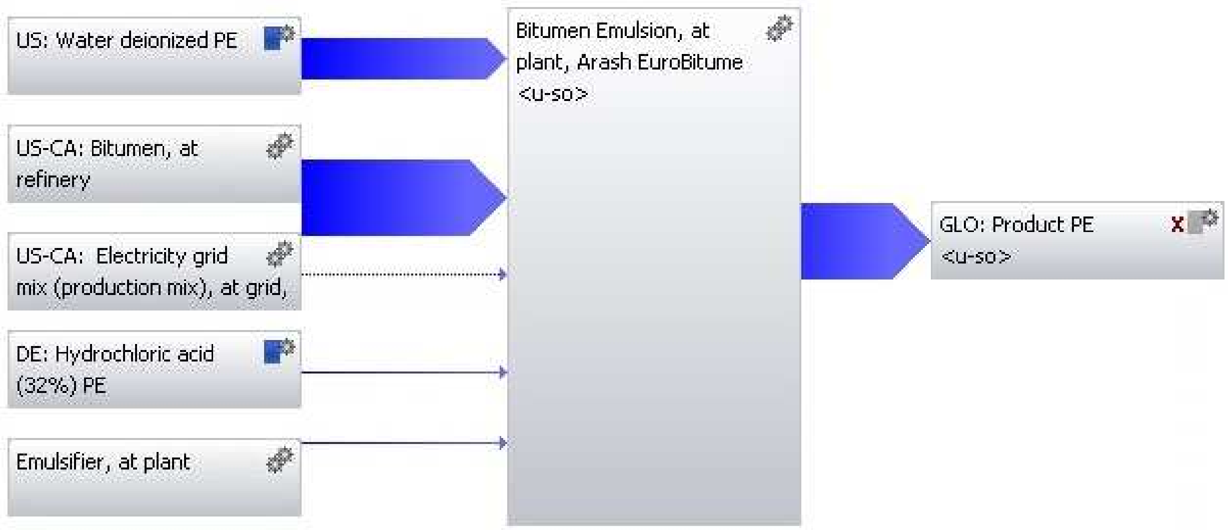
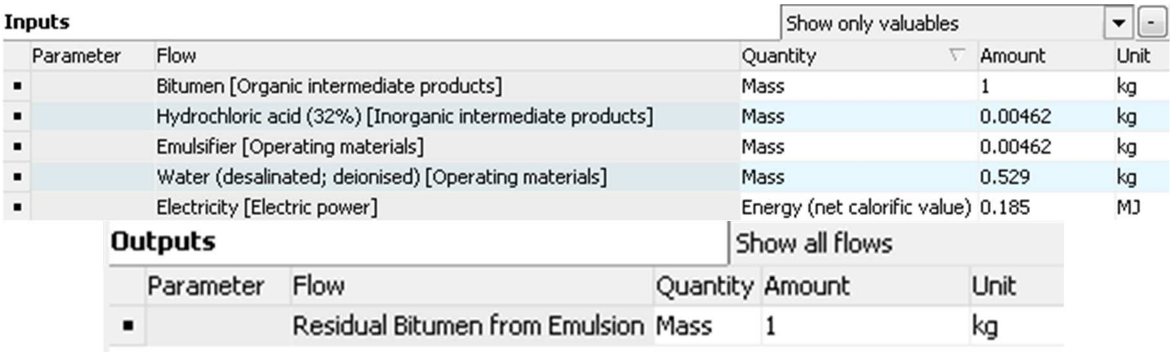


Figure 3.22: The model developed for bitumen emulsion.



Inputs

	Parameter	Flow	Quantity	Amount	Unit
▪		Bitumen [Organic intermediate products]	Mass	1	kg
▪		Hydrochloric acid (32%) [Inorganic intermediate products]	Mass	0.00462	kg
▪		Emulsifier [Operating materials]	Mass	0.00462	kg
▪		Water (desalinated; deionised) [Operating materials]	Mass	0.529	kg
▪		Electricity [Electric power]	Energy (net calorific value)	0.185	MJ

Outputs

	Parameter	Flow	Quantity	Amount	Unit
▪		Residual Bitumen from Emulsion	Mass	1	kg

Figure 3.23: Inputs and outputs of the bitumen emulsion model.

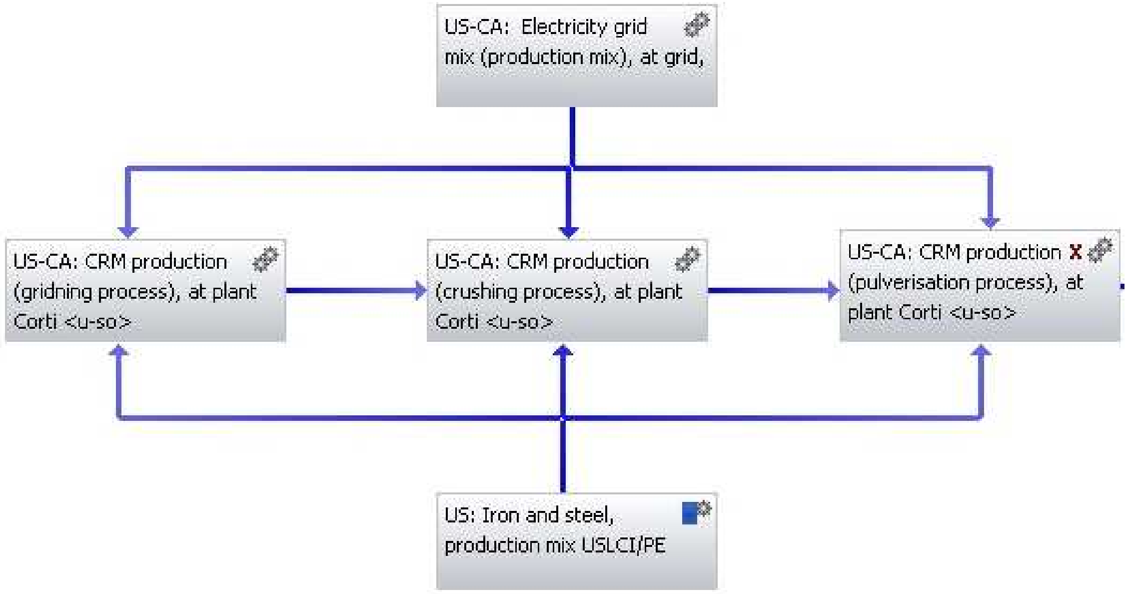
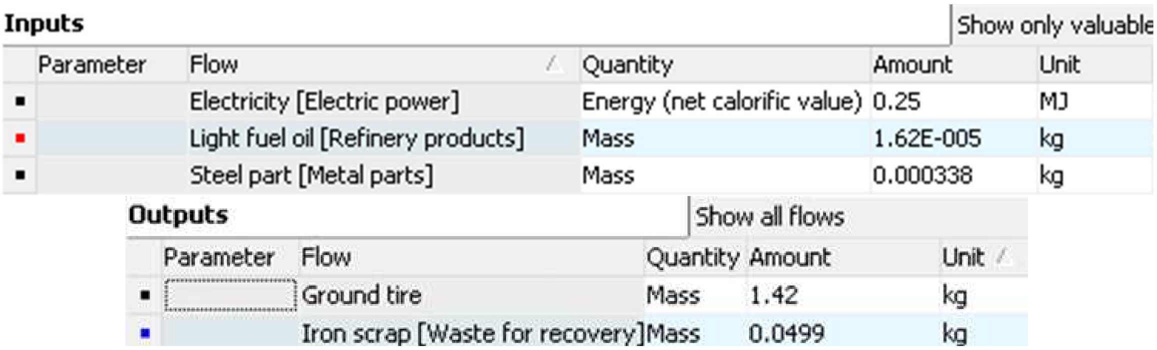


Figure 3.24: *GaBi* model developed for crumb rubber modifier (CRM.)

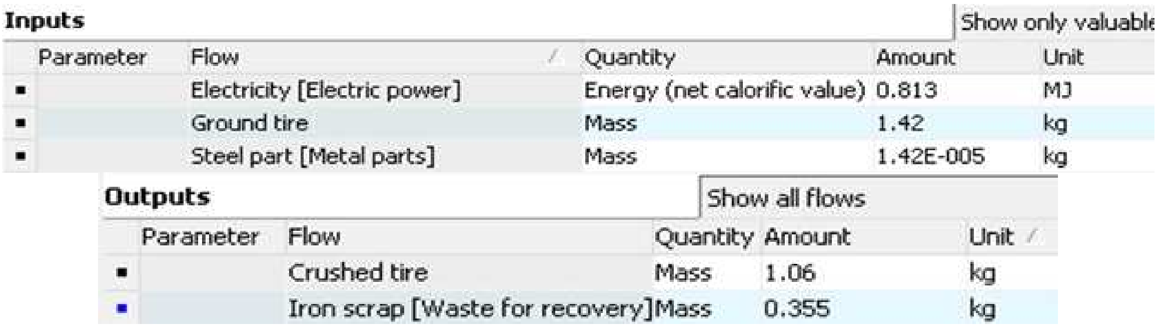

Inputs | Show only valuable

	Parameter	Flow	Quantity	Amount	Unit
▪		Electricity [Electric power]	Energy (net calorific value)	0.25	MJ
▪		Light fuel oil [Refinery products]	Mass	1.62E-005	kg
▪		Steel part [Metal parts]	Mass	0.000338	kg

Outputs | Show all flows

	Parameter	Flow	Quantity	Amount	Unit
▪		Ground tire	Mass	1.42	kg
▪		Iron scrap [Waste for recovery]	Mass	0.0499	kg

Figure 3.25: Inputs and outputs for the grinding process of the CRM model.


Inputs | Show only valuable

	Parameter	Flow	Quantity	Amount	Unit
▪		Electricity [Electric power]	Energy (net calorific value)	0.813	MJ
▪		Ground tire	Mass	1.42	kg
▪		Steel part [Metal parts]	Mass	1.42E-005	kg

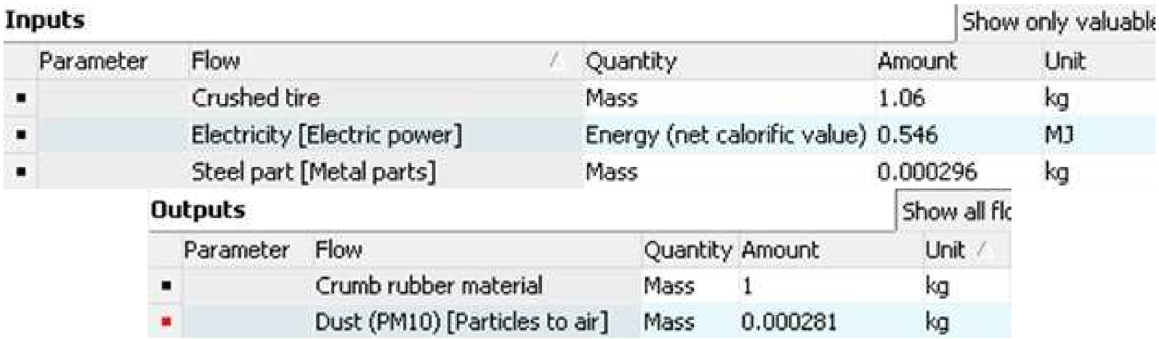
Outputs | Show all flows

	Parameter	Flow	Quantity	Amount	Unit
▪		Crushed tire	Mass	1.06	kg
▪		Iron scrap [Waste for recovery]	Mass	0.355	kg

Figure 3.26: Inputs and outputs for the crushing process of the CRM model.

3.6.8. Dowel and Tie Bar

Dowel and tie bar models were developed in *GaBi* using the software's predefined models for the production of 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 energy consumption of the steel and epoxy production. Figure 3.28 shows the model developed, and Figure 3.29 to Figure 3.33 show the inputs and outputs for each particular bar. The mass of dowel and tie bars was taken from ASTM A615/A615M (2012) and the epoxy specifications were taken from ASTM A775/A775M (2007.)



Inputs

	Parameter	Flow	Quantity	Amount	Unit
■		Crushed tire	Mass	1.06	kg
■		Electricity [Electric power]	Energy (net calorific value)	0.546	MJ
■		Steel part [Metal parts]	Mass	0.000296	kg

Outputs

	Parameter	Flow	Quantity	Amount	Unit
■		Crumb rubber material	Mass	1	kg
■		Dust (PM10) [Particles to air]	Mass	0.000281	kg

Figure 3.27: Inputs and outputs for the pulverization process of the CRM model.

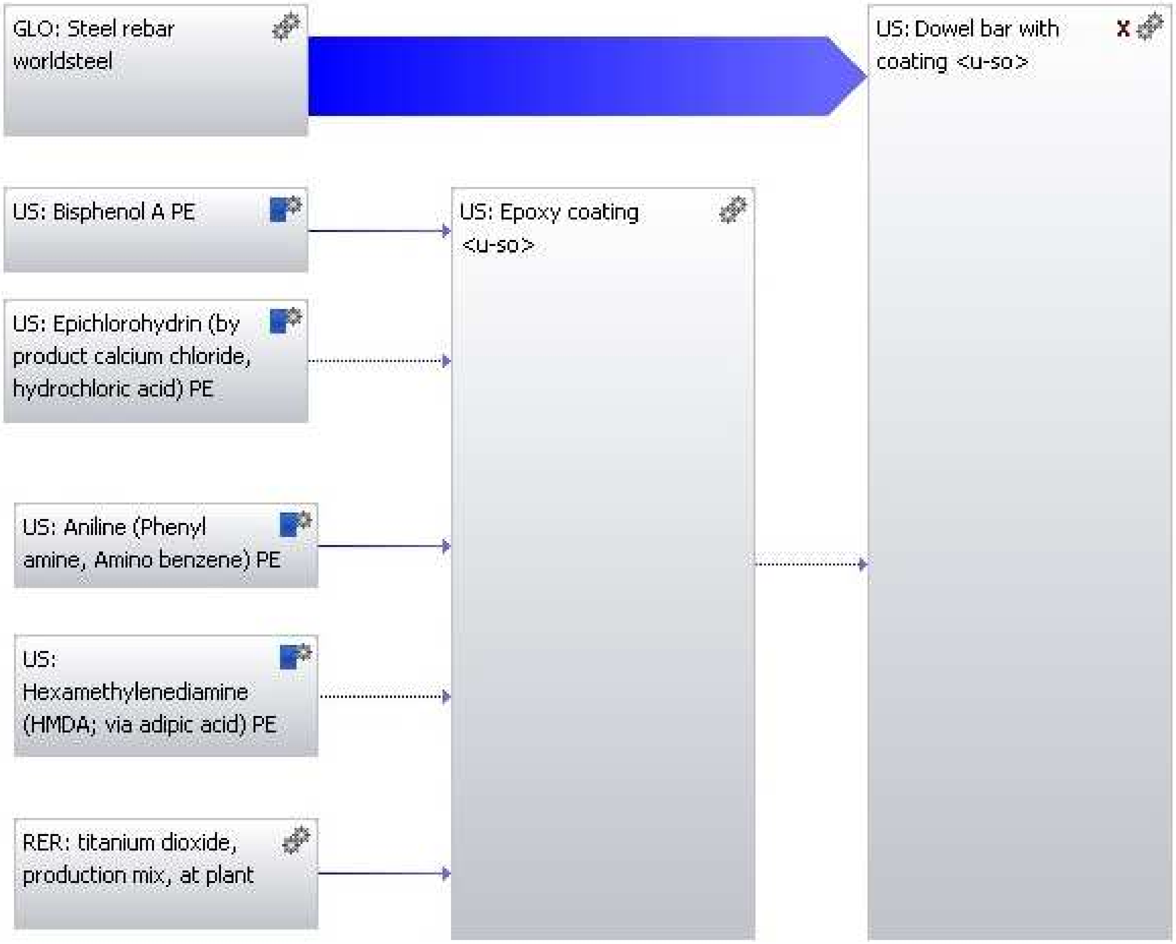
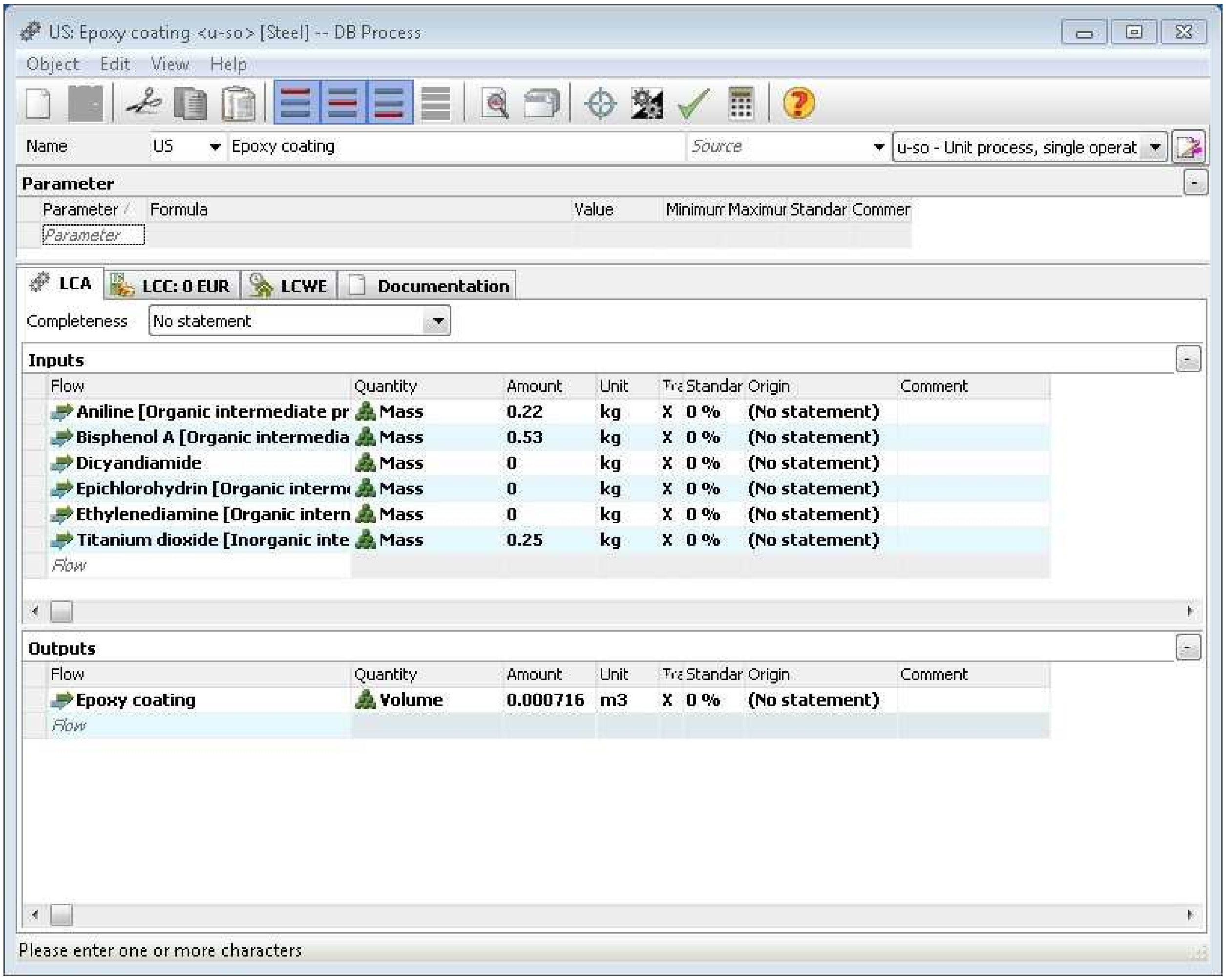


Figure 3.28: Model developed in *GaBi* for dowel and tie bar.
(Note: the mass of steel and epoxy coating would differ for different bar diameters.)



US: Epoxy coating <u-so> [Steel] -- DB Process

Name: US Epoxy coating Source u-so - Unit process, single operat

Parameter

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
Parameter						

Completeness: No statement

Inputs

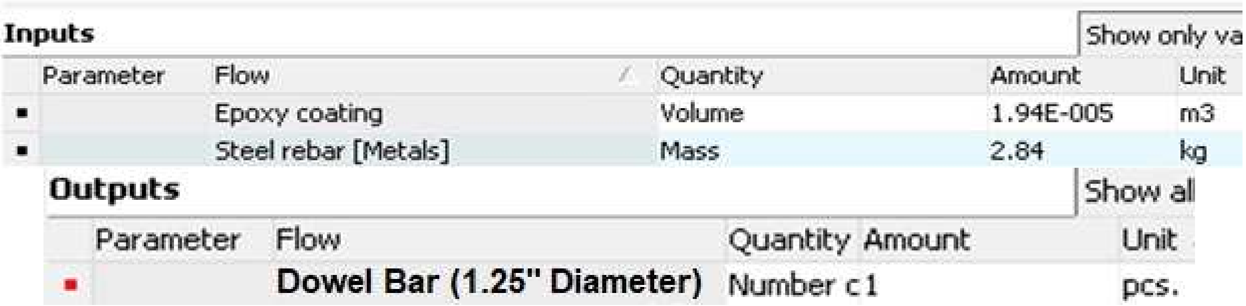
Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Aniline [Organic intermediate pr	Mass	0.22	kg	X	0 %	(No statement)	
Bisphenol A [Organic intermedia	Mass	0.53	kg	X	0 %	(No statement)	
Dicyandiamide	Mass	0	kg	X	0 %	(No statement)	
Epichlorohydrin [Organic interm	Mass	0	kg	X	0 %	(No statement)	
Ethylenediamine [Organic intern	Mass	0	kg	X	0 %	(No statement)	
Titanium dioxide [Inorganic inte	Mass	0.25	kg	X	0 %	(No statement)	
Flow							

Outputs

Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Epoxy coating	Volume	0.000716	m3	X	0 %	(No statement)	
Flow							

Please enter one or more characters

Figure 3.29: Inputs and outputs of the epoxy coating model taken from *GaBi.*



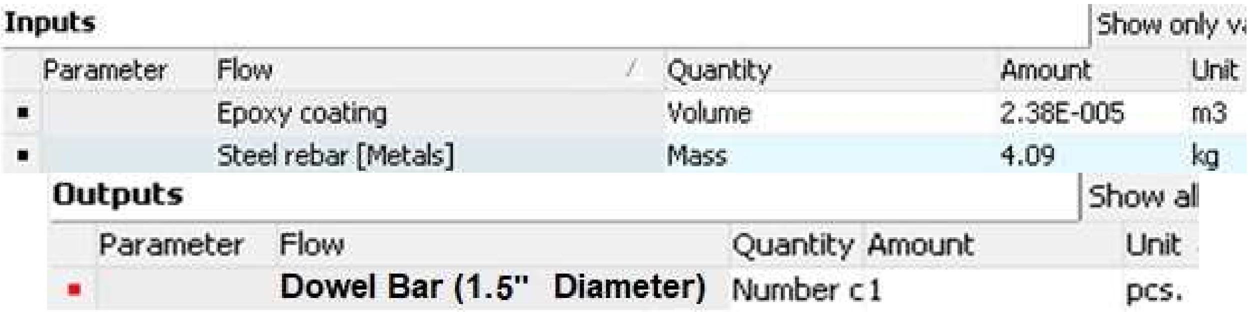
Inputs

	Parameter	Flow	Quantity	Amount	Unit
▪		Epoxy coating	Volume	1.94E-005	m3
▪		Steel rebar [Metals]	Mass	2.84	kg

Outputs

	Parameter	Flow	Quantity	Amount	Unit
▪		Dowel Bar (1.25" Diameter)	Number c	1	pcs.

Figure 3.30: Inputs and outputs for a 1.25 in dowel.



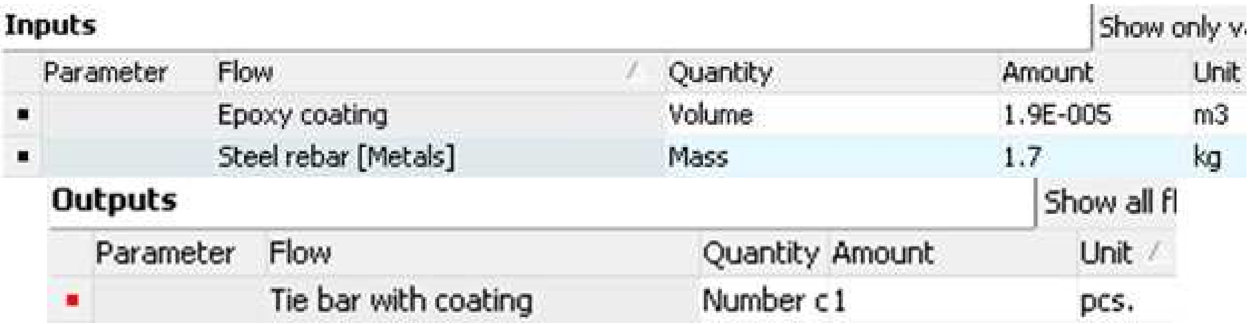
Inputs

	Parameter	Flow	Quantity	Amount	Unit
■		Epoxy coating	Volume	2.38E-005	m3
■		Steel rebar [Metals]	Mass	4.09	kg

Outputs

	Parameter	Flow	Quantity	Amount	Unit
■		Dowel Bar (1.5" Diameter)	Number c	1	pcs.

Figure 3.31: Inputs and outputs for a 1.5 in dowel.



Inputs

	Parameter	Flow	Quantity	Amount	Unit
■		Epoxy coating	Volume	1.9E-005	m3
■		Steel rebar [Metals]	Mass	1.7	kg

Outputs

	Parameter	Flow	Quantity	Amount	Unit
■		Tie bar with coating	Number c	1	pcs.

Figure 3.32: Inputs and outputs for ¾ in tie bar.

3.6.9. Limestone

The model for limestone was taken from the *GaBi* dataset, and the electricity process in the model was replaced with the process developed to represent local California local conditions. Figure 3.33 shows the model and Figure 3.34 shows the inputs and outputs to the model. Limestone was used as background data for the cement and lime models.

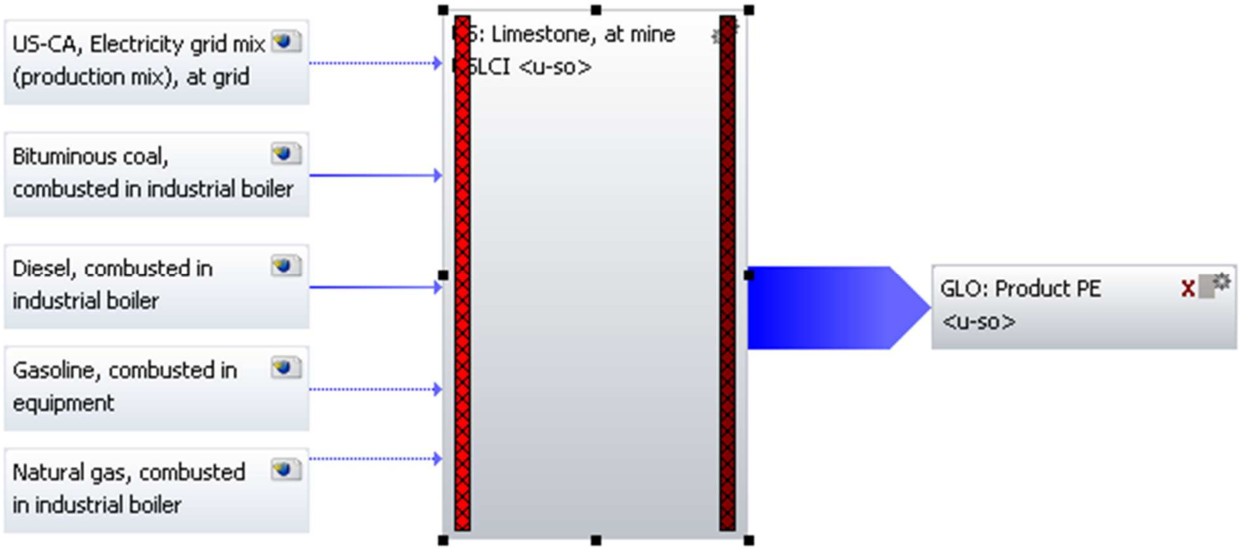
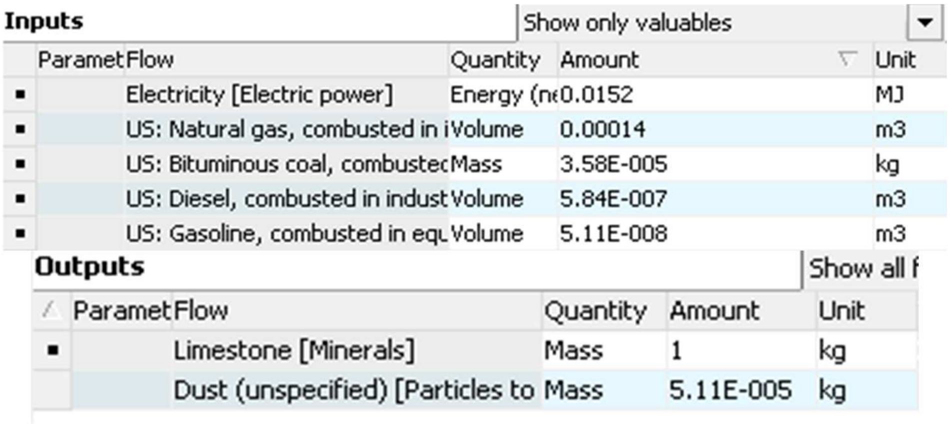


Figure 3.33: The model developed for limestone.


Inputs Show only valuables

	Paramet	Flow	Quantity	Amount	Unit
■		Electricity [Electric power]	Energy (n	0.0152	MJ
■		US: Natural gas, combusted in i	Volume	0.00014	m3
■		US: Bituminous coal, combustec	Mass	3.58E-005	kg
■		US: Diesel, combusted in indust	Volume	5.84E-007	m3
■		US: Gasoline, combusted in equ	Volume	5.11E-008	m3

Outputs Show all f

	Paramet	Flow	Quantity	Amount	Unit
■		Limestone [Minerals]	Mass	1	kg
		Dust (unspecified) [Particles to	Mass	5.11E-005	kg

Figure 3.34: Inputs and outputs of the limestone model.

3.6.10. Paraffin (Wax)

This item was taken directly from *GaBi*, for more information refer to the Supplementary Data.

3.6.11. Quicklime

This item was taken directly from *GaBi.* Refer to the Supplementary Data for more information.

3.6.12. Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) is one of the items for which allocation issues arise. In developing an LCI for RAP it was assumed that a 1 ln-km road is pulverized to a depth of 15 cm (6 in) and the materials are then hauled to a plant for further processing and use in HMA mixes as RAP. The assumed hauling distance was 50 miles, a typical one-way hauling distance for aggregates in California. In the model developed, both of these assumptions can be modified by a user.

The pulverization process was modeled assuming use of a 700 hp milling machine for milling the materials. The milling machine specifications and process details were taken from Caltrans equipment catalogs, the UCPRC case studies report (Wang et al. 2012) and guidelines in the literature. Full models are available in the Supplementary Data, parts of which have been recreated here. Table 3.14 shows how diesel consumption for 1 ln-km of pulverizing an old HMA surface is estimated. The total fuel used is then multiplied by the inventory (and also impact indicators) of diesel combusted in industrial equipment (Section 3.5.2.) to get to the emissions and environmental impacts of the Construction Stage. The transportation impacts are calculated based on the inventories defined later in this report. 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 to calculate the transportation impacts. Table 3.15 shows the impact of hauling the reclaimed materials to a plant 50 miles away; this distance can be adjusted by a user.

Table 3.14. Modeling milling process of a 1 ln-km road to produce RAP

Equipment or Activity	Engine Power (hp)	Hourly Fuel Consumption (gal/hr)	Speed (ft/min)	Speed (km/h)	Time (hr) for One Pass over the Functional Unit (1 lane-km)	Number of Passes	Fuel Used (gal)
Milling	700	20	10	0.183	5.47	1	109.36

Table 3.15. Transportation impacts of hauling 1 ln-km of RAP to the plant for further processing

Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
1 ln-km of RAP	9.20E+03	1.47E+03	2.94E+00	1.32E+05	1.32E+05	0.00E+00

* 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.

** Same note as above applies to PED (nonrenewable.)

At the plant, RAP will replace the virgin aggregate used in HMA production and hence there will be a reduction in environmental impacts. There are two approaches to allocating the reductions in environmental impacts due to avoiding extra emissions in the new mix that contains the RAP. If the cut-off method is used, all the reductions in environmental impacts for replacing the virgin binder and aggregate plus all the impacts of hauling and initial milling are allocated to the downstream project that uses the RAP. In the 50/50 method the total virgin material production impacts, the milling processes at the end of life, and hauling to plant are summed up and divided between the upstream project and downstream project. For virgin material production, the LCI results from Section 3.6.1. were used. Both results, for 1 kg of RAP, are provided here as Table 3.16 and Table 3.17.

Table 3.16. Selected LCI and LCIA results for 1 kg of RAP, using the cut-off method for allocation

Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
Milling	8.91E-04	3.93E-04	6.99E-07	1.23E-02	1.23E-02	0.00E+00
Transportation	6.27E-03	1.00E-03	2.00E-06	8.98E-02	8.98E-02	0.00E+00
Total	7.16E-03	1.39E-03	2.70E-06	1.02E-01	1.02E-01	0.00E+00

* 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.

** Same note as above applies to PED (nonrenewable.)

Table 3.17. Selected LCI and LCIA results for 1 kg of RAP, using the 50/50 method for allocation

Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
Material Production	4.54E-03	8.08E-04	3.25E-06	3.28E-01	3.22E-01	2.41E-01
Milling	4.45E-04	1.97E-04	3.49E-07	6.14E-03	6.14E-03	0.00E+00
Transportation	3.14E-03	5.00E-04	1.00E-06	4.49E-02	4.49E-02	0.00E+00
Total	8.13E-03	1.50E-03	4.60E-06	3.79E-01	3.73E-01	2.41E-01

* 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.

** Same note as above applies to PED (nonrenewable.)

3.6.13. Styrene Butadiene Rubber (SBR)

The LCI data and model for styrene butadiene rubber (SBR) was item was taken directly from *GaBi*. Refer to the Supplementary Data for more information. SBR is a polymer that can be added to hot mix asphalt to modify and improve the bitumen performance, thus increase the pavement durability. Adding SBR has shown to improve the mix performance in terms decreased temperature susceptibility, increased rut resistance, and increased resistance to stripping (Brown et al., 1992.)

3.6.14. Summary of the Material Production Impacts for Conventional Materials

Table 3.18 summarizes the selected LCI and LCIA results for the conventional materials included in the database developed in this project. As noted in Section 3.2.1. , a decision was made to base an inventory for LBNL Heat Island study on two electricity grid mixes since California is pursuing cleaner sources of electricity through the Renewable Portfolio Standard (RPS.) One inventory was based on the year 2012 grid mix and the other was based on the projected California electricity grid mix in the year 2020.

Table 3.19 summarizes the selected LCI and LCIA results for the conventional materials included in the database using the 2020 electricity grid mix. This table only contains the items that could have the electricity process in their model changed.

3.7. 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, Xuejuan Cao (from (Chongqing Jiaotong University), Peilong Li (Xi'an International Studies University), Lijuan Zhang (Shanghai Institute of Applied Physics), and Bo Pang (Beijing Jiaotong University.) Two of the groups are epoxy or resin based and two are water based. Data on the chemical composition and mass breakdown of an example of each type coating were extracted from the literature and sent to thinkstep, *GaBi* software's parent company. Using these data, the company developed models for each reflective coating type and incorporated them into *GaBi* 6.3 and provided this study with the LCIs based on the *GaBi* 2014 database (GaBi, 2014.) 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 3.20 shows the chemicals in each of the four coating types, with the mass breakdown. Producing this table required multiple resources (Cao et al., 2011; Cao et al., 2014; Feng et al., 2012; Santamouris et al., 2011; Wang H. et al., 2012; Li et al., 2016) The table also shows the LCI dataset from *GaBi* (2014) that were used to model each process. For most cases, matching LCI datasets were found and in cases where matching datasets were not available, proxy datasets were utilized. 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 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 percent of the total primary energy demand of the coating.

Table 3.18. Summary of selected LCI and LCIA results for conventional materials (based on 2012 CA electricity grid mix)

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [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
Bitumen	1 kg	4.75E-01	8.09E-02	4.10E-04	4.97E+01	4.93E+01	4.02E+01
Bitumen Emulsion	1 kg of Residual Bitumen	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	1 Each	3.69E+00	1.30E-01	1.39E-03	4.87E+01	4.20E+01	0.00E+00
Limestone	1 kg	4.44E-03	2.11E-04	8.24E-08	7.84E-02	6.80E-02	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
Reclaimed Asphalt Pavement (RAP) [Cut-Off]	1kg	7.16E-03	1.39E-03	2.70E-06	1.02E-01	1.02E-01	0.00E+00
Reflective Coating (BPA) [50/50]	1kg	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 (3/4 in)		2.25E+00	7.99E-02	8.53E-04	3.00E+01	2.60E+01	0.00E+00

* 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.

** Same note as above applies to PED (nonrenewable)

Table 3.19. Summary of LCI and LCIA for conventional materials, energy sources, and transportation (based on 2020 ca electricity grid mix)

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
Aggregate (Crushed)	1 kg	3.13E-3	6.44E-4	1.56E-6	6.72E-2	4.83E-2	0.00E+0
Aggregate (Natural)	1 kg	2.11E-3	3.97E-4	9.24E-7	4.86E-2	3.32E-2	0.00E+0
Bitumen	1 kg	4.63E-1	8.06E-2	4.08E-4	9.76E+0	8.96E+0	4.02E+1
Bitumen Emulsion	1 kg of Residual Bitumen	5.02E-1	8.22E-2	4.16E-4	1.08E+1	1.02E+1	4.02E+1
Cement (PC Type I/II)	1 kg	8.62E-1	7.25E-2	4.97E-4	6.23E+0	5.40E+0	0.00E+0
Crumb Rubber Modifier	1 kg	1.72E-1	5.69E-3	9.99E-5	5.63E+0	3.04E+0	3.02E+2

* 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.
** Same note as above applies to PED (nonrenewable.)

Table 3.20. Chemicals in each coating, mass breakdown, and LCI datasets used (GaBi, 2014)

Coating	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 (Fe2O3) 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 acrylate	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

Coating	Chemical Name	% Mass	Representative LCI Dataset	Dataset Country/Region
	HydroxypropanE-1-sulphonate	1.6	Soaping agent (sodium alkyl-benzenesulphonate)	GLO
	Azirdine	1	Hydrazine hydrate/hydrazine	DE
	Ammonium hydroxide	1	Tetramethyl-ammonium hydroxide (TMAH)	US
	Water	55	Water deionized	US
D. Polyurethane	cis-1,4-cyclohexylene di-isocyanate	8	Isophorone di-isocyanate (IPDI)	DE
(water-based)	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

Table 3.21 summarizes the main LCIA categories and inventory items of interest for the reflective coatings.

Table 3.21. Summary LCI and LCIA of reflective coatings

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [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

* 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.

** Same note as above applies to PED (nonrenewable.)

3.8. Transportation Stage

The LCI and LCIAs for the four major modes of transportation used in the modeling process were all taken directly from *GaBi*. Table 3.22 shows the summary of the main impacts. The comprehensive dataset is available in the Supplementary Data. These four modes of transportation were selected as they are the transportation modes that appear explicitly in this study's *GaBi* plans as subprocesses, and therefore, may be updated later by users.

Table 3.22. Summary of LCI and LCIA for major transportation modes *(GaBi)*

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
Barge Transport	1000 kg-km	3.31E-02	9.58E-03	1.96E-05	4.17E-01	4.17E-01	0.00E+00
Combination Truck, diesel powered	1000 kg-km	9.28E-02	1.53E-02	2.52E-05	1.19E+00	1.19E+00	0.00E+00
Heavy Truck (24 Metric Tonne capacity)	1000 kg-km	7.80E-02	1.24E-02	2.49E-05	1.12E+00	1.12E+00	0.00E+00
Ocean Freighter	1000 kg-km	0.0183	0.0111	1.87E-05	0.231	0.231	0

* 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.

** Same note as above applies to PED (nonrenewable.)

3.9. Mix Designs and Material Production Stage of Various Pavement Surface Treatments

Table 3.23 lists the pavement surface treatments that were considered in this study. Each treatment's impacts can be divided among 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 the previous Sections 3.5, 3.6, and 3.7 were used alongside the mix designs to calculate the material production stage impacts for each treatment. The details of calculations are presented in the Supplementary Data "2. Mixes and Treatments" folder), parts of which are presented in this section where needed and where it was possible to include them. 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, the user can change the default hauling distance in the models available in the Supplementary Data. The construction activities were modeled using the state of the practice that was determined using Caltrans specifications, consultations with local experts, and what was found in the literature. Other than the material production stage 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 show the plant or unit processes for those LCIs appear here. The LCIs and LCIAs of the energy sources and materials developed in Section 3.5 and Section 3.6 were used in an Excel file with most of the mix design information taken from the Caltrans *Maintenance Technical Advisory Guide (MTAG)* to calculate the LCI and LCIA of the material production stage for each of the surface treatments (Caltrans MTAG, 2007).

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 details of the calculation of construction activities are available in the *construction.xlsx* file in the construction folder in the supplementary data, which is also re-created here in Table 3.29. The functional unit for all surface treatments is 1 lane-kilometer (ln-km.) For some of the items, such as PCC and HMA, the thickness can be modified by the user; for other items such as slurry seal and similar treatments, the application rate of aggregate or bitumen emulsion can be changed in terms of mass per surface area. For reporting purposes in this chapter, typical thicknesses or application rates for surface treatments were selected based on common practice, or Caltrans specifications where applicable.

Table 3.23. Pavement surface treatment alternatives considered

Surface Treatments
Bonded Concrete Overlay on Asphalt (BCOA)
Cape Seal
Cement Concrete (Various Applications)
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

3.9.1. Bonded Concrete Overlay on Asphalt (BCOA)

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 12.5 cm (5 in), although the thickness can be selected by the designer. BCOA construction consists of milling of the existing asphalt layer (1.25 to 5 cm [0.5 to 2 in], assumed as 2.5 cm [1 in] in this study), sweeping it multiple times and air blasting it, wetting the surface, placing the concrete, and finally sawing and sealing of the joints every 60 to 180 cm (2 to 6 ft.) (Caltrans MTAG, 2007.) As with the model for portland cement concrete, further down below, sawing, and joint sealing are not included in this model. The thickness of the BCOA is a variable that can be changed by the designer. The LCI results can be linearly scaled based on the default thickness used in this section and the new design thickness. Mix designs for the BCOA mixes used in the Cool Pavement project are listed in Table 3.24 and construction details are presented in Table 3.29.

Table 3.24. Mix design for BCOA with three levels of SCM

Item	Cement (kg)	Slag (kg)	Fly Ash (kg)	Coarse Agg (kg)	Fine Agg (kg)	Water (kg)	Fiber (kg)	Air Entraining (kg)	Retar-der (kg)	Water Reducer (kg)	Total SCM (kg/m^3) [%]
BCOA (PC139-SCM139)	139	56	84	1038	817	173	0	0	0	0	139 [50%]
BCOA (PC267-SCM71)	267	0	71	1085	764	145	2	0	0	0	71 [19%]
BCOA (PC448-SCM0)	448	0	0	1071	598	161	2	1	2	2	0 [0%]

3.9.2. Cape Seal

A cape seal is defined as a slurry seal over a chip seal by the MTAG. Refer to the slurry seal and chip seal subsections for the mix design details.

3.9.3. Cement Concrete

Figure 3.37 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 all ranges of PCCs used in construction projects. Figure 3.38 shows the inputs and outputs of the model and how they can be modified by the user.

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

- lane replacement
- slab replacement (2 mixes)
- local streets
- minor concrete

The selected mix designs for slab replacement were taken from the UCPRC case studies by Wang et al (2012) 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 in state highway projects was used which incorporates use of supplementary cementitious materials (SCMs.) Mix designs for local streets and minor concrete were taken from projects in the City of Santa Rosa and City of Davis. The mix designs are presented in Table 3.25 and construction details are available in Table 3.29.

Table 3.25. Mix designs for PCC items (mass per 1 m^3 of mix)

Item	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) [%]
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	PCC (PC284 SCM50)	284	50	1,068	822	149	0	0.1	0	1.2	50 [18%]

Item	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) [%]
for State Highways)											
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%]

* Abbreviations used in the item codes:
CSA: Calcium Sulfo-aluminate cement
PC: portland cement (type I/II unless explicitly stated as type III)
SCM: Supplementary Cementitious Materials

The thickness of the PCC layer was assumed to be 17.5 cm (6.8 in) as a default, although the thickness of the PCC can be defined by the designer. The construction process consisted of grinding of the old surface, sweeping, and lay-down of the PCC layer using paver. Saw cutting and curing were assumed to make a small contribution to the inventories and their impacts and were not included. The thickness of the new portland cement concrete is a variable that can be changed by the 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 3.6 m (12 ft) wide, 4.5 m (15 ft) long, and 22.5 cm (9 in) thick.

3.9.4. Chip Seal

It was assumed that chip seals are constructed with 1.8 L/m^2 (0.4 gal/sy) of bitumen emulsion and 19 kg/m^2 (35 lb/sy) 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 (Caltrans MTAG, 2007.) Construction details for chip seal are presented in Table 3.29.

3.9.5. Fog Seal

The MTAG states that the emulsion application rate for fog seals should be between 0.45 to 0.7 L/m^2 (0.1 to 0.15 gal/sy), the average of which was used in this study. Construction consists of sweeping, spraying emulsion, and the optional application of sand, which was not assumed in this study (Caltrans MTAG, 2007.) Construction details for fog seal are presented in Table 3.29.

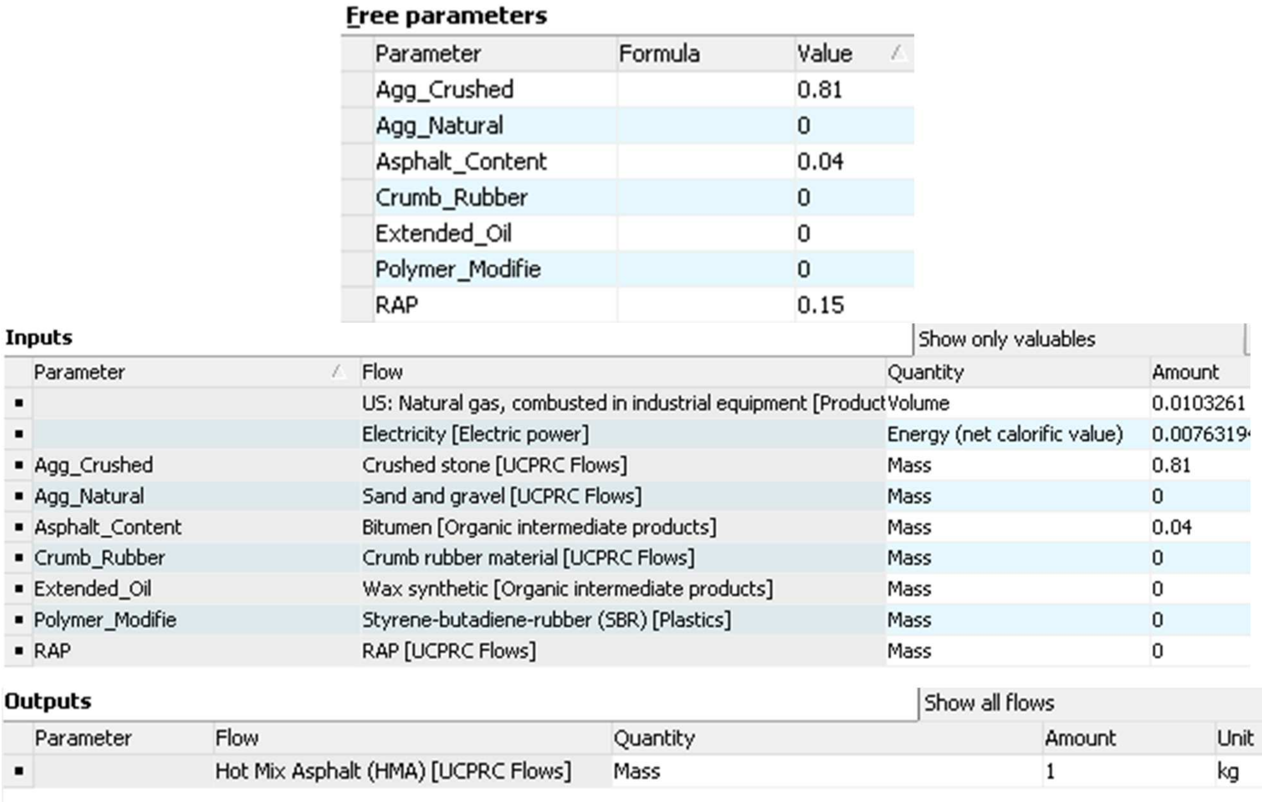
3.9.6. Conventional Asphalt Concrete (Mill-and-Fill and Overlay-Only)

The model developed in *GaBi* for conventional asphalt concrete (interchangeably referred to as “hot mix asphalt” [HMA]) is shown in Figure 3.35. The mix design and the percentage of each of the ingredients can be changed within the model to facilitate calculating LCIs for various mix designs used in different construction projects, as shown in Figure 3.36. The LCIs for two mixes were prepared: one with 15 percent RAP content and the other with no RAP—taken from the UCPRC case studies report—which represents a typical mix used for rehabilitation projects by Caltrans. The details of both mixes are shown in Table 3.26. Construction details for conventional asphalt concrete are presented in Table 3.29.

Table 3.26. HMA with RAP mix design (percent by mass)

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

Figure 3.35: The model developed for HMA (the mix design can be modified)



Free parameters

Parameter	Formula	Value
Agg_Crushed		0.81
Agg_Natural		0
Asphalt_Content		0.04
Crumb_Rubber		0
Extended_Oil		0
Polymer_Modifie		0
RAP		0.15

Inputs

Parameter	Flow	Quantity	Amount
	US: Natural gas, combusted in industrial equipment [Product	Volume	0.0103261
	Electricity [Electric power]	Energy (net calorific value)	0.0076319
Agg_Crushed	Crushed stone [UCPRC Flows]	Mass	0.81
Agg_Natural	Sand and gravel [UCPRC Flows]	Mass	0
Asphalt_Content	Bitumen [Organic intermediate products]	Mass	0.04
Crumb_Rubber	Crumb rubber material [UCPRC Flows]	Mass	0
Extended_Oil	Wax synthetic [Organic intermediate products]	Mass	0
Polymer_Modifie	Styrene-butadiene-rubber (SBR) [Plastics]	Mass	0
RAP	RAP [UCPRC Flows]	Mass	0

Outputs

Parameter	Flow	Quantity	Amount	Unit
	Hot Mix Asphalt (HMA) [UCPRC Flows]	Mass	1	kg

Figure 3.36: Inputs and outputs of the HMA model.

The typical thickness of the asphalt concrete placed was assumed to be 6 cm (2.4 in.) Two construction options are considered for use of asphalt concrete. The first option is mill-and-fill, where the construction consists of milling 4.5 cm (1.8 in) of the surface (assumed thickness) followed by application of a tack coat, lay-down of new asphalt concrete, and compaction of 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, a tack coat is applied on the old surface and then the new HMA is directly put on top. The thickness of the new asphalt concrete is a variable and can be changed by the user. The LCI results can be linearly scaled based on the default thickness used in this section and the new design thickness.

3.9.7. Conventional Interlocking Concrete Pavement (Pavers)

An Environmental Product Declaration (EPD) developed by Angelus Block Inc. was used to determine the environmental impacts of pavers. 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) which has the dimensions of 20 cm × 20 cm × 40 cm (8 in × 8 in × 16 in) and 50 percent voids. Construction details for concrete pavers are presented in Table 3.29.

3.9.8. Permeable Asphalt Concrete Pavement

Permeable asphalt concrete was assumed to consist of a base of thickness of 15 cm (0.5 ft) made from 100 percent crushed and angular aggregate, topped with 11 cm (0.35 ft) of open-graded asphalt concrete, per Caltrans recommendations (Caltrans, 2014.) Construction details for permeable asphalt concrete are presented in Table 3.29.

3.9.9. Permeable Portland Cement Concrete

Permeable PCC was assumed to consist of a 15 cm (0.5 ft) open-graded portland cement concrete layer on top of a 15 cm (0.5 ft) granular base layer, according to Caltrans recommendations (Caltrans, 2014.) Construction details for permeable PCC are presented in Table 3.29.

3.9.10. Reflective Coatings

The construction process for reflective coatings consists of sweeping the pavement surface which is then followed by application of the coating with a tanker. The application rates assumed for this study were based on the average of the ranges found in the literature study (see Table 3.20.) Construction details for reflective coatings are presented in Table 3.29.

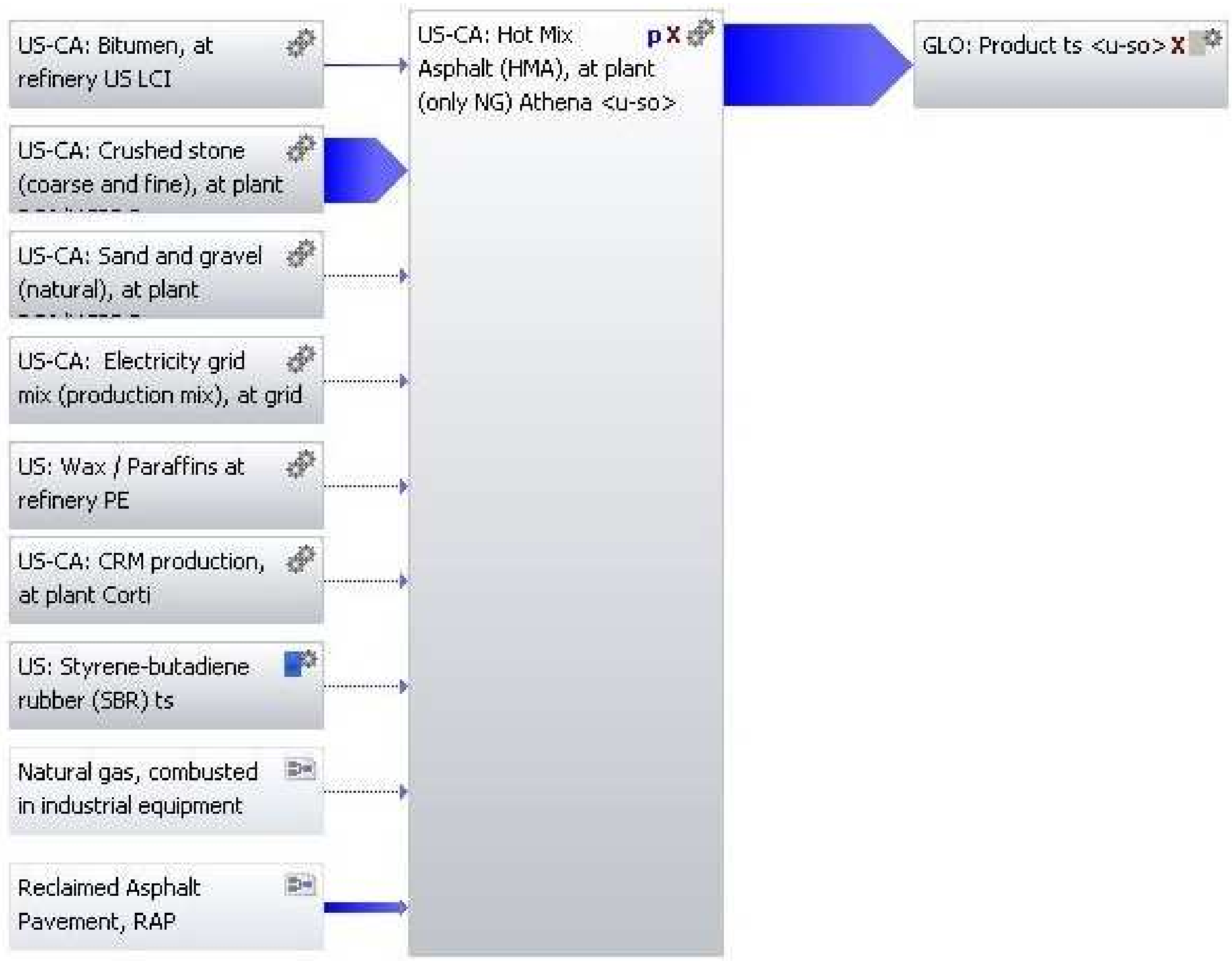
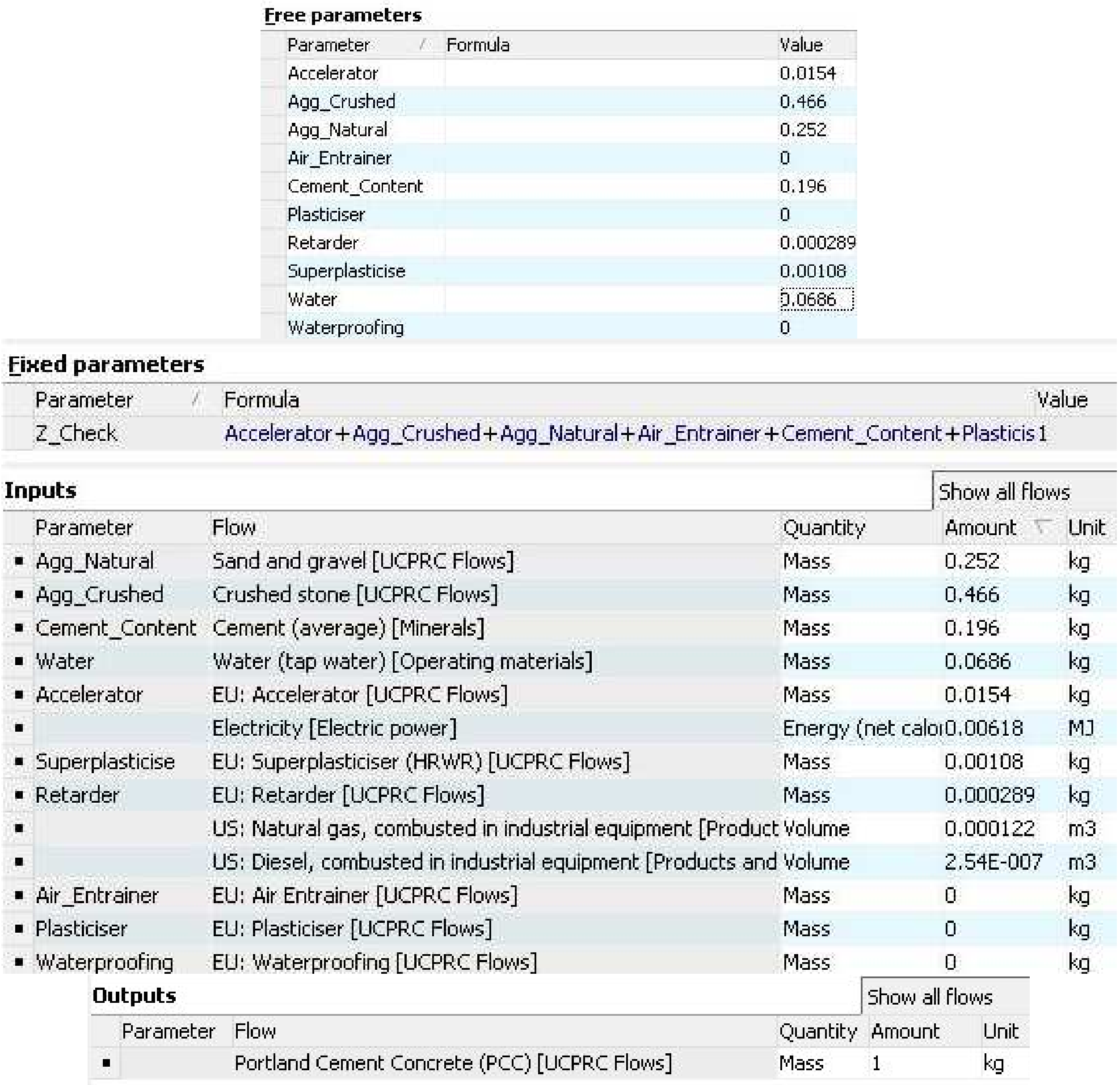


Figure 3.37: The *GaBi* model developed for PCC.



Free parameters

Parameter	Formula	Value
Accelerator		0.0154
Agg_Crushed		0.466
Agg_Natural		0.252
Air_Entrainer		0
Cement_Content		0.196
Plasticiser		0
Retarder		0.000289
Superplasticise		0.00108
Water		0.0686
Waterproofing		0

Fixed parameters

Parameter	Formula	Value
Z_Check	Accelerator+Agg_Crushed+Agg_Natural+Air_Entrainer+Cement_Content+Plasticis	1

Inputs

Parameter	Flow	Quantity	Amount	Unit
Agg_Natural	Sand and gravel [UCPRC Flows]	Mass	0.252	kg
Agg_Crushed	Crushed stone [UCPRC Flows]	Mass	0.466	kg
Cement_Content	Cement (average) [Minerals]	Mass	0.196	kg
Water	Water (tap water) [Operating materials]	Mass	0.0686	kg
Accelerator	EU: Accelerator [UCPRC Flows]	Mass	0.0154	kg
	Electricity [Electric power]	Energy (net calo	0.00618	MJ
Superplasticise	EU: Superplasticiser (HRWR) [UCPRC Flows]	Mass	0.00108	kg
Retarder	EU: Retarder [UCPRC Flows]	Mass	0.000289	kg
	US: Natural gas, combusted in industrial equipment [Product	Volume	0.000122	m3
	US: Diesel, combusted in industrial equipment [Products and	Volume	2.54E-007	m3
Air_Entrainer	EU: Air Entrainer [UCPRC Flows]	Mass	0	kg
Plasticiser	EU: Plasticiser [UCPRC Flows]	Mass	0	kg
Waterproofing	EU: Waterproofing [UCPRC Flows]	Mass	0	kg

Outputs

Parameter	Flow	Quantity	Amount	Unit
	Portland Cement Concrete (PCC) [UCPRC Flows]	Mass	1	kg

Figure 3.38: Inputs and outputs of the PCC model.

3.9.11. 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 UCPRC case studies report (Wang et al., 2012), which presents a typical rubberized asphalt concrete mix used in Caltrans rehabilitation projects. That mix design is presented in Table 3.27.

Table 3.27. RHMA mix design

Item	% by Weight	Item	% by Weight
Aggregate	92.5	Asphalt Binder	7.5
Coarse	68	*Bitumen*	*77.5*
Fine	27	*CRM*	*20*
Dust	5	*Extender Oil*	*2.5*

As with conventional asphalt concrete, two options are provided here: mill-and-fill and overlay-only. The construction process was assumed to be similar to that of conventional asphalt concrete. The thickness of the treatment for both cases was assumed to be 5 cm (2 in), although this thickness is a variable that can be changed by the designer. The LCI results can be linearly scaled based on the default thickness used in this section and the new design thickness, and similar to HMA and PCC, the mix design can also be modified by the user. Construction details for RHMA are presented in Table 3.29.

3.9.12. Sand Seal

Sand sealing consists of the application of bitumen emulsion followed by deposition of a layer of sand on top of it; after that a pneumatic roller is often used to stabilize the sand. The range of emulsion application is between 0.45 to 1.15 L/m^2 (0.1 to 0.25 gal/sy) and sand is applied at 9.5 to 13.5 kg/m^2 (18 to 25 lb/sy.) The average of the ranges was used in both cases in this study (Caltrans MTAG, 2007.) Construction details for sand seal are presented in Table 3.29.

3.9.13. Slurry Seal

A Type II slurry mix design was selected with an application rate of 5.5 to 8 kg/m^2 (10 to 15 lb/sy) of angular aggregate and residual asphalt content of 7.5 to 13.5 percent by weight of aggregate. The average of the ranges was used in both cases in this study (Caltrans MTAG, 2007.) Construction details for slurry seal are presented in Table 3.29.

3.10. End-of-Life (EOL) Treatments: Cold In-Place Recycling and Full-Depth Recycling

The following matrix of end-of-life treatments were modeled using current Caltrans practices in California. The treatments considered are presented in Table 3.28. The cut-off method was used for the allocation of impacts between the upstream and downstream projects (see Table 3.6.) 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 3.30.

Table 3.28. Typical in-place end of life recycling treatments in California

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

AE is asphalt emulsion; PC is portland cement; FA is foamed asphalt; RHMA is rubberized hot mix asphalt; OL is overlay.

3.11. Construction Stage for Various Surface Treatments

Table 3.29 shows the construction process for each of the surface treatments considered in this study.

Table 3.29. Construction process for different surface treatments (modeled based on Caltrans specifications, consultation with local experts, and literature)

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	No. of Passes	Fuel Used (gal)	Total Fuel Used (gal)
Bonder Concrete Overlay on Asphalt (BCOA)	Milling	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	700	20	10	0.183	5.47	1	109.36	284.5
	Prime 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)	Prime 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
	Pavers 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	

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	No. of Passes	Fuel Used (gal)	Total Fuel Used (gal)
	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	
Permeable Portland Cement Concrete	Base layer lay down	350	7.2	25	0.457	2.19	1	15.75	49.9
	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)	Grinding	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	700	20	10	0.183	5.47	1	109.36	284.5
	Prime coat	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)	Prime coat	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

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	No. of Passes	Fuel Used (gal)	Total Fuel Used (gal)
	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	

Table 3.30. Construction process for EOL 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	No. of Passes	Fuel Used (gal)	Total Fuel Used (gal)
CIR (Mechanical Stabilization) with 2.5 cm [1 in] 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	
	Prime 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 (AE & Cement Stabilization) with Overlay	Milling	1000	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	

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	No. of Passes	Fuel Used (gal)	Total Fuel Used (gal)
	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	
	Prime 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	

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

Table 3.31 summarizes the main LCI and LCIA categories of interest for the treatments with the 2012 electricity grid mix. Table 3.32 shows the EOL treatments summary. Table 3.33 represent the same results but based on California electricity grid mix in 2020.

Table 3.31. Summary LCI and LCIA of treatments for default thicknesses and a functional unit of 1 ln-km: 2012 grid mix

Item	Life Cycle Stage	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]
CIR (10 cm [4 in] milled + mechanical stabilization) with 2.5 cm (1 in) 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 (10 cm [4 in] 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 (25 cm [10 in] milled + no stabilization) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 4% AE + 1% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 3% FA + 1% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 2% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 4% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 6% PC) with 6 cm (2.4 in) 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

Item	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]
	Total	2.12E+05	1.60E+04	9.41E+01	2.81E+06	2.73E+06

* 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.

** Same note as above applies to PED (nonrenewable.)

Table 3.32. Summary LCI and LCIA of EOL treatments for a functional unit of 1 ln-km: 2012 grid mix

Item	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]
CIR (10 cm [4 in] milled + mechanical stabilization) with 2.5 cm (1 in) 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 (10 cm [4 in] 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 (25 cm [10 in] milled + no stabilization) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 4% AE + 1% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 3% FA + 1% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 2% PC) with 6 cm (2.4 in) 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 (25 cm [10 in] milled + 4% PC) with 6 cm (2.4 in) 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
	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

Item	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]
FDR (25 cm [10 in] milled + 6% PC) with 6 cm (2.4 in) RHMA OL	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

* 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.

** Same note as above applies to PED (nonrenewable.)

As noted in Section 3.2.1. , the goal and scope definition section of the Heat Island study, since California is pursuing cleaner sources of electricity through the Renewable Portfolio Standard (RPS), a decision was made to base the LCI inventory for the study on two electricity grid mixes. One inventory was based on the year 2012 grid mix and the other was based on the projected California electricity grid mix in the year 2020. The tables in this section present selected LCI and LCIA values for materials, energy sources, and surface treatments that were used in that study. The EOL LCIs are not included in this section as LCIs under 2020 were specific to the treatments in the Heat Island study.

Table 3.33. Summary LCI and LCIA of treatments for 1 ln-km of treatment (with 2020 electricity grid mix)

Item	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
Bonded Concrete Overlay on Asphalt (BCOA)	Material	2.18E+05	1.80E+04	1.16E+02	1.50E+06	1.41E+06	0.00E+00
	Transport	7.04E+03	1.12E+03	2.25E+00	1.01E+05	1.01E+05	0.00E+00
	Construction	1.54E+03	6.80E+02	1.21E+00	2.12E+04	2.12E+04	0.00E+00
	Total	2.27E+05	1.98E+04	1.19E+02	1.62E+06	1.53E+06	0.00E+00
Cape Seal	Material	4.96E+03	8.22E+02	4.02E+00	1.07E+05	9.92E+04	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	7.10E+03	1.58E+03	5.39E+00	1.37E+05	1.29E+05	3.75E+05
Chip Seal	Material	3.59E+03	5.96E+02	2.90E+00	7.72E+04	7.16E+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	4.88E+03	1.03E+03	3.69E+00	9.53E+04	8.96E+04	2.69E+05
Fog Seal	Material	1.05E+03	1.72E+02	8.72E-01	2.27E+04	2.13E+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	1.28E+03	2.69E+02	1.04E+00	2.58E+04	2.44E+04	8.42E+04
Conventional Asphalt Concrete (Mill-and-Fill) Mix 1 (15% RAP)	Material	2.54E+04	2.40E+03	1.68E+01	4.31E+05	4.00E+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	3.22E+04	4.43E+03	2.06E+01	5.26E+05	4.94E+05	8.95E+05
	Material	2.54E+04	2.40E+03	1.68E+01	4.31E+05	4.00E+05	8.95E+05

Item	Life Cycle Stage	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
Conventional Asphalt Concrete (Overlay) Mix 1 (15% RAP)	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	3.09E+04	3.85E+03	1.95E+01	5.08E+05	4.76E+05	8.95E+05
Conventional Asphalt Concrete (Mill-and-Fill) Mix 2 (No RAP)	Material	3.00E+04	3.20E+03	2.11E+01	7.08E+05	6.66E+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	3.36E+04	4.73E+03	2.39E+01	7.57E+05	7.16E+05	1.29E+06
Conventional Asphalt Concrete (Overlay) Mix 2 (No RAP)	Material	3.00E+04	3.20E+03	2.11E+01	7.08E+05	6.66E+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	3.23E+04	4.16E+03	2.28E+01	7.39E+05	6.98E+05	1.29E+06
Conventional Interlocking Concrete Pavement (Pavers)	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
Permeable Asphalt Concrete	Material	4.98E+04	5.21E+03	3.22E+01	8.66E+05	7.81E+05	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	6.72E+04	8.63E+03	3.88E+01	1.11E+06	1.03E+06	1.59E+06
Permeable Portland Cement Concrete	Material	2.66E+05	2.25E+04	1.41E+02	1.90E+06	1.76E+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	2.85E+05	2.56E+04	1.47E+02	2.16E+06	2.02E+06	0.00E+00
Portland Cement Concrete	Material	3.01E+05	2.48E+04	1.60E+02	2.07E+06	1.94E+06	0.00E+00
	Transport	9.69E+03	1.55E+03	3.10E+00	1.39E+05	1.39E+05	0.00E+00
	Construction	5.35E+02	2.36E+02	4.20E-01	7.38E+03	7.38E+03	0.00E+00
	Total	3.11E+05	2.66E+04	1.63E+02	2.21E+06	2.08E+06	0.00E+00
Portland Cement Concrete with SCM	Material	1.39E+05	1.21E+04	7.99E+01	1.05E+06	8.95E+05	0.00E+00
	Transport	9.69E+03	1.55E+03	3.10E+00	1.39E+05	1.39E+05	0.00E+00
	Construction	5.35E+02	2.36E+02	4.20E-01	7.38E+03	7.38E+03	0.00E+00
	Total	1.49E+05	1.39E+04	8.34E+01	1.19E+06	1.04E+06	0.00E+00
Reflective Coating – BPA	Material	1.04E+04	4.46E+02	2.75E+00	2.52E+05	2.46E+05	0.00E+00
	Transport	1.38E+02	2.21E+01	4.43E-02	1.98E+03	1.98E+03	0.00E+00
	Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	0.00E+00
	Total	1.07E+04	5.57E+02	2.95E+00	2.57E+05	2.51E+05	0.00E+00
Reflective Coating – Polyester Styrene	Material	1.22E+04	5.77E+02	1.42E+01	2.55E+05	2.43E+05	0.00E+00
	Transport	1.38E+02	2.21E+01	4.43E-02	1.98E+03	1.98E+03	0.00E+00
	Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	0.00E+00

Item	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total)* [MJ]	PED (Non-Ren)** [MJ]	Feedstock Energy [MJ]
	Total	1.25E+04	6.88E+02	1.44E+01	2.59E+05	2.47E+05	0.00E+00
Reflective Coating – Polyurethane	Material	8.66E+03	3.78E+02	3.42E+00	1.91E+05	1.81E+05	0.00E+00
	Transport	1.85E+02	2.94E+01	5.90E-02	2.64E+03	2.64E+03	0.00E+00
	Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	0.00E+00
	Total	9.05E+03	4.96E+02	3.63E+00	1.96E+05	1.87E+05	0.00E+00
Reflective Coating – Styrene Acrylate	Material	5.76E+03	2.35E+02	1.82E+00	1.36E+05	1.31E+05	0.00E+00
	Transport	1.85E+02	2.94E+01	5.90E-02	2.64E+03	2.64E+03	0.00E+00
	Construction	2.01E+02	8.88E+01	1.58E-01	2.77E+03	2.77E+03	0.00E+00
	Total	6.15E+03	3.53E+02	2.04E+00	1.41E+05	1.36E+05	0.00E+00
Rubberized Asphalt Concrete (Mill-and-Fill)	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)	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	Material	1.56E+03	2.58E+02	1.26E+00	3.38E+04	3.13E+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	2.65E+03	6.57E+02	1.98E+00	4.89E+04	4.64E+04	1.18E+05
Slurry Seal	Material	1.38E+03	2.26E+02	1.12E+00	2.97E+04	2.76E+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	2.22E+03	5.52E+02	1.70E+00	4.15E+04	3.94E+04	1.06E+05

* 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.

** Same note as above applies to PED (nonrenewable.)

3.13. Data Quality Requirements and Data Validation

ISO 14040 requires defining data quality requirements (DQR) as part of the goal and scope definition phase of an LCA study (ISO, 2006). Data validation is a part of life-cycle inventory phase where the collected data are evaluated based on DQR. 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 data quality requirements for the intended application have been fulfilled." This section first defines the DQR according to the goal and scope of the studies and then conducts data validation according to the defined DQR.

3.13.1. Data Quality Requirements

This section is conducted using ISO 14044 as the main guideline, as well as the FHWA Pavement LCA Framework. The data quality requirements should be determined based on the goal and scope of the study for which the dataset is going to be used. Considering the defined scope of studies in this chapter, the following are required in terms of data quality; where applicable Table 3.34 was used for assessment of the quality of the data:

Time-related coverage. It is required that all the data sources used for developing the LCI have been collected within the last 10 years under the assumption that the technology, production/construction procedures, and energy sources have not changed drastically during that time. Use of older data sources is only permitted if the data is still representative of the data the current practice and technology and no newer data source is available.

Geographical coverage. At minimum, all the data sources should be based on national average data, although 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 proved that the international data is representative of the US practice.

Technology coverage. It is required that the data represent technologies used at least at the national level, although use of data sources representing 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 proved that the international data is representative of technologies used in the US. Also, the data should represent the particular technology used in the area of the study; in case there is a lack of such data, modeling based on a mix of technologies used within US borders is permitted. Also, the data should represent the particular technology used in the area of the study; in case there is 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; this could be due to uncertainty in data, models, or assumptions.

Table 3.34. Quality assessment methodology used for selected criteria

Criteria	Poor	Fair	Good	Excellent
Time Coverage	15+ year-old data	10 to 15-year-old data	5 to 10-year-old data	Less than 5-year-old data

Criteria	Poor	Fair	Good	Excellent
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%

3.13.2. 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/literature. Table 3.35 shows the results of data quality assessment of the UCPRC LCI database considering the data quality requirements defined in the previous section. 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 discussed in this chapter. The representativeness of each item was calculated by averaging the score that the item received in each of the four categories identified in Table 3.2 (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 3.36 shows the result of comparing GWP and primary energy demand for some of the items in the inventory using different sources. Table 3.36 compares the UCPRC results versus results from other sources in form of ratios of "UCPRC value/value from the other source." Table 3.37 provides more details for the main processes taken directly from *GaBi* that were used to build the UCPRC models.

Cases where this ratio is more than 1.5 are in bold type. However, as stated earlier, the model developed by UCPRC for PCC is a general model in which the mix proportions can be modified; the values presented here are only for a single mix design and these values can change significantly depending on the specified PCC mix design. The other major difference is between the UCPRC GHG values for natural aggregates and those from Stripple (Stripple, 2001.) A comparison of Athena numbers for crushed and natural aggregates reveals a difference of two orders of magnitude and there is no documentation to explain why this significant difference exists. However, PED numbers for crushed and natural aggregate between UCPRC and Athena are close. Therefore, it was assumed that the Stripple (2001) numbers for aggregates were not accurate and no further investigation was conducted.

However, as stated earlier, the model developed by UCPRC for PCC is a general model in which the mix proportions can be modified; the values presented here are only for several examples 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 (2006) GHG values for natural aggregates and those from Stripple (2001.) A comparison of Athena numbers (2006) for crushed and natural aggregates reveals a difference of two orders of magnitude and there is no documentation to explain why this significant difference exists. However, PED numbers for crushed and natural aggregate between UCPRC and Athena are close. Therefore, it was assumed that the Stripple (2001) numbers for aggregates were not accurate for a North American context and no further investigation was conducted.

Table 3.35. (a) Data quality assessment of constituent materials and transportation modes

Item		Time Cov.	Geog. Cov.	Tech. Cov.	Completeness	Representativeness	Reproducibility	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.
Bitumen		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.
Bitumen 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 & 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*.

Item		Time Cov.	Geog. Cov.	Tech. Cov.	Completeness	Representativeness	Reproducibility	Source of Data	Uncertainty	Notes
Limestone		Excellent	Fair	Good	Good	Good	N	*GaBi*	-	Model taken from *GaBi*, calibrated to local conditions based on CA grid mix.
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.
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*.

Item	**Time Cov.**	**Geog. Cov.**	**Tech. Cov.**	**Completeness**	**Representativeness**	**Reproducibility**	**Source of Data**	**Uncertainty**	**Notes**
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*.

Table 3.33. (b) Data quality assessment of composite materials

Surface Treatment	**Life-Cycle Stage**	**Time Cov.**	**Geog. Cov.**	**Tech. Cov.**	**Completeness**	**Representativeness**	**Reproducibility**	**Source of Data**	**Uncertainty**
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 & 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 & 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 & Contractors	Variability in construction process and the equipment used on site

Surface Treatment	Life-Cycle Stage	Time Cov.	Geog. Cov.	Tech. Cov.	Completeness	Representativeness	Reproducibility	Source of Data	Uncertainty
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 & 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 & Contractors	Variability in construction process and the equipment used on site
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 & 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*/	Variability in construction process and the equipment used on site

Surface Treatment	Life-Cycle Stage	Time Cov.	Geog. Cov.	Tech. Cov.	Completeness	Representativeness	Reproducibility	Source of Data	Uncertainty
								Experts & Contractors	
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 & 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 & Contractors	Variability in construction process and the equipment used on site
Reflective Coating	Material Production	Good	Poor	Fair	Fair	Fair	Y	Literature	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 & 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 & 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/	Variability in construction process and the equipment used on site

Surface Treatment	Life-Cycle Stage	Time Cov.	Geog. Cov.	Tech. Cov.	Completeness	Representativeness	Reproducibility	Source of Data	Uncertainty
								CA4PRS/ Experts & Contractors	
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 & 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 & Contractors	Variability in construction process and the equipment used on site
Bonder Concrete Overlay on 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 & Contractors	Variability in construction process and the equipment used on site

Table 3.36. Comparison of results for some of the database items with other sources

GWP (kg CO_2e)	**Unit**	**UCPRC**	***ecoinvent***	**UCPRC/ ecoinvent**	**Stripple**	**UCPRC/ Stripple**	**Athena**	**UCPRC/ Athena**
Aggregate (Crushed)	kg	3.43E-03	NA	NA	1.43E-03	240%	NA	NA
Aggregate (Natural)	kg	2.36E-03	NA	NA	7.35E-05	3211%	NA	NA
Bitumen	kg	4.75E-01	4.29E-01	111%	1.73E-01	275%	NA	NA
Portland Cement	kg	8.72E-01	7.18E-01	121%	8.06E-01	108%	NA	NA
HMA	kg	4.77E-02	NA	NA	3.44E-02	139%	5.92E-02	81%
PCC	kg	1.96E-01	1.09E-01	180%	1.37E-01	143%	1.20E-01	164%
PED (MJ)	**Unit**	**UCPRC**	***ecoinvent***	**UCPRC/ ecoinvent**	**Stripple**	**UCPRC/ Stripple**	**Athena**	**UCPRC/ Athena**
Aggregate (Crushed)	kg	6.04E-02	NA	NA	7.86E-02	77%	5.76E-02	105%
Aggregate (Natural)	kg	4.31E-02	NA	NA	7.67E-02	56%	3.60E-02	120%
Bitumen	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	NA	NA	5.51E-01	81%	5.31E-01	84%
RHMA	kg	5.47E-01	NA	NA	4.04E-01	135%	3.75E-01	146%
PCC	kg	1.24E+00	6.04E-01	205%	8.67E-01	143%	NA	NA

Table 3.37. Data sources for the main processes that were taken directly from GaBi

Item	**Source**	**Location Coverage**	**Time Coverage**
Diesel, combusted in industrial equipment	USLCI/ts	RNA	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

RNA: Region-North America
ts: thinksteps

3.14. Summary

This chapter presents the most comprehensive and up-to-date life cycle inventory database, the UCPRC LCI Database, developed for transportation infrastructure management projects in the state of California as of early 2019. This database includes an extensive list of all the energy sources, materials, mixes, transportation modes, and construction processes used in the projects at state and local government levels. The electricity grid mix and other energy sources used in various life cycle stages are modified to represent the state’s local conditions. Mix designs are defined based on specifications enforced by Caltrans and also cover designs used by local governments. Construction practices are closely simulated based on data collected from local contractors and experts in addition to the collection of primary data collection from a few field projects. The LCI database developed and presented in this chapter has been verified by a third party according to ISO recommendations. This database was developed using the latest data from available databases, literature, and communications with experts and contractors. The UCPRC LCI Database needs to be continually reviewed and get updated because of the continuous improvements in material production technologies, construction practices, and energy sources used for generating electricity and running the material plants. The revision and update process for the UCPRC LCI Database should be repeated every few years using the latest available information. However, the most critical measure that can be taken to improve the quality of the data is to collect primary data from local material production plants and contractors.

CHAPTER 4. LCA Comparison of Urban Street Design Methodologies: Complete Streets versus Conventional Streets, with Sensitivity Analysis on Key Model Parameters

4.1. Introduction

Complete streets are considered solutions for transportation corridors to improve social, economic, and environmental conditions of a neighborhood or community compared to conventional streets (Harvey et al., 2018) and are meant to provide safe access for all users of all ages and abilities using all modes of transport (Smart Growth America webpage on Implementing Complete Streets.) Besides improving safety and providing access for all users, especially non-motorized transportation, other benefits of compete streets mentioned in the literature are reduced costs and environmental burdens, and creation of more livable communities (Caltrans 2017.) Reduced environmental burdens are not the only purpose of complete streets but it is often mentioned in the literature that complete streets are designed to encourage active modes of transport and there is often an explicit or implicit assumption that they will therefore reduce vehicle miles travelled. However, there is no environmental life cycle comparison of complete streets and conventional ones that takes into consideration the possible changes in traffic patterns. This chapter addresses this gap in the knowledge.

4.2. Goal and Scope

The goal of this chapter is to quantify the environmental impacts of implementing complete streets (CS) guidelines using the life cycle assessment methodology and compare with the impacts of streets designed under conventional methods.

Six types of urban streets were benchmarked and compared under two design scenarios:

- A conventional design using Section Four of the Sacramento County Office of Engineering Improvement Standard (Sacramento County, 2009), which is an example of a standard currently in use for designing conventional streets, and
- A complete streets design using the Complete Streets Manual from the Department of Urban Planning of the City of Los Angeles, (City of LA, 2014.)

The system boundary for each street type includes material production, transportation of raw materials from extraction site to processing plant and from there to the construction site, and construction activities; this is referred to as a cradle-to-laid LCA. Throughout this chapter, the LCA results for these stages of the life cycle are referred to as MAC impacts (Material, transportation, And Construction.)

An analysis period of 30 years was selected for conducting the LCA and calculating payback periods for offsetting the differences in environmental impacts due to complete streets designs compared with conventional designs. The functional unit for all cases in this chapter is considered as one block, except where stated otherwise.

Throughout this chapter, the Sacramento County Standard is referred to as SAC-DG (Sacramento Design Guide), and the design option for each urban street type under SAC-DG is referred to as Conv-Option (Conventional [Design] Option.) Similarly, the manual developed by the City of Los Angeles will be referred to as LA-DG (LA Design Guide), and the design option for each street type under LA-DG is referred to as the CS-Option (Complete Street [Design] Option.) All study details are covered in the "Assumptions and Modeling Details" section, followed by results and discussion.

A sensitivity analysis was also conducted in which the assumed reductions in VMT for CS-Options were evaluated for offsetting the extra MAC emissions of CS-Options compared to Conv-Options. The sensitivity analysis considered a range of changes in vehicle miles traveled for the street type in question and the surrounding network affected by the complete street. The change in vehicle miles traveled data was found in a report from the City of San Jose, as were the following two cases of vehicle speed changes on the complete street, which were also assumed to occur in the portion of traffic that moved to parallel routes in the surrounding network:

- The typical conventional design maximum speed, and
- The design maximum speed recommended for complete streets by the National Association of City Transportation Officials (NACTO)

The results of the LCA study and the limited sensitivity analysis in this chapter provide a quantitative comparison of the environmental impacts of designing urban streets under conventional design guidelines versus complete streets guidelines and includes sensitivity to different assumptions. However, it should be noted that the scope of the LCA study in this chapter is limited to material production, transportation of materials to the site, construction activities, and changes in vehicle miles traveled and vehicle speed, and their effects on selected emissions from the production (well to pump) and combustion (pump to wheel) of vehicle fuel in the use stage. The assessment does not include the end-of-life of the built infrastructure, or any other effects on vehicles or the use of alternative modes of transportation in lieu of motorized vehicles.

All vehicles are assumed to burn gasoline and only passenger cars and light-duty trucks (SUVs) are considered, which means that consideration of any heavier freight vehicles is excluded.

A limitation of many complete street designs is that they do not consider existing use of a conventional street for freight vehicles (it can be said that they are "incomplete" in that sense.) Any changes in freight vehicle routes, changes in speed and operation of freight vehicles, and changes to smaller freight vehicles that can operate on complete streets and any other logistical changes are not considered in this sensitivity analysis.

In addition to those impacts already mentioned, complete streets can have other important impacts not considered in the limited sensitivity analysis presented in this chapter. Additional case studies for field projects can include consideration of expansion of the system boundaries for LCA, which were limited by the scope and budget of this framework development project.

4.3. Assumptions and Modeling Approach

Six major urban street types identified in SAC-DG were chosen for this study and are listed in Table 4.1. The goal of the LCAs in this section is to benchmark the selected environmental impacts, primary energy demand,

and material consumption of building various urban street types under the two different conventional (SAC-DG and LA-DG) and complete street design guidelines. The main audience for this work is city planners and local governments.

For the LCI and LCIA phases of the LCA, the first step is to quantify the amount of materials needed in each case during the analysis period. SAC-DG has detailed drawings for the cross-section of each conventional street type and other elements such as curb and gutters. SAC-DG drawings (Figure 4.1 below and App-Figures 1 to 3 in Appendix III) were used to determine the dimensions (Table 4.1) needed to calculate the quantity of materials. Minimum aggregate base (AB) and asphalt concrete (AC) thicknesses were also taken from the same reference. Figure 4.2 and Figure 4.3 show design recommendations for thoroughfares by LA-DG and NACTO (2013), respectively (see App-Figures 4 to 13 Appendix III.)

SAC-DG does not offer any recommendations for block length, but it does have requirements regarding maximum speed and minimum stopping sight distance. Due to lack of data availability and because this study is more focused on relative changes in environmental impacts of CS-Options versus Conv-Options, block length for each street type was considered as the minimum stopping sight distance multiplied by two.

Table 4.1. Conventional street dimensions (Sacramento County, 2009)

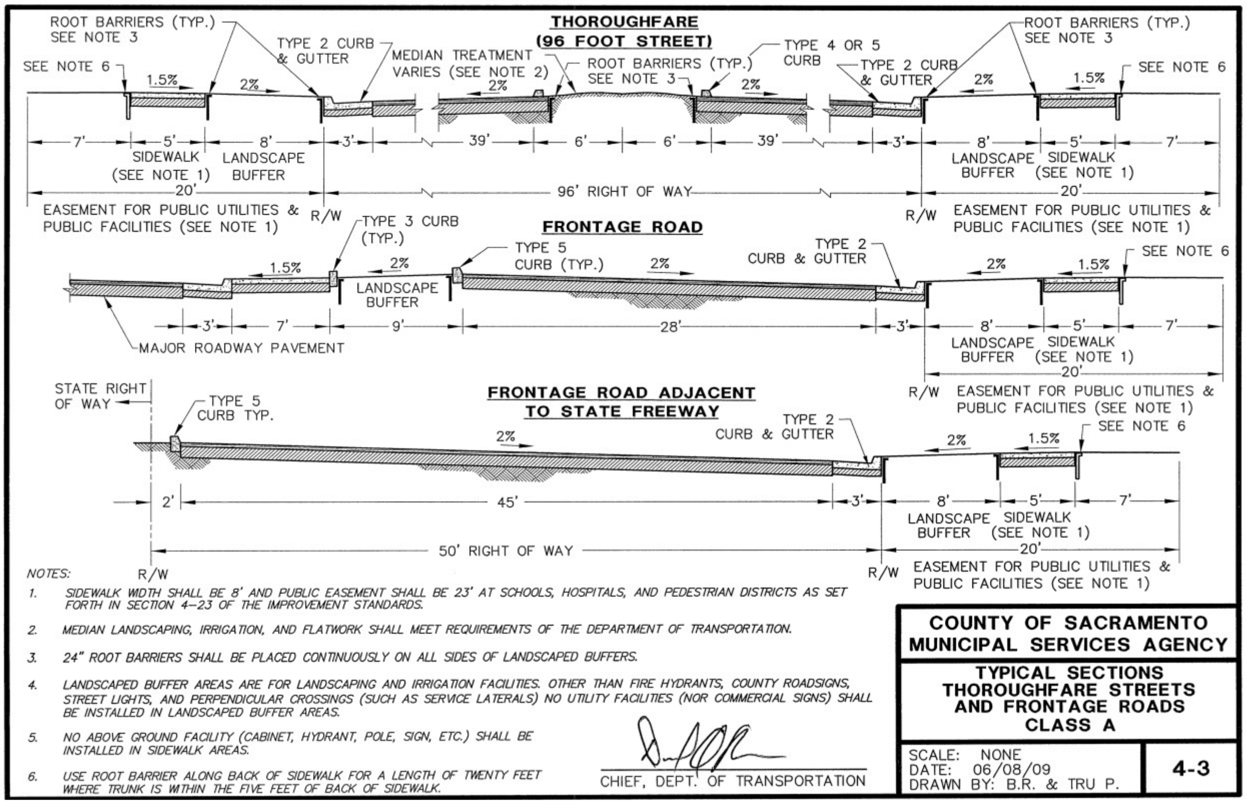
Street Type	Minimum Conventional Asphalt Thickness (in)	Minimum Aggregate Base Thickness (in)	Pavement Width (ft)	Block Length (ft)
32-ft Minor Residential	3	10	26	300
38-ft Primary Residential	3	10	32	400
48-ft Collector	3.5	13	42	500
60-ft Major Collector	4	14	54	600
74-ft Arterial	5.5	20.5	56	720
96-ft Thoroughfare	6.5	23	78	860
Street Type	**Minimum Asphalt Thickness (in.)**	**Minimum Aggregate Base Thickness (in.)**	**Pavement Width (ft)**	**Block Length (ft)**
32-ft Minor Residential	3	10	26	300
38-ft Primary Residential	3	10	32	400
48-ft Collector	3.5	13	42	500
60-ft Major Collector	4	14	54	600
74-ft Arterial	5.5	20.5	56	720
96-ft Thoroughfare	6.5	23	78	860

SAC-DG and LA-DG use different terminologies for street types. Table 4.2 shows how the street types in the two guidelines are matched based on width and traffic levels.

Table 4.2. Street types in SAC-DG and their assumed equivalent categories in LA-DG

Sacramento County	City of LA
Minor Residential (32 ft)	Local Street Standard
Primary Residential (38 ft)	Collector
Collector (48 ft)	Avenue III (Secondary Highway)
Major Collector (60 ft)	Avenue II (Secondary Highway)
Arterial (74 ft)	Avenue I (Secondary Highway)

Sacramento County	City of LA
Thoroughfare (96 ft)	Boulevard I (Major Highway Class I)



NOTES:

1. *SIDEWALK WIDTH SHALL BE 8' AND PUBLIC EASEMENT SHALL BE 23' AT SCHOOLS, HOSPITALS, AND PEDESTRIAN DISTRICTS AS SET FORTH IN SECTION 4–23 OF THE IMPROVEMENT STANDARDS.*
2. *MEDIAN LANDSCAPING, IRRIGATION, AND FLATWORK SHALL MEET REQUIREMENTS OF THE DEPARTMENT OF TRANSPORTATION.*
3. *24" ROOT BARRIERS SHALL BE PLACED CONTINUOUSLY ON ALL SIDES OF LANDSCAPED BUFFERS.*
4. *LANDSCAPED BUFFER AREAS ARE FOR LANDSCAPING AND IRRIGATION FACILITIES. OTHER THAN FIRE HYDRANTS, COUNTY ROADSIGNS, STREET LIGHTS, AND PERPENDICULAR CROSSINGS (SUCH AS SERVICE LATERALS) NO UTILITY FACILITIES (NOR COMMERCIAL SIGNS) SHALL BE INSTALLED IN LANDSCAPED BUFFER AREAS.*
5. *NO ABOVE GROUND FACILITY (CABINET, HYDRANT, POLE, SIGN, ETC.) SHALL BE INSTALLED IN SIDEWALK AREAS.*
6. *USE ROOT BARRIER ALONG BACK OF SIDEWALK FOR A LENGTH OF TWENTY FEET WHERE TRUNK IS WITHIN THE FIVE FEET OF BACK OF SIDEWALK.*

CHIEF, DEPT. OF TRANSPORTATION

COUNTY OF SACRAMENTO
MUNICIPAL SERVICES AGENCY

TYPICAL SECTIONS
THOROUGHFARE STREETS
AND FRONTAGE ROADS
CLASS A

SCALE: NONE
DATE: 06/08/09
DRAWN BY: B.R. & TRU P.

4-3

Figure 4.1: Cross section of a thoroughfare (Sacramento County, 2009.)

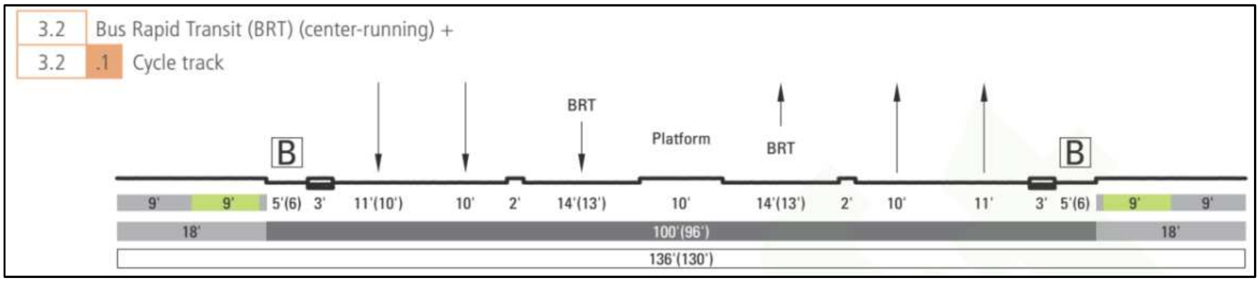


Figure 4.2: LA-DG recommendation for thoroughfare as a complete street (City of LA, 2014)

Figure 4.3: NACTO recommendation for thoroughfare from urban street design guide (NACTO, 2013) pp. 13.

The next phase in LCA is impact assessment (LCIA.) LCIA results were calculated using the TRACI 2.1 impact assessment methodology developed by the U.S. EPA (Bare, 2012.) A reduced set of TRACI impact indicators was used for this study. LCIs and LCIA values are available in the database with appropriate units (per kg of materials and mixes, per ton-km of materials transported, or per lane-km of construction activities.) Full details of all the assumptions and data sources used for developing the UCPRC LCI Database can be found in the UCPRC LCI Documentation report (Saboori et al., 2020.) App-Table 6 in Appendix III shows the list of materials and values of selected LCIA impact categories and primary energy demand (PED) for each. App-Table 7 provides similar data for different surface treatments used in pavement projects in which the functional unit for surface treatment is one lane-kilometer (ln-km), and the system boundary includes material production, transportation, and construction impacts (the values in the table are MAC values.) A few items, such the additional paint and plantings used in complete streets, were directly taken from GaBi LCA software (GaBi webpage) and are not reported in the UCPRC LCI documentation; these items are designated with (GaBi) in their titles.

The impact indicators considered in this chapter are:

- Global Warming Potential (GWP): in kg of CO_2e.
- Photochemical Ozone Creation Potential (POCP): in kg of O_3e (a measure of smog formation.)
- Human Health (Particulate): in kg of $PM_{2.5}$ (particulate matters smaller than or equal to
- 2.5 micrometers in diameter.)
- Total Primary Energy Demand (PED): in MJ.
- Primary Energy Demand (Non-Fuel): in MJ.

Non-Fuel PED is also referred to as “feedstock energy” and represents the energy stored in material that can be recovered for combustion later if need be. The feedstock energy in asphalt binder (as a petroleum product) is a typical example: even though it is not a common practice to recycle binder out of pavement to combust it for energy purposes because of the cost and high emissions, the primary energy stored in the binder can theoretically be recovered for this purpose. On the contrary, the energy used in various combustion processes in the system boundary cannot be recovered. Therefore, the PED (Non-Fuel) should be reported separately (Harvey et al., 2016.)

Table 4.2 shows a complete list of all the CS elements recommended in LA-DG which are sorted into four categories:

- Intersections and Crossings
- Off-Street Non-Vehicular Treatments and Strategies
- Roadways
- Sidewalk Area

LCI and LCIA of the materials and surface treatments presented in App-Tables 6 and 7 were used to calculate the LCI and LCIA for the LA-DG CS elements shown in Table 4.2. The results are presented in App-Table 8 in Appendix III.

For each element (either conventional or CS) a service life was assumed and used to determine the number of times that each will be treated with a typical maintenance, rehabilitation, or reconstruction treatment during the 30-year analysis period. Although the assumptions used in this study are generally more conservative than those in actual practice, it was assumed that the entire conventional street and complete street infrastructure would be replaced at the end of their service life. If any items have remaining service life at the end of the analysis period, a linearly pro-rated salvage value was calculated and credited to the item.

4.4. Data Sources and Data Quality

Table 4.3 summarizes the data sources for all the data used in this study and presents further details about the quality of the data used in this study.

Table 4.3. Data sources and data quality assessment

Item	Data Sources	Geog-raphy	Time	Technol ogy	Com plete ness	Repr oduci bility	Repres entativ eness	Uncert ainty
Electricity	*GaBi*/	Good	Excellent	Excellent	Good	Y	Good	Low
Natural Gas (Combusted)	*GaBi*	Fair	Excellent	Good	Good	Y	Good	Low
Aggregate (Crushed)	*GaBi*/Lit.	Good	Good	Good	Good	Y	Good	Low
Bitumen	*GaBi*/Lit.	Good	Very Good	Good	Good	Y	Good	Low
Crumb Rubber Modifier	*GaBi*/Lit.	Good	Good	Good	Good	Y	Good	High
Extender Oil	*GaBi*	Fair	Good	Poor	Fair	N	Fair	High
Paint	*GaBi*	Fair	Good	Good	Good	Y	Good	Low
RAP	*GaBi*/Lit.	Fair	Excellent	Good	Good	Y	Good	Low

4.5. Study Limitations and Gaps

The main limitation of this study was the lack of reliable model for predicting changes in VMT and traffic speed. Another issue that was not within the scope of this study was the consequential changes in areas outsides the physical system boundary. Energy consumption for lighting and maintaining the landscapes during the use stage was also not included in the study.

4.6. Results and Discussion

Appendix III presents detailed LCA results for each street type designed under SAC-DG (App-Tables 9 to 14) conventional street design, and similar results under LA-DG (App-Tables 15 to 20) complete street design. In this section, the summary and comparison of all results are presented. For each street type, Table 4.4 shows MAC impacts (absolute values) under different impact categories for Conv-Option and CS-Option. Table 4.5 presents the absolute change in each impact category when switching from the Conv-Option to the CS-Option.

Figure 4.4 shows the breakdown of total GWP between CS elements and conventional elements.
In all CS cases, conventional elements of urban streets, meaning the pavement, curbs, and gutters, etc., claim 90 percent or more of total MAC GWP. CS elements in thoroughfares have the maximum share of total GWP among all street types, 10 percent, while CS elements of arterials claim the lowest share, 0.7 percent.

As stated earlier, comparing different street types with each other is not part of the goal of this study, and it does not add much value since functionalities are different. Comparing the same street type under two design methods by just looking at the absolute values of impacts is not very beneficial as these numbers are directly proportional to the length of each block. This approach would have been suitable if the goal was to minimize total emissions or reduce project-level emissions by a certain amount (where absolute values of emissions are important.) However, for this specific research, because the goal is to conduct a preliminary comparison between the two designs and get a first order estimate of changes in impacts, calculating relative values seems most appropriate.

Table 4.4. Absolute values of various impacts categories for the two design options for the materials, transportation, and construction (MAC) stages: conventional (Conv) and complete streets (CS)

Impacts of Conv-Option	**GWP**	**POCP**	**PM2.5**	**PED (Total)**	**PED (Non-Fuel)**
Street Type	**(kg CO_2e)**	**(kg O_3e)**	**(kg)**	**(MJ)**	**(MJ)**
32 ft. Minor Red.	4.80E+04	5.43E+03	2.59E+01	4.66E+05	3.34E+05
38 ft. Primary Red.	1.09E+05	1.34E+04	5.95E+01	1.16E+06	1.37E+06
48 ft. Collector	1.67E+05	2.14E+04	9.09E+01	1.87E+06	2.47E+06
60 ft. Major Collector	2.65E+05	3.47E+04	1.45E+02	3.05E+06	4.51E+06
74 ft. Arterial	4.62E+05	6.10E+04	2.53E+02	5.37E+06	7.99E+06
96 ft. Thoroughfare	8.21E+05	1.11E+05	4.52E+02	9.81E+06	1.62E+07
Impacts of CS-Option	**GWP**	**POCP**	**PM2.5**	**PED (Total)**	**PED (Non-Fuel)**
Street Type	**(kg CO_2e)**	**(kg O_3e)**	**(kg)**	**(MJ)**	**(MJ)**
32 ft. Minor Red.	5.06E+04	5.62E+03	2.72E+01	4.81E+05	2.94E+05
38 ft. Primary Red.	1.14E+05	1.38E+04	6.19E+01	1.20E+06	1.35E+06
48 ft. Collector	1.70E+05	2.49E+04	4.68E+02	1.85E+06	2.45E+06
60 ft. Major Collector	2.87E+05	3.66E+04	1.57E+02	3.21E+06	4.42E+06
74 ft. Arterial	4.59E+05	6.07E+04	2.51E+02	5.34E+06	7.97E+06
96 ft. Thoroughfare	8.13E+05	1.07E+05	4.47E+02	9.38E+06	1.42E+07

Table 4.5. Absolute change in MAC Impacts (impacts of CS-Option minus impacts of Conv.-Option)

Street Type	GWP (kg CO_2e)	POCP (kg O_3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
32-ft Minor Residential	2.57E+03	1.90E+02	1.33E+00	1.48E+04	-3.91E+04
38-ft Primary Residential	4.48E+03	3.76E+02	2.44E+00	3.08E+04	-1.95E+04
48-ft Collector	2.65E+03	3.54E+03	3.77E+02	-1.91E+04	-2.09E+04
60-ft Major Collector	2.26E+04	1.95E+03	1.23E+01	1.60E+05	-8.33E+04
74-ft Arterial	-2.33E+03	-3.16E+02	-1.45E+00	-2.69E+04	-2.55E+04
96-ft Thoroughfare	-8.10E+03	-4.41E+03	-5.92E+00	-4.30E+05	-2.02E+06

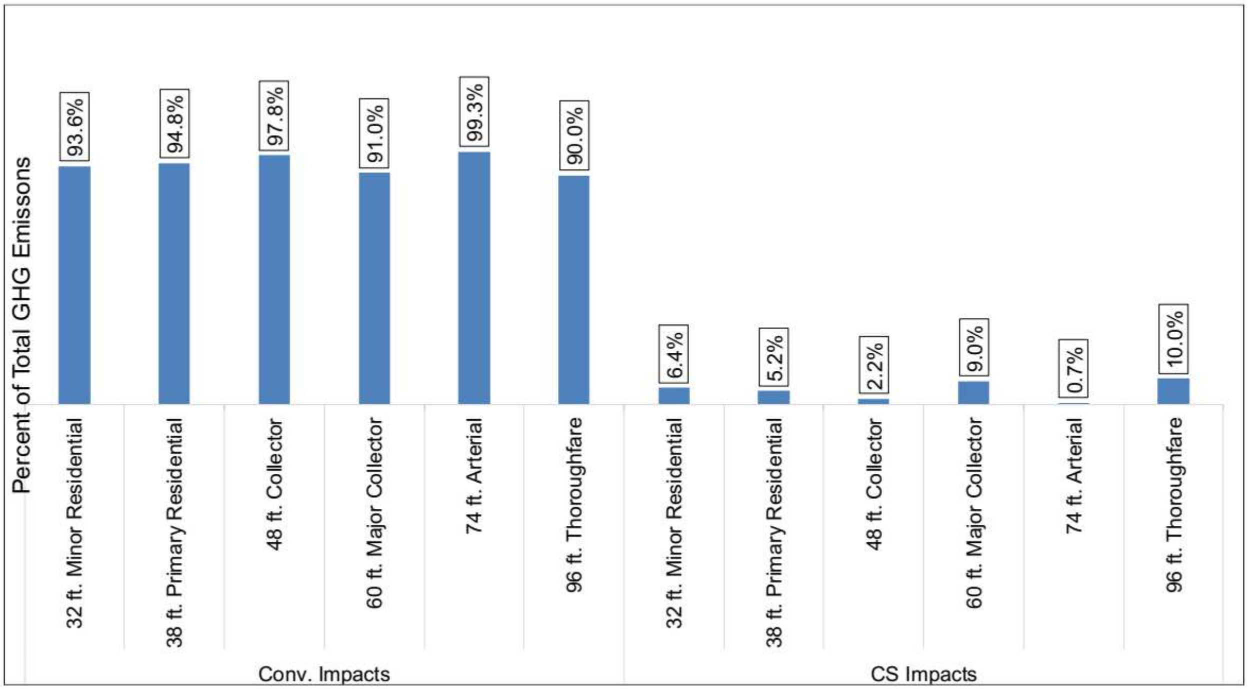


Figure 4.4: Breakdown of materials and construction (MAC) GWP of complete streets between their conventional (Conv.) elements and complete street (CS) elements.

Table 4.6 shows the relative change in MAC impacts. The table shows the percent increase in MAC impacts (in different impact categories) when switching from the Conv-Option to the CS-Option. GWP, POCP, and PM2.5 all increase for residential and collector streets, ranging between a 1.6 to 8.5 percent increase in GWP, a 0.8 to 5.6 percent increase in POCP (smog formation) and a 1.5 to 8.5 percent increase in particulate matter. However, for arterials and thoroughfares, switching from the Conv-Option to the CS-Option results in impact reductions across all categories, ranging between 0.5 to 1.0 percent decrease in GWP, 0.5 to 4.0 percent decrease in POCP (smog formation) and 0.6 to 1.3 percent decrease in particulate matter. These changes are due to differences in the quantities used for different types of materials, primarily asphalt, concrete, and aggregate base resulting from the reduction in total pavement surface area in the complete street designs for these types. These changes in the impact indicators are nearly all less than +/- 10 percent, reflecting the fact that the conversion to a complete street involves relatively small changes in the amounts and types of materials used on a complete street versus a conventional street. PED (Non-Fuel) is the only category in which all street types show a decrease in impacts when switching to CS-Options, with reductions ranging from 0.3 to 12.4 percent. This decrease is mostly because CS elements replace asphalt pavement that has high PED (Non-Fuel) values compared to other items.

As mentioned, PED (Non-Fuel) has no environmental impact and is a measure of use of a non-renewable resource (oil.)

Table 4.6. Percent change in MAC impacts (CS-Conv.)/Conv.

Street Type	GWP (kg CO_2e)	POCP (kg O_3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
32-ft Minor Residential	5.40%	3.50%	5.10%	3.20%	-11.70%
38-ft Primary Residential	4.10%	2.80%	4.10%	2.60%	-1.40%
48-ft Collector	1.60%	0.80%	1.50%	0.70%	-2.10%
60-ft Major Collector	8.50%	5.60%	8.50%	5.30%	-1.80%
74-ft Arterial	-0.50%	-0.50%	-0.60%	-0.50%	-0.30%
96-ft Thoroughfare	-1.00%	-4.00%	-1.30%	-4.40%	-12.40%

4.7. Sensitivity Analysis and Conclusions

4.7.1. Change in VMT

Reducing vehicle miles traveled by facilitating active modes of transportation (biking and walking) is a major goal of CS design guidelines. In this section, a sensitivity analysis that considers a range of changes in VMT is shown. The analysis was performed to provide both an example quantification of the environmental impacts/savings due to such changes, and an idea of the variables influencing the results. The results were then combined with the materials and construction LCA results of the previous section to see the relative sensitivities of MAC, assumed speed change, and assumed VMT change on the model outputs. The results indicate the importance of 1) always including sensitivity to these variables in the framework, and 2) collecting data to use with models to quantify the range of possible values.

To calculate the emissions due to changes in VMT, the environmental impacts of fuel combustion in vehicles during use stage under each design scenario were calculated first. The following assumptions were made for this purpose.

- The assumed daily traffic (number of vehicles/day) values were taken from SAC-DG for each street type.
- The environmental impacts of fuel consumption were calculated in two separate stages:
    - Gasoline production, which includes all the upstream impacts: crude oil extraction, transportation to the refinery plant, processes conducted at the refinery, and transportation to the filling station. These data were collected from the GaBi life cycle assessment software (GaBi webpage) using the process titled "US: Gasoline mix (regular) at filling station ts." The sum of all the upstream contributions is called the "well-to-pump" impact.
    - Tailpipe emissions, also called "pump-to-wheel" emissions, are due to combustion of fuel by the vehicle. The EMFAC2017 Web Database, developed by the California Air Resources Board, was used for this stage (EMFAC2017 Web Database.) The emission rates of light-duty autos (LDA, or passenger cars) and light-duty truck type 1 (LDT1, or sports utility vehicles, SUVs) vehicles in Sacramento county in 2018 were extracted. Results were reported only for gasoline vehicles. It was assumed that 60 percent of the vehicles are passenger cars and 40 percent are light duty trucks. This assumption does not consider changes in VMT of freight vehicles and buses and is therefore only a first-order estimate.

- To calculate well-to-pump impacts, the total amount of fuel used for each vehicle-speed scenario was needed and, as EMFAC does not report fuel consumption values, US EPA's MOtor Vehicle Emission Simulator (*MOVES*) was run to get fuel consumption rates versus speed for all the vehicle speed combinations *(MOVES* webpage.)
- The modeling only considered constant speeds and did not include changes in the drive cycles because *EMFAC* does not have detailed drive cycle data. In addition, two design speeds were considered for complete streets: design speeds for conventional streets and the reduced speeds recommended by NACTO in their f (NACTO, 2013)

Table 4.7 shows the assumptions made for traffic volume and speed for each street type, and Table 4.8 shows the well-to-wheel impacts of vehicle fuel consumption during the use stage for the conventional design scenarios.

Table 4.7. Traffic assumptions made for traffic levels and speeds

Street Type	Traffic (Vehicles per Day)	Conventional Design Speed (mph)
32-ft Minor Residential	1,000	25
38-ft Primary Residential	5,000	30
48-ft Collector	10,000	35
60-ft Major Collector	15,000	40
74-ft Arterial	30,000	45
96-ft Thoroughfare	50,000	50

Table 4.8. Well-to-wheel impacts of vehicle fuel combustion during the 30-year analysis period for conventional design scenarios

Street Type	GWP (kg CO_2e)	POCP (kg O_3e)	PM2.5 (kg)	PED (Total) (MJ)	PED (Non-Fuel) (MJ)
32-ft Minor Residential	3.00E+05	1.00E+01	3.00E+03	4.00E+06	0.00E+00
38-ft Primary Residential	2.00E+06	1.00E+02	2.00E+04	3.00E+07	0.00E+00
48-ft Collector	4.00E+06	2.00E+02	5.00E+04	6.00E+07	0.00E+00
60-ft Major Collector	8.00E+06	4.00E+02	8.00E+04	1.00E+08	0.00E+00
74-ft Arterial	2.00E+07	9.00E+02	2.00E+05	2.00E+08	0.00E+00
96-ft Thoroughfare	4.00E+07	2.00E+03	4.00E+05	5.00E+08	0.00E+00

There is no reliable and widely accepted model for estimating VMT reduction due to implementation of CS elements for different street types, as was discussed in Chapter Three. While some studies report as much as a 15 percent reduction in VMT (Smart Growth America 2015 Conference webpage) other studies show mixed results with a high level of variability. For example, Figure 4.5 shows the histogram of percent reduction in daily traffic in different streets in San Jose after implementing a road diet (Nixon et al., 2017.) The San Jose study measured VMT changes on the complete street and on adjacent streets, so the changes measured can be considered to represent the network of parallel alternative routes around the complete street, not just the complete street itself. It is important to appreciate the importance of this matter as it is reasonable to assume that a portion of the traffic would use parallel routes to avoid traffic calming measures and dedicated lanes for active modes of transport in complete streets.

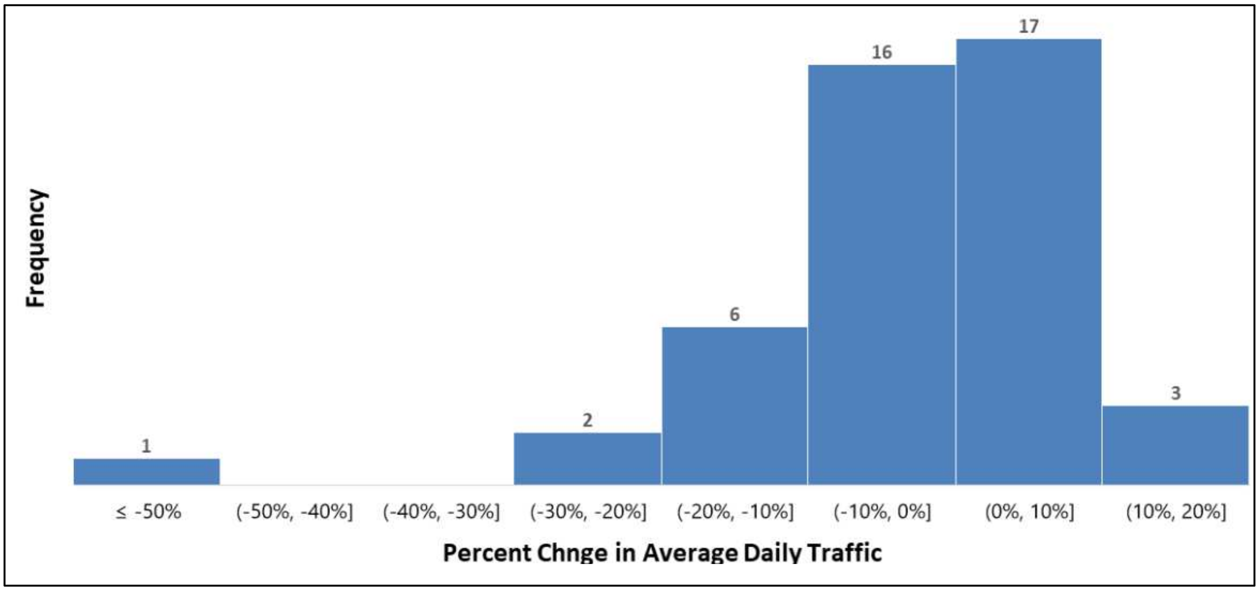


Figure 4.5: Histogram of changes in daily traffic after implementing road diets on conventional streets in San Jose (Nixon et al., 2017.)

Therefore, it was decided to select a range of changes in VMT and to run the model for each case to gain a better understanding of the sensitivity of the results to changes in traffic. The model was run for five cases of VMT change for each street type, and the assumptions were made based on the San Jose report that these VMT changes were for the complete street and the streets around it, combined. The change in VMT ranged between -15 percent to +5 percent. Any changes in congestion were not considered.

Figure 4.6 and figure 4.7 compare the difference in GHG emissions of MAC and well-to-wheel for the CS-Option versus the Conv-Option for minor residential and thoroughfare streets across the range of changes in VMT levels. These two street types have the lowest and highest traffic and slowest and fastest traffic speeds, respectively, and therefore show the range of impacts of VMT and speed change. Defining the total life cycle impacts as the summation of MAC and well-to-wheel impacts during the life cycle, the figures show that relatively small changes in VMT can result in major changes in total life cycle GHG emissions. This is because well-to-wheel impacts are initially one to two orders of magnitude larger than MAC impacts (compare the values in Table 4.4 and Table 4.8); therefore, any small change in traffic patterns drives the net change in total impacts. Figure 4.8 and Figure 4.9 show the cumulative GHG emissions with time for the same two street types, highlighting the payback period for each case of change in VMT. While it takes at least two years to fully offset the extra MAC impacts of CS-Options with reductions in well-to-wheel impacts for the best-case scenario of 15 percent reduction in VMT, this payback can never be realized if the VMT does not change or increases. For thoroughfares, the situation is different, as the MAC of the CS-Option is actually lower than the MAC of the Conv-Option. So, as long there is no increase in VMT, implementation of the CS option results in reduction of total impacts.

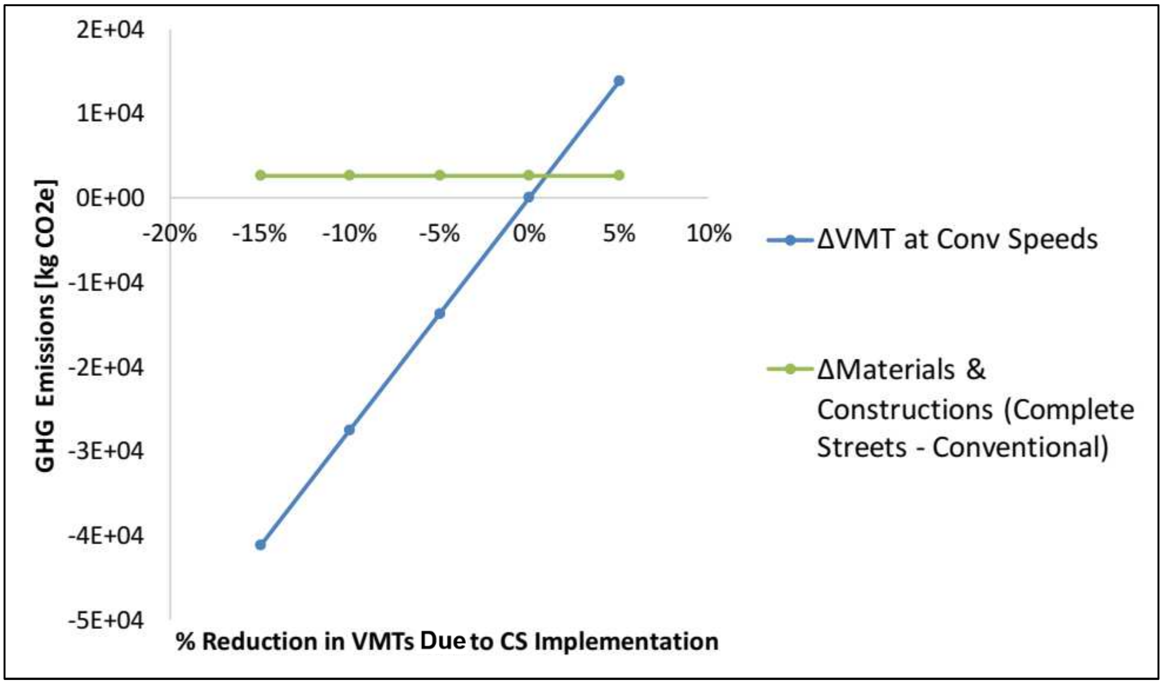


Figure 4.6: Difference in well-to-wheel and MAC GWP [kg CO$_2$e] impacts (CS-Conv) during the analysis period (30 years) for 32-ft minor residential only considering changes in VMT for well-to-wheel.

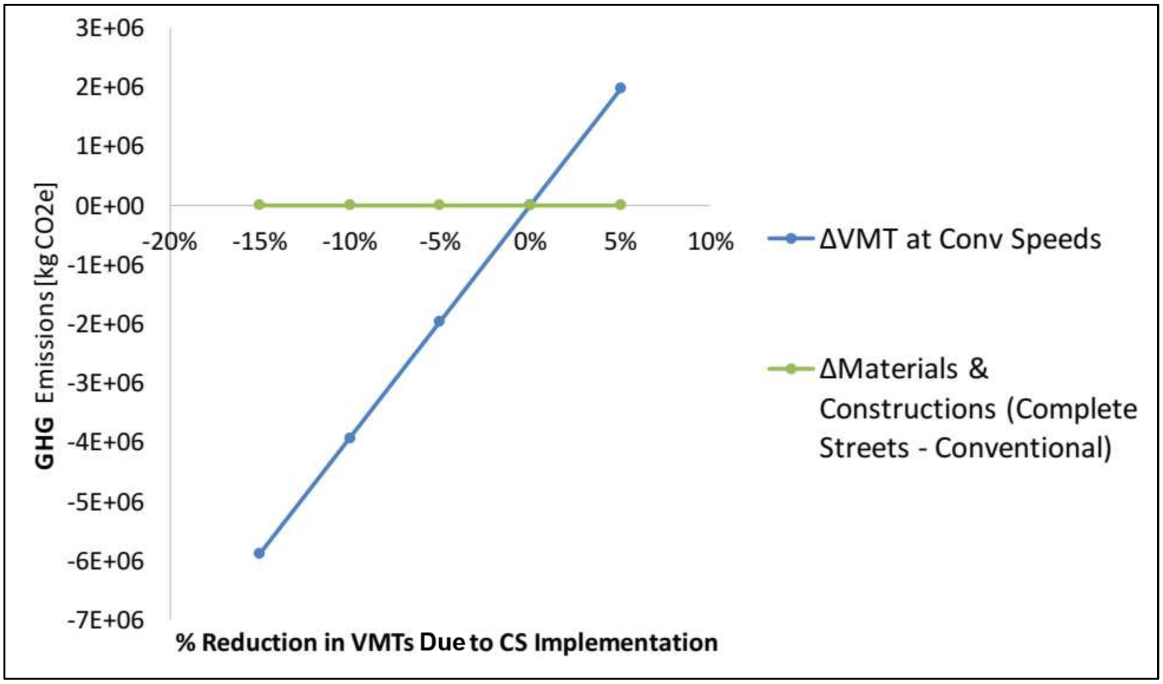


figure 4.7: Difference in well-to-wheel and MAC GWP [kg CO$_2$e] impacts (CS-CONV) during the analysis period (30 years) for 96-ft thoroughfare only considering changes in VMT for well-to-wheel

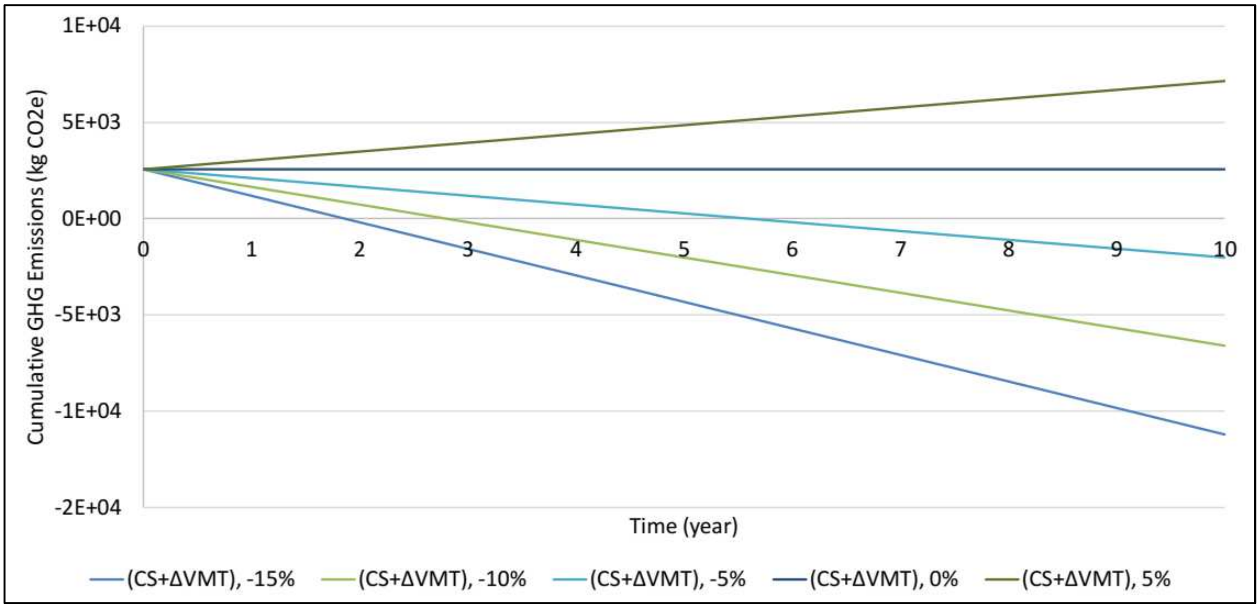


Figure 4.8: Cumulative GHG emissions for 32-ft minor residential assuming only changes in VMT.

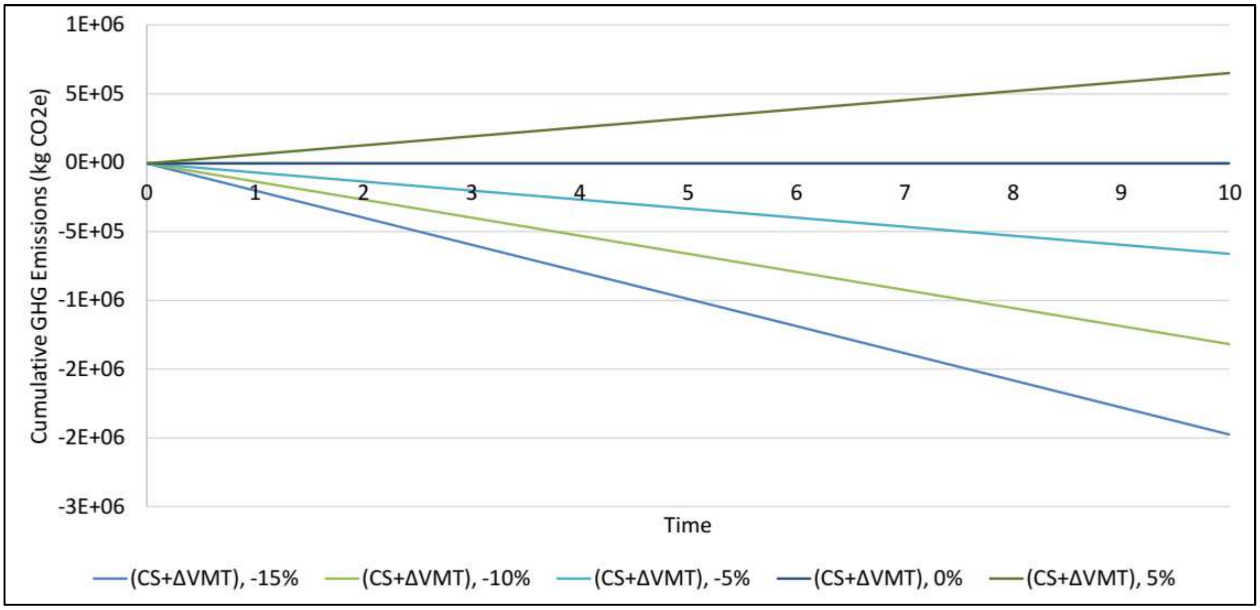


Figure 4.9: Cumulative GHG emissions for 96-ft thoroughfare assuming only changes in VMT.

4.7.2. Changes in Traffic Speed

In addition to reducing VMT and encouraging active modes of transportation, urban designers prefer using traffic calming designs that reduce traffic speed to increase safety and make active transportation modes more attractive to the public. In this section, the impact of such measures is quantified by considering the effects of reduced speed on vehicle fuel consumption using the lower speed limits recommended in the NACTO design guide (NACTO, 2013.) Table 4.9 shows the conventional design speed limits and the speed limits recommended by NACTO. Reducing traffic speed can improve safety, and potentially increase mode change from vehicles to active transportation as discussed in Chapter Three, however, it can have negative impacts on the fuel efficiency of vehicles. Figure 4.10 shows the changes in vehicle fuel efficiency, expressed as miles per gallon (mpg) or miles travelled per gallon of fuel, versus speed for passenger cars and light duty trucks based on data collected from the *MOVES* model *(MOVES* webpage.) Figure 4.11 and Figure 4.12 show similar trends by plotting tailpipe global warming potential and PM 2.5 emissions based on data collected from the EMFAC model (EMFAC2017 Web Database.)

The sensitivity analysis for changes in VMT presented in the previous section was repeated for the design speeds recommended by NACTO and the results are plotted in Figure 4.13 and Figure 4.14 for minor residential streets and thoroughfares, respectively. As the results in the figures show, reductions in traffic speed can have significant impacts on the well-to-wheel emissions of the traffic during the use stage. For minor residential streets, reduction of design speeds from 25 to 20 miles per hour results in an increase in well-to-wheel impacts for complete street versus conventional options across all values of change in VMT. This is because within the speed range of residential streets, any speed reduction results in dramatic decreases in fuel efficiency and increases in tailpipe emissions, and the resulting increased emissions cannot be offset by even a 15 percent reduction in VMT.

However, the opposite is true for thoroughfares because when design speed is changed from the conventional value of 50 miles per hour (mph) to the NACTO recommended speed of 45 mph for thoroughfares, the fuel consumption of passenger cars decreases to its minimum value across all speeds (45 mph is an optimal speed for fuel consumption according to the model.) Therefore, for the case of the thoroughfare, the speed limit reduction further intensifies the reduction of well-to-wheel impacts due to VMT reduction. Figure 4.15 which shows well-to-wheel GHG emissions (kg CO_2e per mile) for a traffic mix of 60 percent passenger cars and 40 percent light-duty truck type 1 vehicles, can be used to identify the speed range in which a traffic speed reduction results in lowered GHG emissions and avoids the unintended consequence of increased GHG emissions due to reduced speed.

Table 4.9. Conventional design speed limits and NACTO recommended values for different street types

Street Type	Traffic (Vehicles per Day)	Conventional Design Speed (mph)	NACTO Design Speed (mph)
32-ft Minor Residential	1,000	25	20
38-ft Primary Residential	5,000	30	25
48-ft Collector	10,000	35	25
60-ft Major Collector	15,000	40	30
74-ft Arterial	30,000	45	35
96-ft Thoroughfare	50,000	50	45

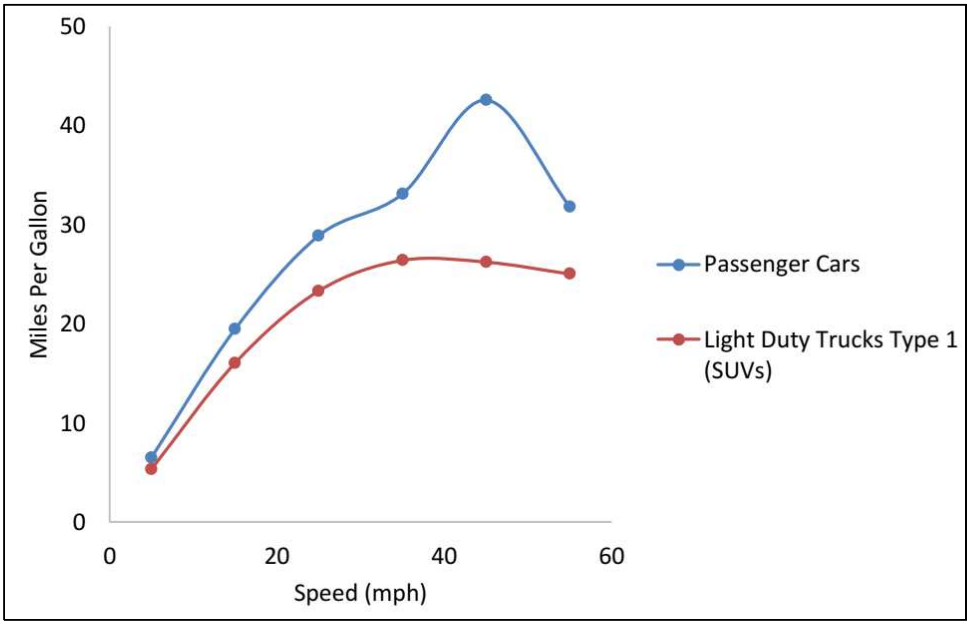


Figure 4.10: Changes in MPG with speed based on US EPA's MOVES data.

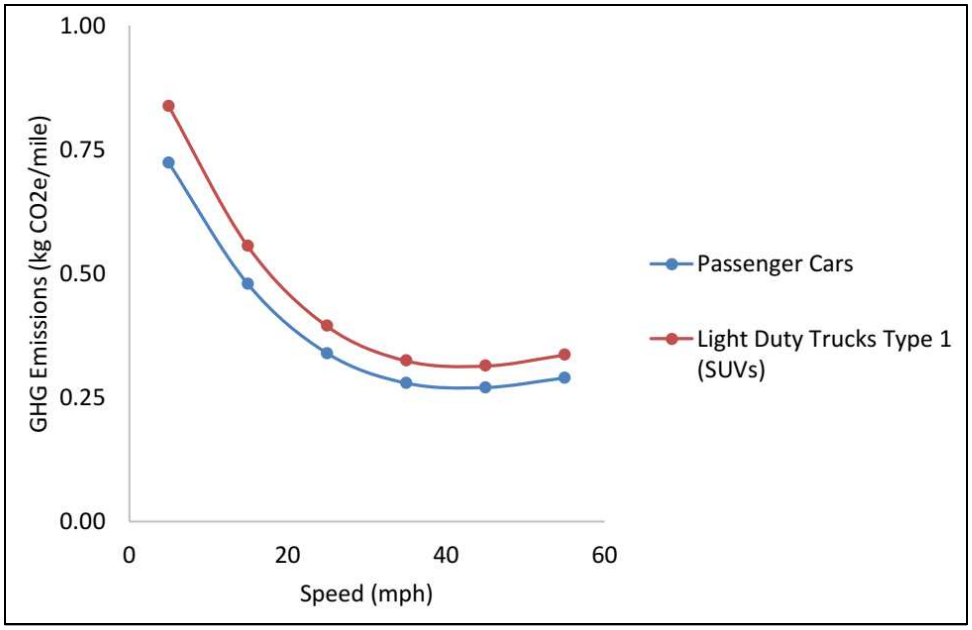


Figure 4.11: Changes in tailpipe GHG emissions based on EMFAC model.

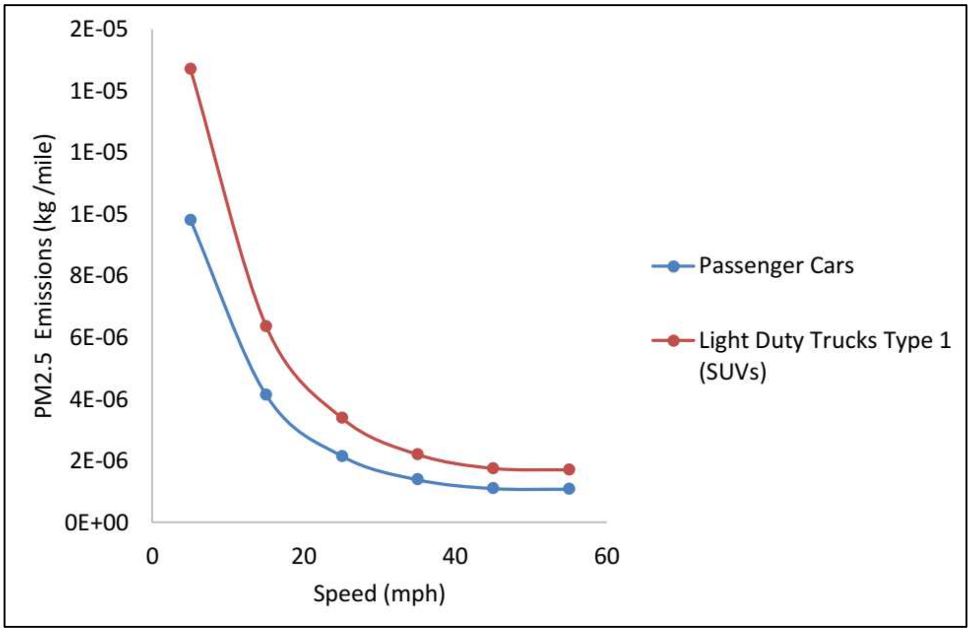


Figure 4.12: Changes in tailpipe PM2.5 emissions based on EMFAC.

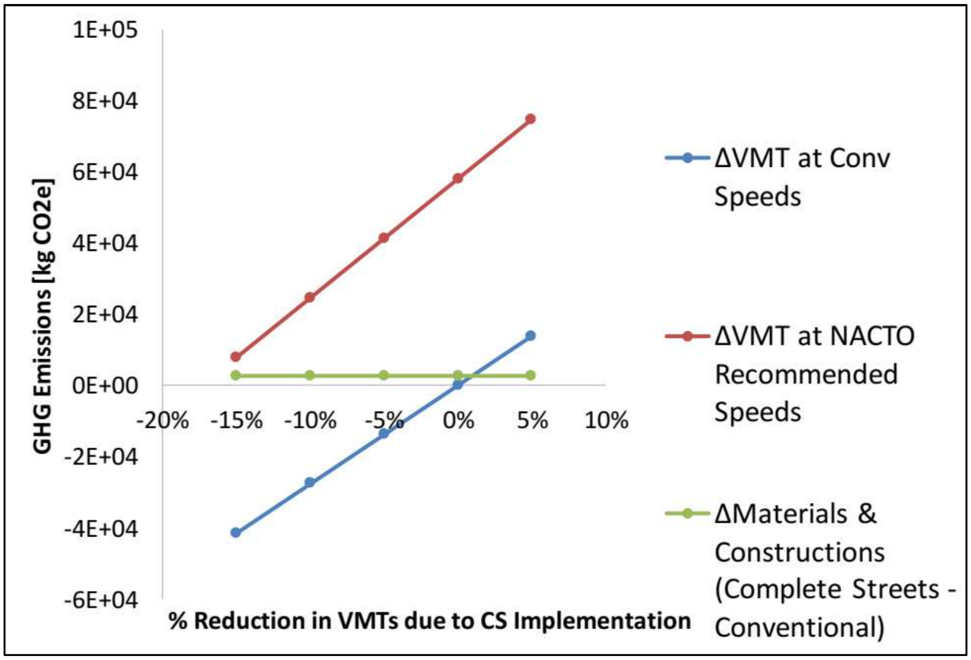


Figure 4.13: Difference in well-to-wheel and MAC GWP [kg CO_2e] impacts (CS-Conv) during the analysis period (30 years) for 32-ft minor residential considering changes in both VMT and traffic speed for well-to-wheel impacts.

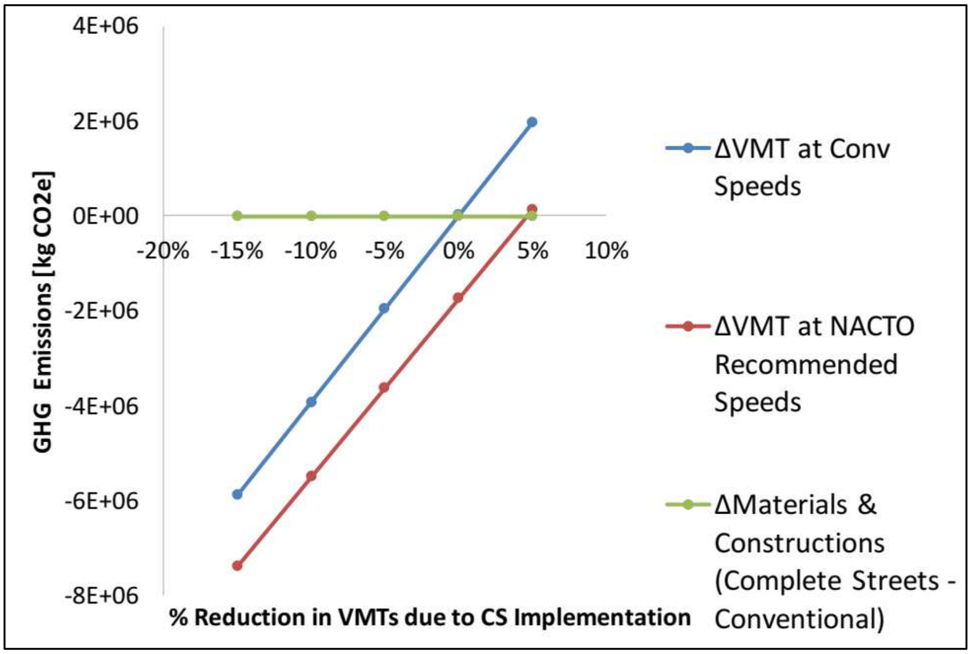


Figure 4.14: Difference in well-to-wheel and MAC GWP [kg CO_2e] impacts (CS-Conv) during the analysis period (30 years) for 96-ft thoroughfare considering changes in both VMT and Traffic Speed for well-to-wheel impacts.

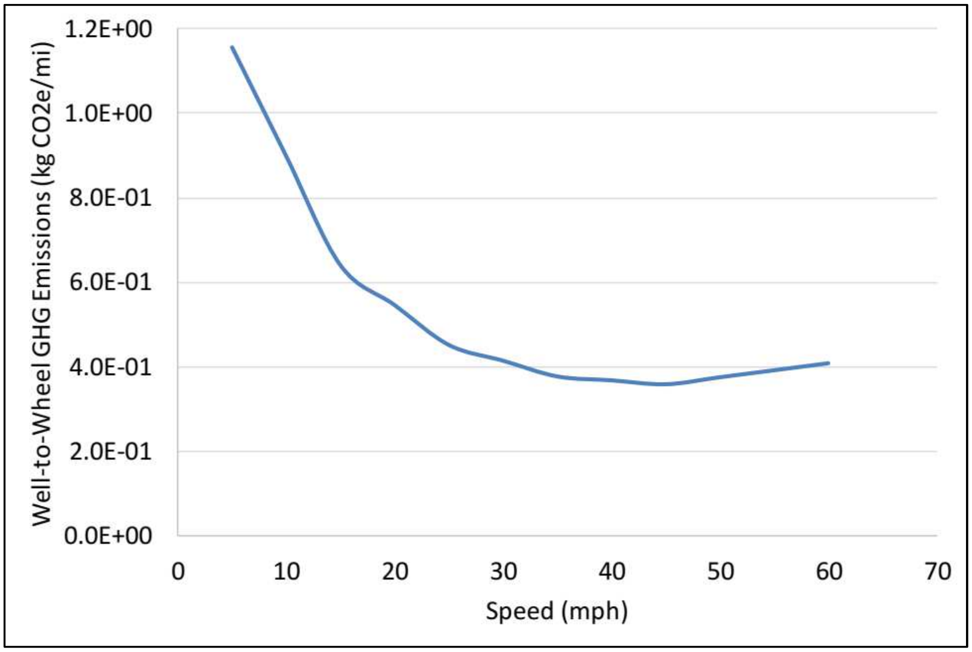


Figure 4.15: Well-to-Wheel GHG emissions versus speed for a mix of 60% passenger cars and 40% light duty trucks type 1.

4.8. Summary

A preliminary set of rudimentary assumptions was used to demonstrate the use of LCA to consider the full life cycle environmental impacts of conversion of several types of conventional streets to complete streets.

The importance of objective and reliable models for changes in traffic volume and congestion from the implementation of complete streets and comparison with conventional streets cannot be overstated. The full system impacts of complete streets on environmental impact indicators, considering materials, construction, and traffic changes, are driven by changes in reduction in VMT and changes in the operation of the vehicles with regard to speed and drive cycle changes caused by congestion, if it occurs. To avoid situations where well-intended efforts might result in greater environmental impacts, utilization of life cycle assessment should be used as a robust and objective methodology that consider the full life cycle of the alternatives. Each LCA study should use 1) high-quality data, 2) a correct definition of the system boundary, and 3) include a thorough investigation, identification, and quantification of possible significant unintended consequences.

The initial results indicate that application of the complete streets networks to streets where there is little negative impact on vehicle drive cycles from speed change will have the most likelihood of causing overall net reductions in environmental impacts.

The results also indicate that there is a range of potential VMT changes to which environmental impacts are more sensitive than they are to the effects of the materials and construction stages, and that changes in vehicle speed have different effects on environmental impacts depending on the context of their implementation, including the street type. These results indicate that the effects on environmental impacts due to implementing a complete street should be analyzed on a project-by-project basis, and that the effects will not always be positive. This preliminary conclusion leads to recommendations that this type of analysis be performed on a project-by-project basis, that the analysis include the surrounding network, and that a sensitivity analysis should also be included.

CHAPTER 5. Assessment of Different Pathways for Adoption of Alternative Fuel Vehicles by Caltrans Fleet Services Considering Changes in GHG Emissions and Life Cycle Costs

5.1. Introduction

The transportation sector is a major source of greenhouse gas (GHG) emissions and is responsible for more than 28 percent of the 6,511 million Metric Tonnes (MMT) of CO_2e emissions in the U.S. (EPA webpage on the U.S. GHG Emissions) and 38.5 percent of the 429 MMT of GHGs emitted in California in 2016 (CARB webpage on CA GHG Emissions.) Figure 5.1 shows the breakdown of GHG emission in the U.S. and California.

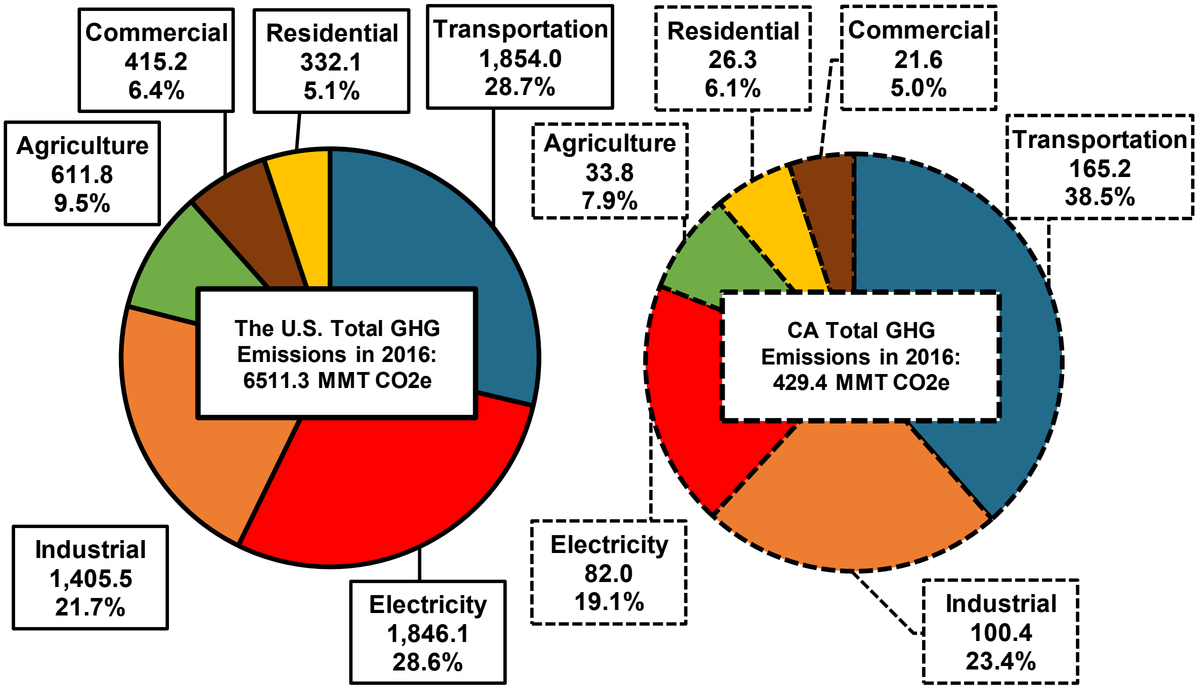


Figure 5.1:Breakdown of the national and statewide GHG emissions (MMT CO_2e) by sector in the U.S. and California in 2016 (EPA webpage on the U.S. GHG emissions, CARB webpage on CA GHG emissions.)

There are aggressive reduction targets for GHG emissions in California to mitigate climate change and global warming. These targets are mandated by landmark legislation such as Assembly Bill 32-California Global Warming Solutions Act of 2006 (CARB webpage on AB32) Senate Bill 32 (CA legislature webpage on SB32), and Executive Order EO-B-30-15 (CA State webpage on Climate Change), which set the 2030 GHG reduction target at 40 percent below 1990 levels, and then mandate an 80 percent reduction of 1990 levels by 2050. The California 2017 Scoping Plan (CARB webpage on CA Scoping Plan) is the overarching plan for meeting the state's ambitious targets in mitigating climate change.

Multiple programs are aiming at reducing GHG emissions of the transportation sector in California. These programs can be divided into three main categories: 1) land use, 2) cleaner fuels, 3) alternative vehicle technologies.

The land use policies are aimed at reducing vehicle miles traveled (VMT) through various modified land use planning and urban design philosophies, promotion of active modes of transport, public transit improvement projects, provision of local shopping and service centers, reduction of urban sprawl and provision of incentives and benefits for programs such as car-sharing, car-pooling, and more. SB375 is the main regulation for reducing transportation GHG emissions through land use policies (CARB webpage on SB375.)

The Low Carbon Fuel Standard (LCFS) is the main program for transitioning to cleaner fuels that have lower carbon footprints (CARB webpage on LCSF.) LCFS was initially approved in 2009 and is a market-based instrument that sets targets for reductions in carbon intensity (CI) of fuel mix across the whole market. The CI is calculated by conducting life cycle assessment (LCA) on each fuel pathway available in the market. Application of LCA allows accounting of all the environmental impacts that occur during the full life cycle of a fuel pathway, from raw material extraction from the ground to transportation to refinery plants, processes conducted in the plant, transportation to the gas stations, and combustion in vehicles. CI is expressed in grams of CO_2e emitted per Megajoule of energy (gCO_2e/MJ.)

New vehicles technologies are divided into zero emission vehicles (ZEV) and near-zero emission vehicles (NZEV.) ZEVs and NZEVs are expected to play a major role in curbing GHG emissions from the transportation sector by replacing the conventional internal combustion engine vehicles (ICEVs.) California 2016 ZEV Action Plan (CA State webpage on ZEV Action Plan) mandates 1.5 million ZEVs and NZEVs, such as plug-in hybrid electric vehicles (PHEVs), battery-electric vehicles (BEVs, also referred to as EVs), and hydrogen fuel cell vehicles (FCVs), by 2025 and 4.2 million by 2030.

The State of California has begun two initiatives for state agencies to reduce the environmental impacts of their fleet and buildings (Green CA webpage.) This chapter focuses on adoption of alternative fuel vehicles (AFVs) for the Caltrans fleet. A brief background of AFVs is presented followed by a model to calculate life cycle costs, fuel consumption, and GHG emissions of multiple pathways for transitioning Caltrans fleet to reduce GHG emissions. The results of this chapter can be used to compare different pathways in terms of costs and environmental impacts, identify the tradeoffs between options, and choose the most suitable approach to meet the agency's sustainability goals while controlling life cycle costs.

5.2. Background

The Energy Policy Act (EPAct) of 1992 (AFDC webpage on EPAct) defined alternative fuels and assigned the United States Department of Energy (U.S. DOE) to develop a regulatory program for selected state fleets[1] as

---

[1] *"State and alternative fuel provider fleets are considered covered fleets if they own, operate, lease, or otherwise control 50 or more non-excluded light-duty vehicles (less than or equal to 8,500 pounds) and if at least 20 of those vehicles are used primarily within a single Metropolitan Statistical Area/Consolidated Metropolitan Statistical Area and are centrally fueled or capable of being centrally fueled."* https://epact.energy.gov/

launching pads for advanced vehicles using alternative fuels. Energy Policy Act of 1992 considers the followings as alternative fuels:

- Methanol, ethanol, and other alcohols
- Blends of 85 percent or more of alcohol with gasoline
- Natural gas and liquid fuels domestically produced from natural gas
- Liquefied petroleum gas (propane)
- Coal-derived liquid fuels
- Hydrogen
- Electricity
- Fuels (other than alcohol) derived from biological materials, including pure biodiesel (B100)
- P-Series[2]

5.2.1. Key Federal Statutes

Major federal statutes that established key transportation regulatory activities (DOE webpage on EPAct) are listed below:

- Clean Air Act Amendments of 1990 which encouraged production and use of AFVs
- Energy Policy Act of 1992
- Energy Conservation Reauthorization Act of 1998 which allowed the fleets covered under EPAct to include biodiesel blend use as credits towards compliance.
- Energy Policy Act of 2005 allowed covered fleets to reduce petroleum consumption instead of acquiring alternative fuel vehicles.
- Energy Independence and Security Act of 2007 added certain electric drive vehicles and investments in infrastructure, equipment, and emerging technologies to the list of items to gain credit for compliance.

5.2.2. Major Initiatives in California

Senate Bill 522, passed in 2003, adopted the recommendations from the California State Vehicle Fleet Fuel Efficiency Report and required the collection of statewide fleet data and the publishing of annual public reports about the fleet composition (CA Legislature webpage on SB522.)

Assembly Bill 236, passed in 2007, required increased use of alternative fuel vehicles to meet the following targets: a 10 and 20 percent reduction or displacement of conventional vehicles by January 1, 2012, and January 1, 2020, respectively (CA Legislature webpage on AB236.)

Executive Order B-16-12, issued by Governor Brown in 2012, directed state fleets to increase the purchase of ZEVs through the normal course of fleet replacement, requiring them to have at least 10 percent of light-duty vehicle purchases from ZEVs by 2015. This target would increase to 25 percent by 2020 (CA State webpage on EO-B1612)

---

[2] *"P-Series is a family of renewable, non-petroleum, liquid fuels that can substitute for gasoline. They are a blend of 25 or so domestically produced ingredients. About 35 percent of P-Series comes from liquid by-products, known as "C5+" or "pentanes-plus", which are left over when natural gas is processed for transport and marketing."*

Senate Bill 1275, Charge Ahead California Initiative, passed in 2014 established a state goal of one million zero-emission and near-zero-emission vehicles in service by 2020 (CA Legislature webpage on SB1275.)

Executive Order (EO) B-30-15, issued by Governor Brown, directed "that all state agencies with jurisdiction over sources of greenhouse gas emissions shall implement measures, pursuant to statutory authority, to achieve reductions of greenhouse gas emissions to meet the 2030 and 2050" reductions targets of 40 percent and 80 percent below 1990 GHG emission levels, respectively.

The California State Administrative Manual set the ZEV purchasing policy for state agencies, which includes the "ZEV and hybrid vehicle first" policy which requires departments to purchase light-duty following this priority structure: (1) pure ZEVs, (2) PHEVs, and (3) hybrids. The policy also increased the ZEV purchasing mandate annually by 5 percent so that it will be 50 percent by 2025 (CA DGS webpage on ZEV Purchasing Policy.)

Section 3627 of the State Administrative Manual mandates the use of renewable diesel instead of conventional diesel and biodiesel fuel for bulk transportation fuel purchases (CA DGS webpage on Fuel Purchasing Policy.) Section 3620.1 of the Manual sets the vehicle fuel efficiency requirements, expressed in miles per gallon (mpg) of fuel, for light-duty passenger vehicles to 38 and light-duty trucks, vans, and sport utility vehicles (SUVs) to 22.2 (CA DGS webpage on Fuel Efficiency Requirements.)

5.2.3. AFVs Acquired by Fleets Regulated under EPAct at National-Level

This section focuses on AFV acquisitions by covered fleets[3] after the U.S. Congress passed the Energy Policy Act in 1992. The goal is to observe adoption trends and popularity of different fuel types among fleet services. The data were collected from the Alternative Fuel Data Center webpage maintained by the U.S. Department of Energy (AFDC webpage on EPAct History.) The top graph in Figure 5.2 shows the number of AFVs acquired by covered fleets between 1992 and 2017 and the bottom graph represents the distribution of AFVs by fuel type in each year.

Compressed natural gas (CNG) and liquefied petroleum gas (LPG) vehicles were initially the popular choices among fleet services between 1992 and 2000, as shown in Figure 5.2. However, gasoline mixed with ethanol up to 85 percent (E85) started gaining traction from the second half of the 1990s, quickly reaching the first rank among all fuel types. More than 90 percent of all AFVs acquired by covered fleets since 2005 are E85 vehicles.

Electric vehicles (EVs) adoption rates were highest between 1997 and 1999 with growth rates between 56 and 71 percent in the number of EVs acquired each year. During that time interval EVs were comprising 4 to 7.4 percent of all AFVs acquired each year. The two-digit growth rates quickly diminished to 3 to 8 percent range until 2015 after which EVs have once again become a popular choice with growth rates of 10 to 11 percent in annual acquisitions, making EVs the second most popular choice among all AFV options, after E85 vehicles.

---

[3] "*State and alternative fuel provider fleets are considered covered fleets if they own, operate, lease, or otherwise control 50 or more non-excluded light-duty vehicles (less than or equal to 8,500 pounds) and if at least 20 of those vehicles are used primarily within a single Metropolitan Statistical Area/Consolidated Metropolitan Statistical Area and are centrally fueled or capable of being centrally fueled." –https://epact.energy.gov*

Figure 5.3 shows two pie charts of acquired AFVs by fuel type. The right section of the figure shows acquisitions made in 2017, and the left chart shows all the AFVs acquired by covered fleets since 1992. Eighty percent of more than 304 thousand AFVs acquired between 1992 and 2017 are E85 vehicles, 13 percent are CNG vehicles followed by four percent LPGs and three percent EVs. However, more than 93 percent of the 20,000 AFVs acquired in 2017 are E85, which is more than 93 percent of all AFVs. Next are EVs with 3.4 percent share of annual acquisitions followed by CNGs with only 2.7 percent.

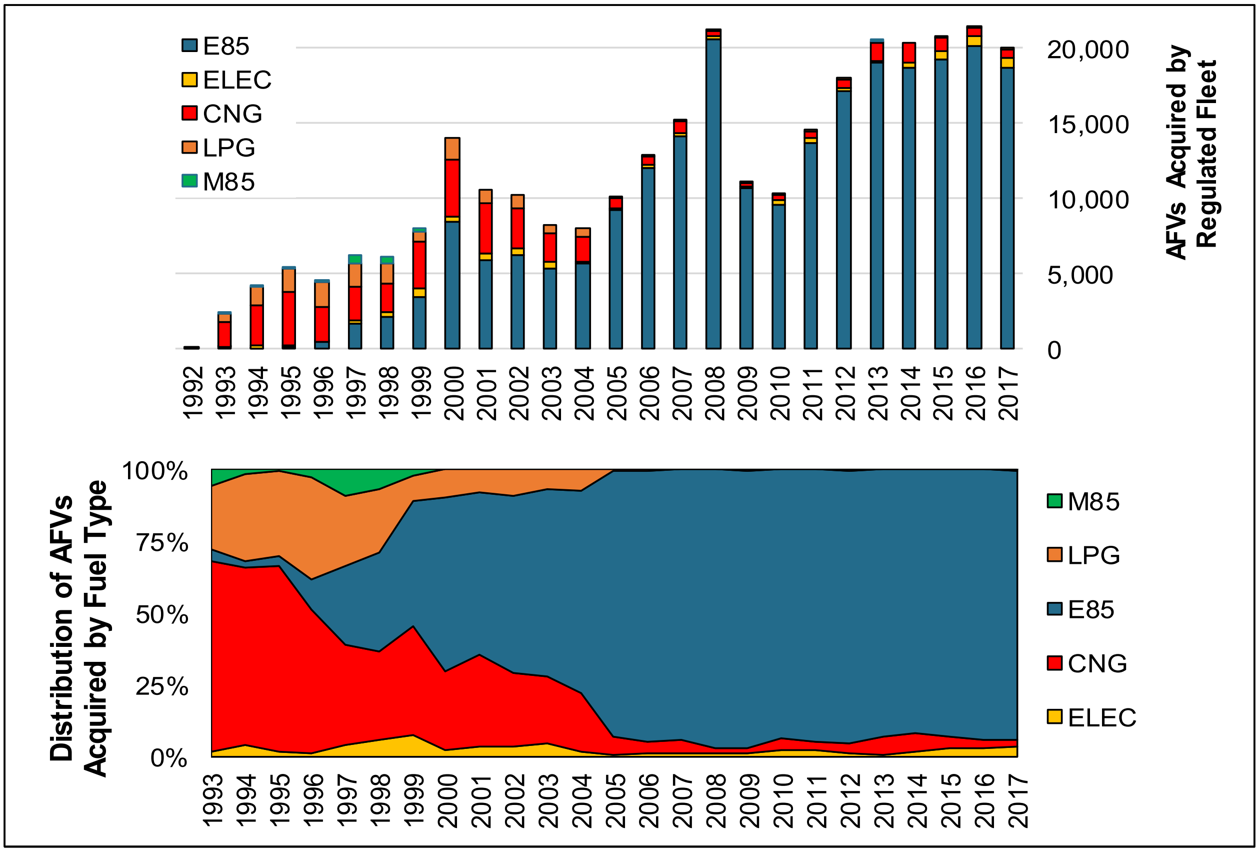


Figure 5.2: AFV acquisitions by regulated fleets per year by fuel type (top figure) and distribution of AFV acquisitions per year by fuel type (bottom figure)

While the total number of AFVs acquired per year has increased by an average of 10 percent per year, EVs have had the highest growth rates since 2015 with an average of 11 percent year to year growth. The growth rate for E85 vehicles which used to be as high as 27 percent in 2008, is currently less than 10 percent.

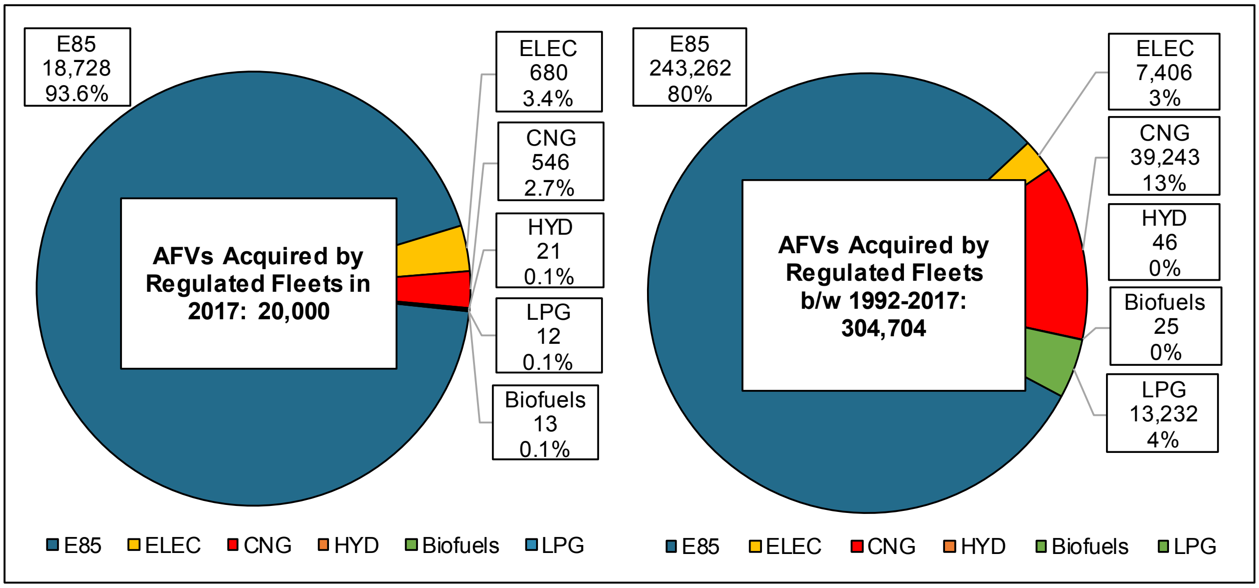


Figure 5.3: Breakdown of AFV acquired by fleets regulated under EPAct between 1997-2017.

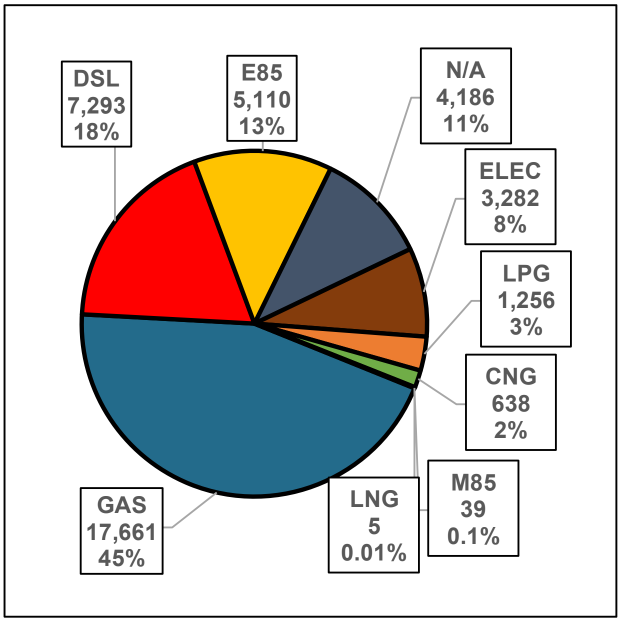
5.2.4. AFVs Acquired by State Agencies' Fleet Services in California

The California Department of General Services (DGS) maintains a database of vehicles used by state agencies' fleet services. The 2014 version of this database, available publicly on their webpage, was accessed to study the trend of AFV acquisition by state agencies in California. Table 5.1 shows the top ten agencies in terms of the total number of vehicles in their fleet. The California Department of Transportation, Caltrans, had the greatest number of vehicles with 28 percent of the total 39,471 state-owned vehicles in 2014.

Figure 5.4 shows the breakdown of state-owned vehicles by fuel type. Forty-five percent are gasoline vehicles followed by diesel vehicles at 18 percent, and E85 vehicles at 13 percent share of the total count.

Table 5.1. Top 10 state agencies in California based on fleet size (out of 64 fleets reporting to DGS in the year 2014. The total state vehicle count was 39,471)

#	Agency	Count	% of Total	Cumulative
1	Transportation, Department of	10,938	28.0%	28.0%
2	Corrections & Rehabilitation, Department of	5,231	13.4%	41.4%
3	Cal State University	3,767	9.6%	51.0%
4	Parks & Recreation, Department of	3,504	9.0%	60.0%
5	Forestry & Fire Protection, Department of	2,808	7.2%	67.2%
6	Fish & Wildlife, Department of	2,735	7.0%	74.2%
7	General Services, Department of	2,576	6.6%	80.9%
8	Water Resources, Department of	1,418	3.6%	84.4%
9	Prison Industry Authority	823	2.1%	86.5%
10	Food & Agriculture, Department of	682	1.7%	88.3%



CNG: Compacted Natural Gas, DSL: Diesel, E85: Gas with 85% Ethanol, Elec: Electricity,
Gas: Gasoline, LNG: Liquefied Natural Gas, LPG: Liquefied Petroleum Gas, M85: Gas with 85% Methanol,

Figure 5.4: Breakdown of state agencies fleet vehicles by fuel type in the year 2014.

5.2.5. AFVs Currently Available in the Market

A literature survey was conducted to identify AFVs options currently available in the market in each vehicle category. The most reliable and comprehensive database available is the Alternative Fuel Data Center (AFDC) webpage (maintained by the U.S. DOE.) Figure 5.5 shows the number of AFVs (by make and model) available for different vehicle categories based on fuel type. Hybrid electric vehicles (HEVs) and PHEVs are the most common types for automobiles, while E85 vehicles offer the greatest number of alternatives for SUVs, pickups, and vans. CNG, B20 (diesel with 20 percent bio-based diesel), and LPG are dominant choices for trucks.

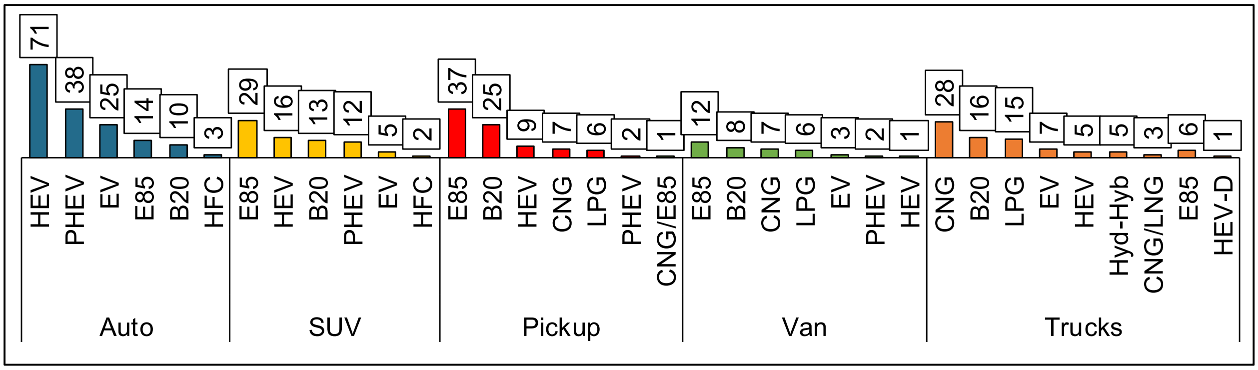


Figure 5.5: Current model offerings for AFVs by vehicle category (AFDC webpage on AFVs.)

Table 5.2 shows the breakdown of AFVs in light-duty vehicles, based on registration data across the whole country. Flexible fuel vehicles (FFVs, using up to 85 percent ethanol) have the highest market share with 81.6 percent, followed by HEVs, EVs, and PHEVs at 15.5, 1.4, and 1.4 percent, respectively.

Table 5.2. Alternative fuel light-duty vehicle registration in the U.S. by 2018 (AFDC webpage on AFVs)

AFV Type	Acronym	Registrations	Market Share
Flexible Fuel Vehicle	FFV	21,261,500	81.6%
Hybrid Electric Vehicle	HEV	4,041,500	15.5%
Electric Vehicle (100% Battery)	EV	366,900	1.4%
Plug-In Electric Vehicle	PHEV	354,000	1.4%
Compressed Natural Gas	CNG	29,680	0.1%
Hydrogen Fuel Cell	HFC	3,430	0.0%
Liquefied Petroleum Gas	LPG	240	0.0%
Total		**26,057,250**	**100.0%**

5.3. Goal and Scope Definition

The goal of this study is to compare the environmental impacts of multiple scenarios for transitioning Caltrans fleet to alternative fuel vehicles. The study scope covers the environmental impacts of the complete life cycle of all the vehicles in the Caltrans fleet which are divided into:

- Vehicle cycle:
    - vehicle production stage: which includes all the processes from raw material extraction to delivery of the vehicle to end user,
    - vehicle end-of-life: the vehicle is either recycled, landfilled, or transferred to a third party for which salvage value is assigned.
- Use stage:
    - fuel emissions and costs including:
    - all the upstream impacts of fuel production (well-to-pump), and
    - fuel consumption in the vehicle (pump-to-wheel),
    - maintenance and repairs,

The functional unit for the study is all the vehicles categorized as either automobile, SUV, pickup, van, or truck in Caltrans fleet. The system boundary of this study includes the complete vehicle cycle and complete fuel cycle but does not cover the infrastructure of fueling stations.

In addition to environmental life cycle assessment, life cycle cost analysis was also conducted to allow a more informed comparison between different scenarios.

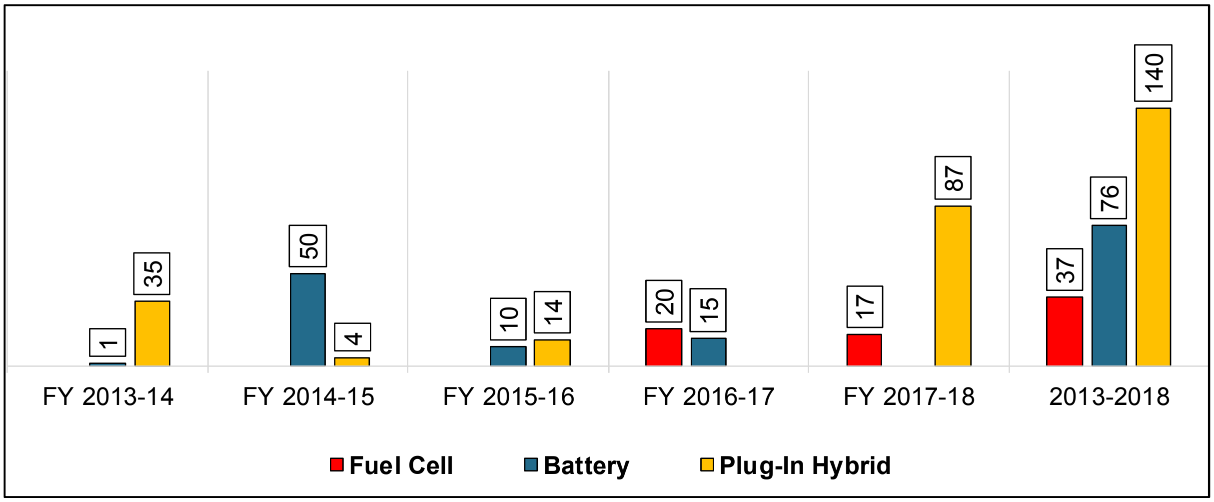


Figure 5.6: Alternative fuel vehicles acquired by Caltrans since 2014 (Caltrans, 2018b)

5.4. Assumptions and Modeling Approach

The first step for conducting this study was to develop a framework for how to conduct the analysis based on the goal and scope definition phase. The framework developed, shown in Figure 5.7, served as the road map for this study, and the main data sources are identified there. The following sections in this report provide a detailed description of each step with comprehensive data visualization of collected data to facilitate understanding of trends and comparison of the alternatives considered.

The model was run under three different scenarios for the replacement schedule of fleet vehicles:

- Business as Usual (BAU): which follows the historical vehicle replacement practiced by Caltrans based on data analysis done on DB2011-14
- Department of General Services (DGS): following the DGS policy for vehicle replacement
- All-at-Once: changing all vehicles to AFVs in the year 2018
- Worst-Case: AFVs were assigned based on Table 5.4 for all three scenarios mentioned above. However, an extra scenario was added to calculate the impacts for a worst-case scenario in which Caltrans keeps the current fleet mix (in terms of vehicle type and fuel combination, following BAU replacement schedule) throughout the analysis period and only uses regular and HPR diesel. This case is coded as the “Worst-Case” scenario in the results section.

Table 5.3 shows the replacement schedule for the BAU and DGS cases. The AFV substitute for each vehicle type was chosen based on information provided in the introduction section regarding 1) AFVs currently available in the market and 2) the trend of AFV acquisition by state agencies as was presented in Table 5.4. The range of EVs per charge was assumed to be 150 miles, and for vehicles that had average daily VMTs greater than 150, PHEVs were assigned instead of EVs. This assumption was made to maintain the original functionality and level of service in terms of recharging.

Table 5.3. Two vehicle replacement schedules considered in this study

Vehicle	Based on Historical Trends		Based on DGS Policy	
	Change Age (years)	Change Mileage	Change Age (years)	Change Mileage
Auto-Sub	9.3	125,770	6.0	65,000
Auto-Comp	9.5	130,507	6.0	65,000
Auto-Mid	10.3	142,315	6.0	65,000
Auto-Full	11.1	146,923	6.0	65,000
SUV-LD	12.0	173,957	7.0	85,000
Pickup-LD	10.9	168,599	5.0	65,000
Pickup-MD	8.0	147,583	6.0	70,000
Van-LD	11.4	132,726	8.0	80,000
Van-MD	13.6	110,841	5.0	65,000
Truck-LD	15.8	163,485	6.0	70,000
Truck-MD	16.7	139,099	11.0	115,000
Truck-HD	17.0	161,366	11.0	115,000

AFVs were assigned based on Table 5.4 for all three scenarios mentioned earlier in this section. However, an extra scenario was added to calculate the impacts for a worst-case scenario in which Caltrans keep the current fleet mix (in terms of vehicle type and fuel combination, following BAU replacement schedule) throughout the analysis period and only use regular and B20 diesel. This case is coded as the "Worst-Case Scenario" in the results section.

Table 5.4. AFVs substitutes chosen for various vehicle types in Caltrans fleet

Vehicle Type	AFV Substitute 1	AFV Substitute 2
Auto-Sub	ELEC	PHEV
Auto-Comp	ELEC	PHEV
Auto-Mid	ELEC	PHEV
Auto-Full	ELEC	PHEV
SUV-LD	ELEC	PHEV
Pickup-LD	ELEC	PHEV
Pickup-MD	DSL-R100	-
Van-LD	E85	-
Van-MD	E85	-
Truck-LD	E85	-
Truck-MD	DSL-R100	-
Truck-HD	DSL-R100	-

The model developed in this study is capable of considering possible reductions in vehicle fuel efficiency with time as a user input for each vehicle type. However, online research showed insignificant changes in fuel efficiency assuming regular maintenance is conducted. Therefore, no changes in vehicle efficiency were considered for the results presented in this report.

Changes in vehicle miles traveled per year can also be incorporated in the model. Reduction in VMT is a plausible situation as there are ongoing debates about setting tax rates based on VMT rather than gallons of fuel purchased by consumers. The debates are mainly due to improvements in vehicle efficiency that has resulted in shrinking revenues from state fuel taxes. The results presented in this report does not consider any changes in the annual VMT of vehicles.

A discount rate of 4 percent was considered for life cycle cost calculations which can be modified by the user. It should be noted that state vehicles are exempt from registration fees and taxes and fleet insurance is typically handled through in-house insurance programs. However, the model has the capability of calculating these values to provide an order of magnitude for comparison with other cost items.

The model allows the user to either use average annual vehicle miles traveled (AVMT) values (calculated based on vehicle type) for all the 9,325 records in the model, or use actual AVMT based on 2017 data collected through communication with DGS (missing and false data in actual AVMTs were replaced by average AVMT of data records with similar vehicle type and model year in the data cleaning process.) The results presented in this report are based on actual AVMT of the Caltrans fleet.

The salvage value for vehicles in service at the end of the analysis period for both vehicle costs and vehicle cycle GHG emissions were calculated based on remaining useful life of each vehicle (explained in detail in subsequent sections in this report.)

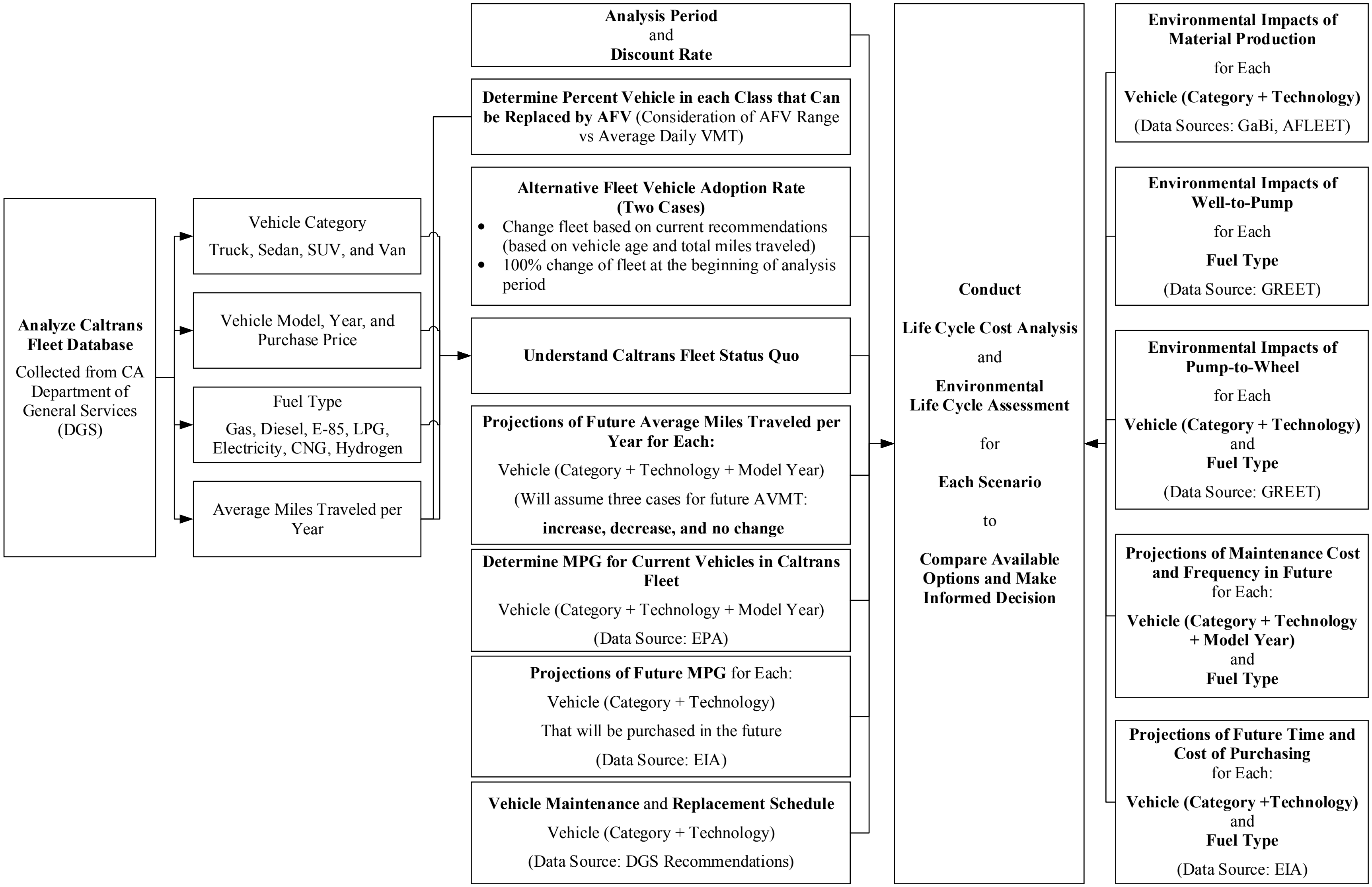


Figure 5.7: Flowchart of model development used for this study.

It was assumed that there would be no new vehicle purchases in the year 2050 and the salvage value, both in terms of vehicle cost and vehicle cycle GHG emissions, were calculated based on remaining useful life of each vehicle (explained in detail in subsequent sections in this report.)

5.4.1. Caltrans Fleet Statistics

Data were collected from two sources regarding the Caltrans fleet. One database was the California State Fleet database which is publicly available on the Department of General Services' (DGS) webpage (CA DGS webpage on State Fleet.) The other database was specific to Caltrans fleet and contained data for the year 2017 which was obtained through email correspondence with Caltrans' staff. The reason for using two separate databases was that the 2017 database did not include data related to vehicle acquisitions and disposals which were needed for the cost analysis section of this study.

The database collected from DGS webpage, was a comprehensive database of all state agencies' fleet data for reporting years 2011 to 2014. The database contained more than 106 thousand rows of data related to Caltrans fleet (out of the initial more than the 257 thousand data rows for all state agencies.) Data related to passenger vehicles, vans, and trucks constituted 79,218 rows of Caltrans data (for four years of reported data.)

The rest of the DB collected from DGS was related to motorcycles, construction equipment, general purpose equipment, low-speed vehicles, riding lawn mowers, and buses, which were excluded from this study. It should also be noted that each reporting year includes data about the current fleet and the vehicles that are already disposed of by Caltrans. Therefore, of more than 27 thousand vehicles reported in year 2014, only 10,392 were still in the possession of Caltrans. This filtered version of the Caltrans fleet database for reporting years 2011-14 is referred to as DB2011-14 throughout this chapter.

The DB2011-14 consisted of the following major data categories:

- Vehicle information (vehicle identification number (VIN), plate number, model year, make, model, vehicle type, weight class, fuel type, engine configuration, payload, and wheel type)
- Acquisition (year, price, mileage) and disposal (if yes: date, mileage, sold amount) information
- Fuel consumption and miles traveled (with poor data quality and many missing/unrealistic values)
- Other information such as vehicle application, a justification for purchase, and more.

The second database, which contained 2017 data was acquired through email correspondence with the DGS and consisted of the most recent data on Caltrans fleet. This database consisted of more than twelve thousand rows of data, of which 9,325 were selected representing the passenger vehicles, vans, and trucks. This database, which will be referred to as DB2017 throughout this chapter, consisted of the following information:

- Vehicle information (model year, make, model, vehicle type, weight class, actual weight, and fuel type)
- Vehicle miles traveled per each month and the total number of days used in the year 2017

The reason for using two separate databases was that the 2017 database did not include data related to vehicle acquisitions and disposals which were needed for the cost analysis section of this study. The main use of DB2011-14 was to study historical trends in terms of annual expenditure on buying new vehicles, typical salvage value realized, and typical mileage at which vehicles were disposed of by Caltrans.

Caltrans fleet vehicles are divided into four major categories and 12 vehicle types, as shown in Table 5.5. There are 9,325 vehicles in Caltrans fleet as of 2017.

Table 5.5. Vehicle categories and types in Caltrans fleet

Vehicle Category	Vehicle Type
Passenger Car	Auto-Sub Auto-Comp Auto-Mid Auto-Full SUV-LD
Pickup	Pickup-LD Pickup-MD
Van	Van-LD Van-MD
Truck	Truck-LD Truck-MD Truck-HD

* L: Light, M: Medium, H: Heavy, D: Duty

Figure 5.8 shows the breakdown of Caltrans fleet by vehicle category and Figure 5.9 shows the fleet statistical summary by graphing vehicle distribution by fuel type and gross weight category. Pickups constitute more than 43 percent of all Caltrans vehicles, followed by trucks and passenger cars with 36 and 15 percent shares, respectively. Passenger cars collectively refer to subcompact, compact, midsize, full-size sedans, and SUVs in this report. SUVs have the highest share of passenger cars followed by compact automobiles, with 37 and 34 percent, respectively.

Gasoline, diesel, and E85 are the top three ranking fuel types with 44.5, 29.8, and 15.6 percent share of all vehicles, respectively. Most vehicles are in the "6,001-10,000" gross vehicle weight range (GVWR) with 37.4 percent share of the fleet followed by "6,000 and less" and "33,000 and more" category with 18.6 and 13.7 percent share, respectively.

Figure 5.10 shows the age distribution of Caltrans fleet. The average fleet age is 10.5 years (8.5 for passenger cars, 9.8 for pickups, 11.9 for vans, and 11.8 for trucks.)

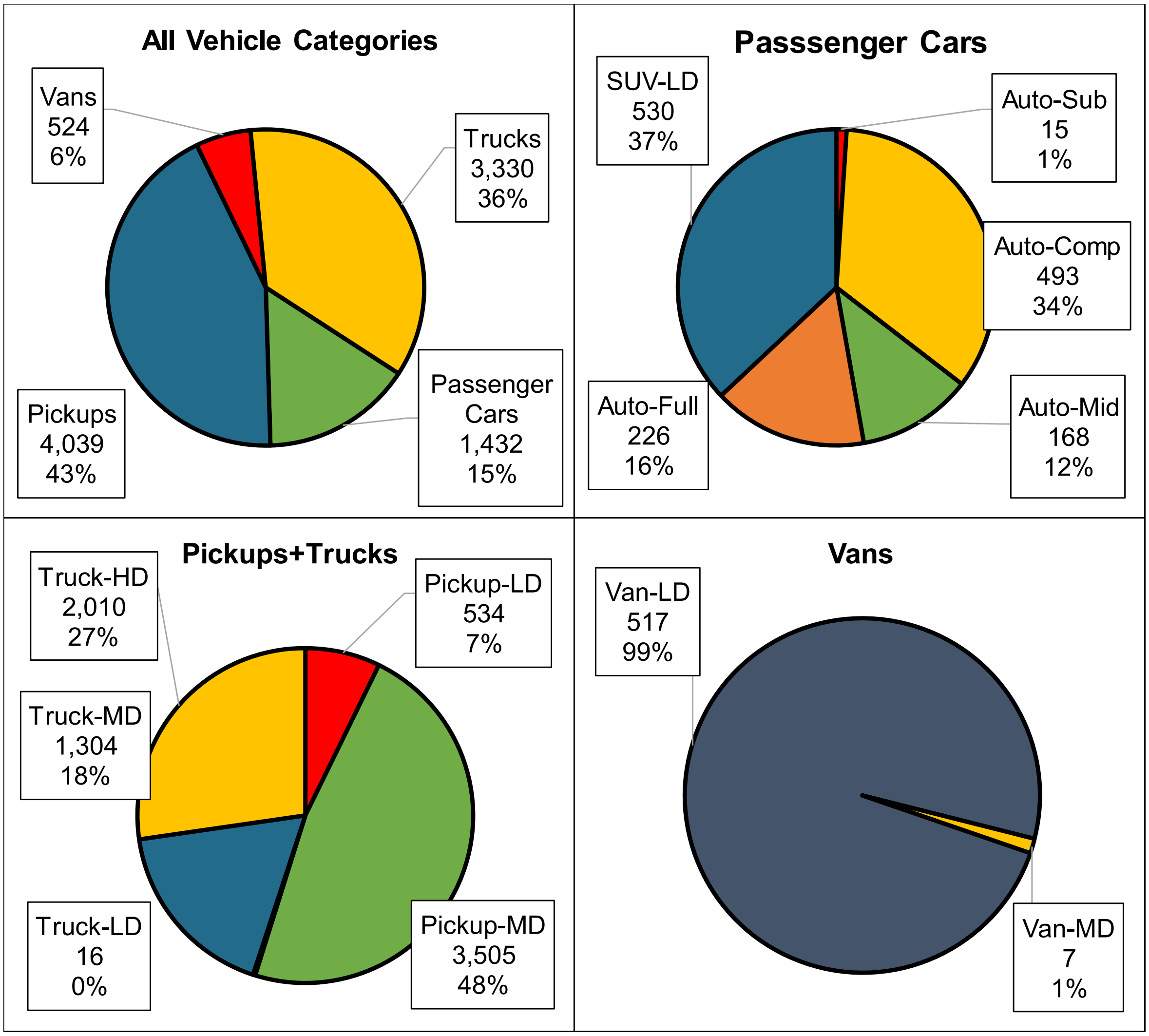


Figure 5.8: Breakdown of each general category (sedans, vans, and trucks) into asset types in 2017 Caltrans fleet.

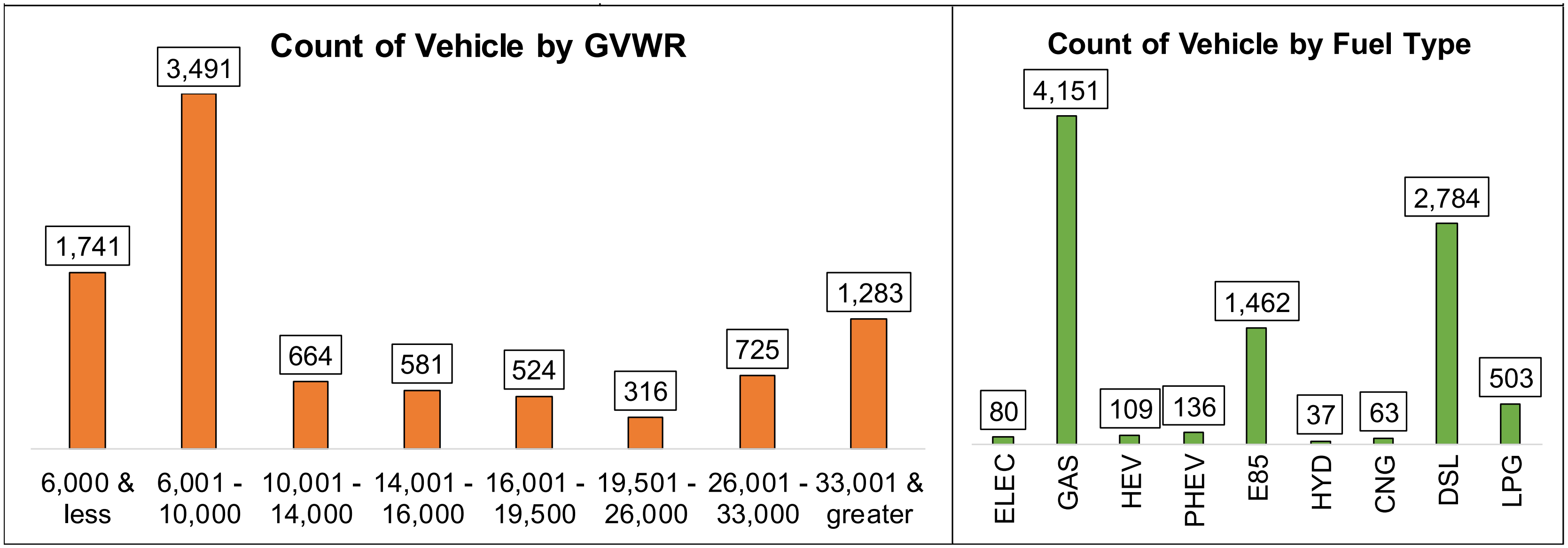


Figure 5.9: Summary statistics of Caltrans fleet in 2017.

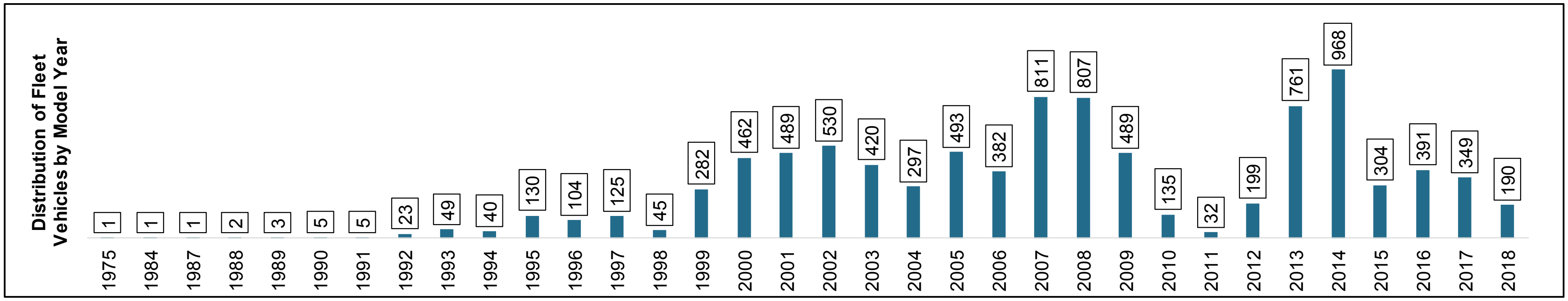


Figure 5.10: Caltrans fleet age distribution.

5.4.2. Annual Vehicle Miles Traveled (AVMT)

Table 5.6 shows the average annual vehicle miles traveled (AVMT) by vehicle category based on DB2017. Light-duty trucks had the greatest AVMT with 23,172 miles per year, while medium-duty vans had the lowest AVMT of 7,800. Data for sub-compact automobiles category did not exist in the database. Therefore, it was assumed that sub-compact sedans have the same AVMT of compact vehicles. Forty-three percent of all vehicles had 25 to 50 VMT per day which is the dominant VMT/day category across all vehicle types, as shown in Figure 5.11.

Table 5.6. Average annual vehicle miles traveled by vehicle category (DB2017)

Vehicle Category	Average AVMT
Auto-Sub	12,887
Auto-Comp	12,887
Auto-Mid	12,696
Auto-Full	12,899
Pickup-LD	13,247
Pickup-MD	14,436
SUV-LD	15,386
Van-LD	8,959
Van-MD	7,800
Truck-LD	23,172
Truck-MD	12,345
Truck-HD	13,015

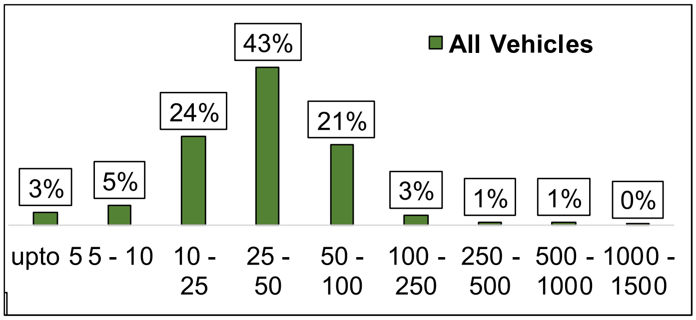


Figure 5.11: Distribution of vehicles by vehicle miles traveled per day.

5.4.3. Vehicle Fuel Efficiency

5.4.3.1. MPG by Vehicle Technology - Historical Data

National average data for vehicle fuel efficiency data were collected from the EPA (webpage on Fuel Economy Trends) and the Energy Information Administration (EIA) (webpage on AER2018). The results are shown in Figure 5.12. The data collected in this section were used to estimate the fuel consumption based on AVMT assigned to each vehicle currently in Caltrans fleet.

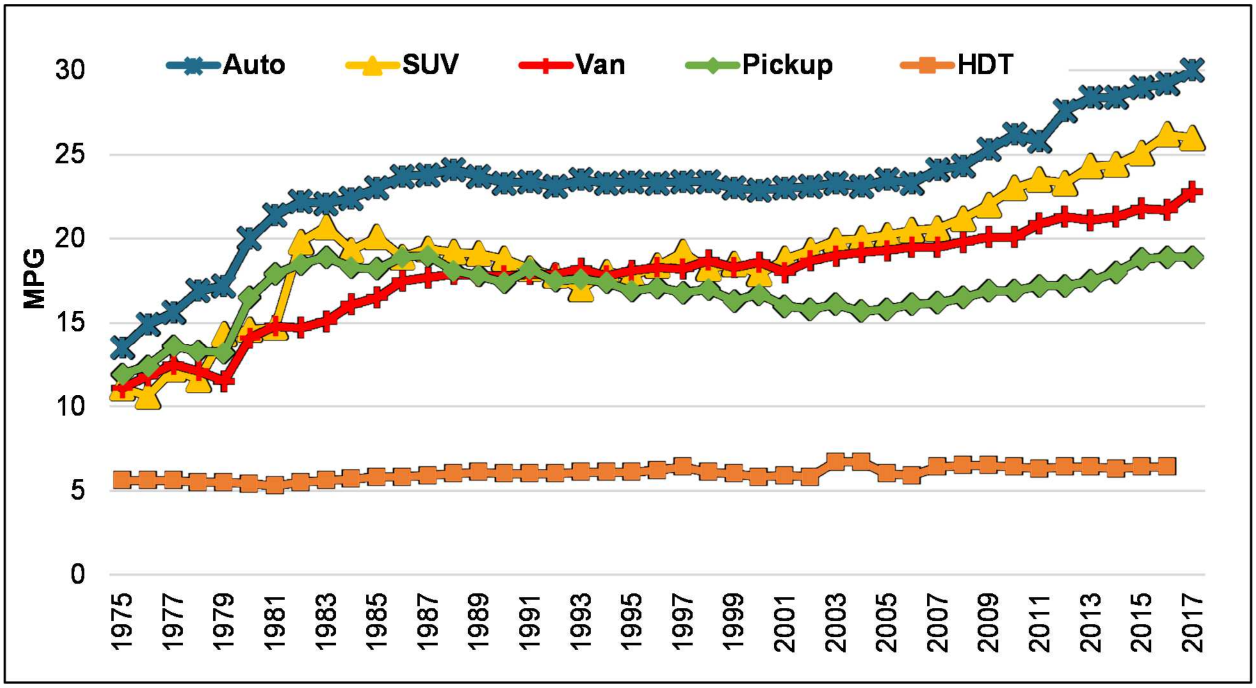


Figure 5.12: Historical fuel efficiency values by vehicle category (EPA webpage on Fuel Economy Trends and EIA webpage on AER2018)

5.4.3.2. MPG by Vehicle Technology – Projections

The projection data for vehicle fuel efficiency were taken from EIA's webpage. EIA had more granular data for mpg projections, in terms of vehicle type and fuel combinations, compared to historical mpg values collected from the same resource. The full dataset collected is available in the main model, and a comparison of fuel efficiency values between 2018 and 2050 for selected vehicle fuel combinations are presented in Figure 5.13.

The left section of Table 5.7 shows average annual growth rates in mpg for different vehicle types between 2018 to 2050. The right section of the same table shows similar projection data averaged by fuel type. Figure 5.14 shows the actual values for each vehicle and fuel combination (it should be noted that the actual data did not necessarily follow a linear growth trend.)

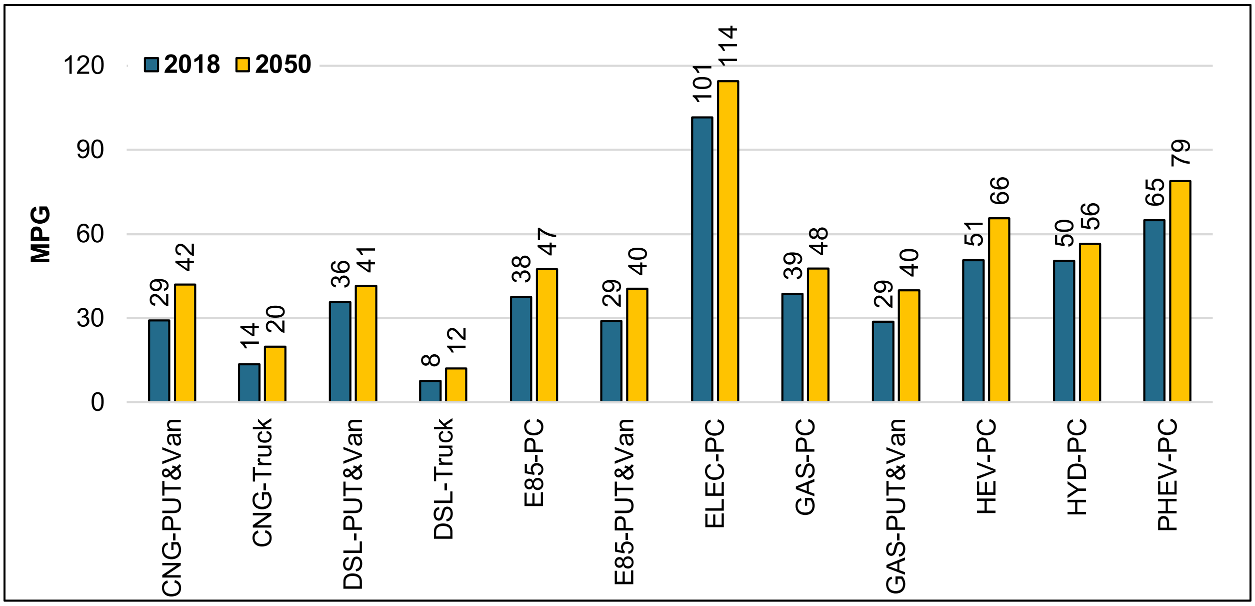


Figure 5.13: MPG projections for selected vehicle fuel combinations, PUT: pickup truck, PC: passenger car.)

Table 5.7. The average annual growth rate for vehicle fuel efficiency (EIA webpage on AER2018)

Vehicle Category	Average Annual Growth Rate Across All Fuel Types	Fuel Category	Average Annual Growth Rate Across All Vehicle Types
Truck-MD	1.7%	LPG	1.4%
Van-MD	1.3%	CNG	1.3%
Truck-HD	1.3%	GAS	1.0%
Truck-LD	0.9%	E85	0.9%
Pickup-MD	0.8%	DSL	0.8%
Pickup-LD	0.8%	PHEV	0.7%
Van-LD	0.8%	ELEC	0.4%
Auto-Full	0.6%	HYD	0.4%
Auto-Sub	0.6%		
SUV-LD	0.6%		
Auto-Mid	0.5%		
Auto-Comp	0.5%		

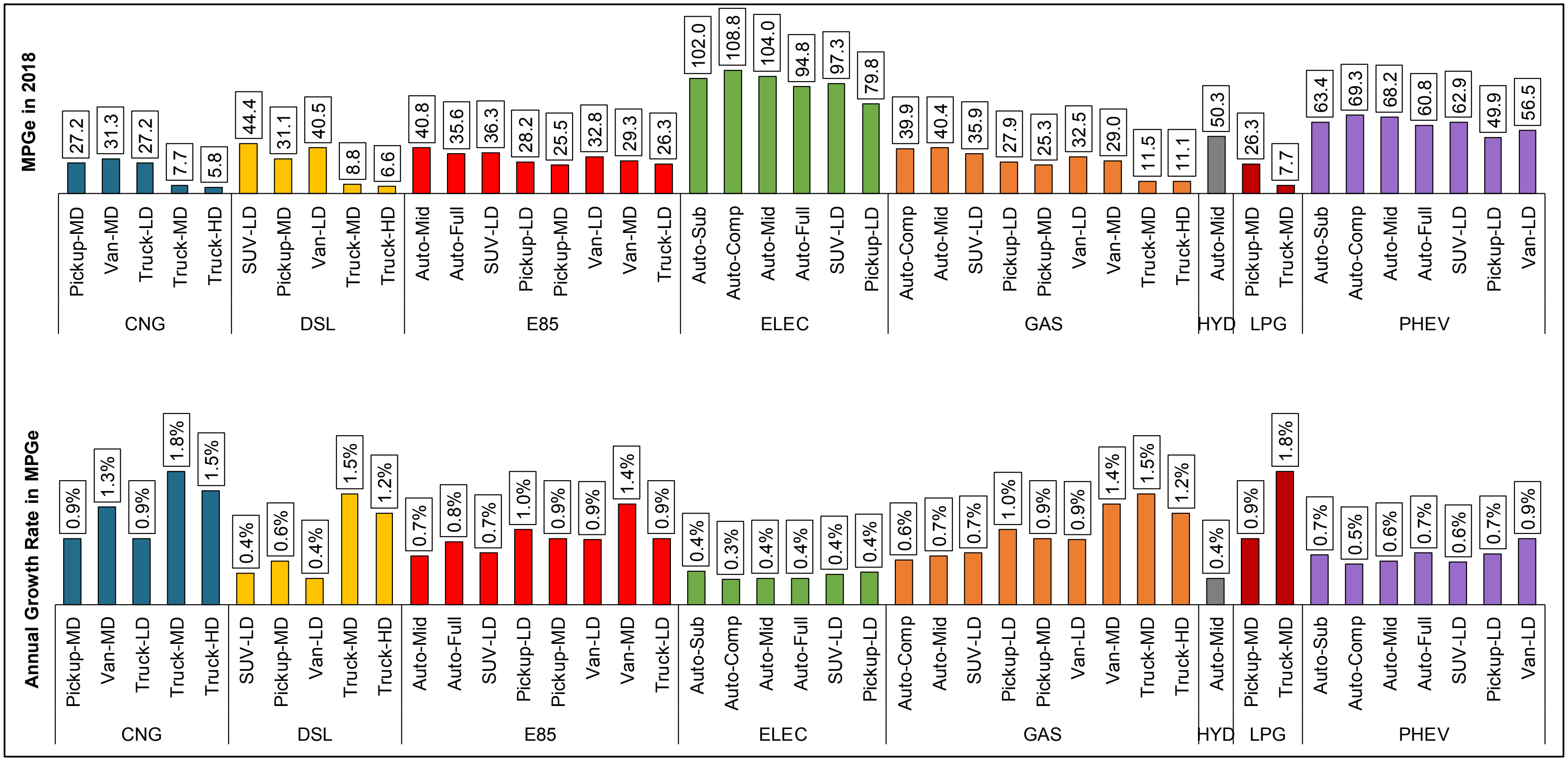


Figure 5.14: Fuel efficiency in miles per gallon equivalent (MPGe) in the year 2018 by fuel and vehicle category (bar charts on top) and the annual growth rate in MPGe (bottom bar charts.)

5.4.4. Fuel Costs

5.4.4.1. Fuel Prices - Historical Data

Historical prices for alternative fuel were collected from the AFDC webpage on Fuel Prices and are shown in Figure 5.15. The prices are expressed in units of "dollars per gasoline gallon equivalent (GGE.)" The data in this section will be later combined with mpg values to calculate the cost of "one mile traveled" for each vehicle fuel combination. LPG, B100 (100 percent biodiesel), and E85 have been consistently the most expensive fuels among all alternative fuels since 2013 while electricity has been the cheapest one.

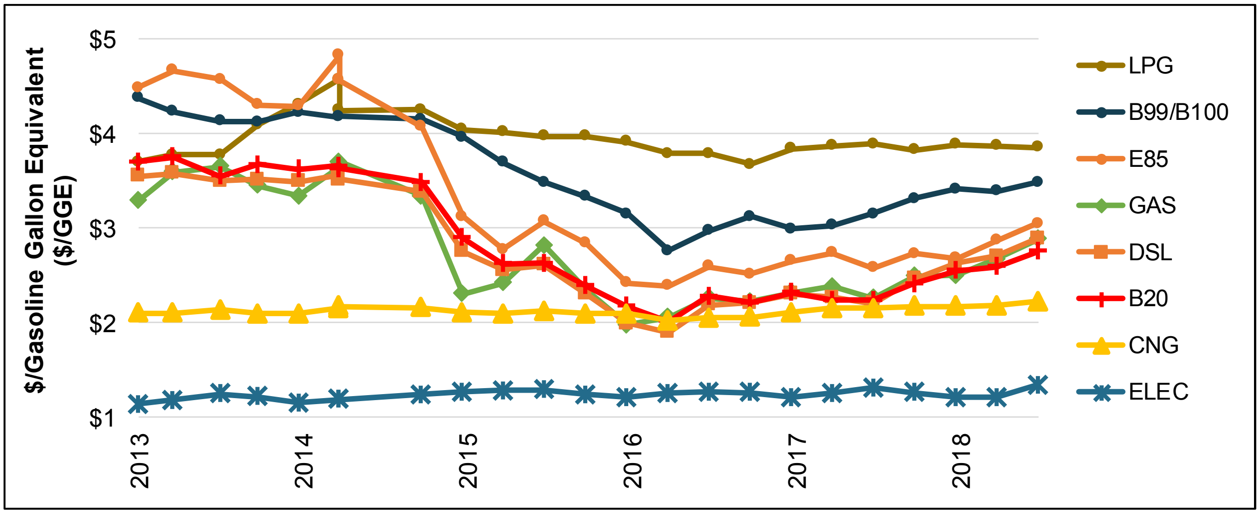


Figure 5.15: Historical prices of alternative fuels, dollar per gallon gasoline equivalent (GGE) (AFDC webpage on Fuel Prices.)

Figure 5.16 shows the boxplot of alternative fuel prices for comparison of alternative fuel prices and their variability within the last 5 years. E85 and B20 had the highest variability while CNG and electricity had the least volatile prices among all available options. These variabilities are an integral part of risk assessment and probabilistic analysis if the management decides on conducting such studies (AFDC webpage on Fuel Prices.)

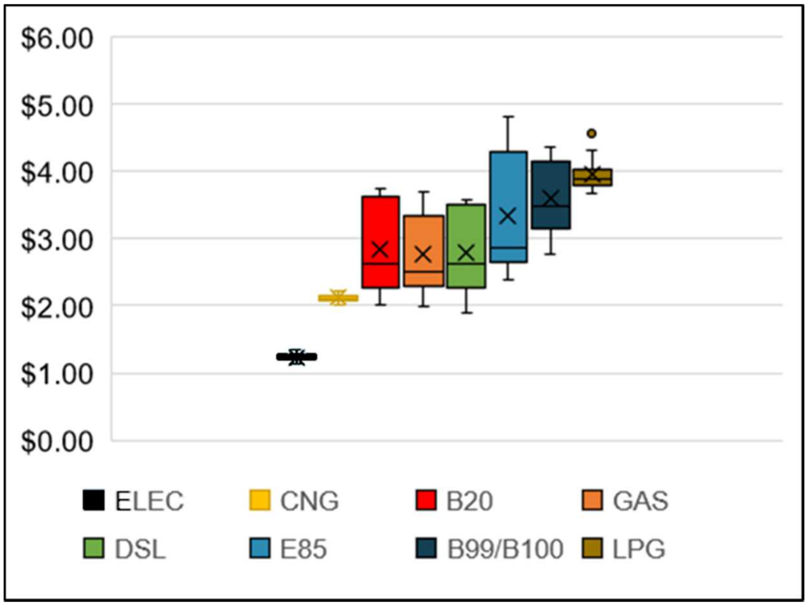


Figure 5.16: Variation in fuel historical prices 2012-2017 (AFDC webpage on Fuel Prices.)

5.4.4.2. Fuel Prices – Projections

Projections of future fuel prices were also taken from the EIA webpage. EIA only provides price projections for regular diesel; therefore, historical data were used to calculate the price ratio of B100 and B20 over regular diesel in the past three years. The calculated price ratios were then applied to EIA's projections of regular diesel price to obtain price projections for B20, B100. The results showed that on average B20 was priced at 95 percent of regular diesel since 2016 in the U.S. market while B100 was about 39 percent more expensive. Figure 5.17 shows the final values used in the model.

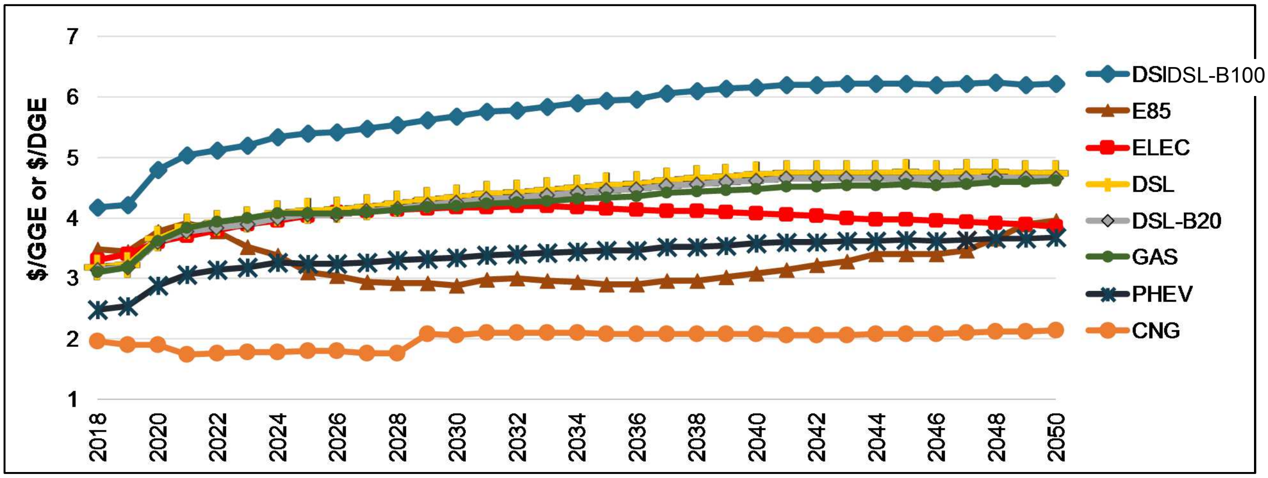


Figure 5.17: Projection of future prices of fuels (EIA webpage on AEO2018.)

5.4.4.3. Consideration of Difference in CA Prices versus National Averages

To account for differences in energy prices in California versus national averages, historical data were collected for gasoline, diesel, electricity, and natural gas; as shown in Figure 5.18, Figure 5.19, Figure 5.20, and Figure

5.22, respectively. Figure 5.21 shows the variation of electricity price ratios (California over the U.S. average prices) across various economic sectors.

Annual average gasoline prices in California has consistently been higher, and more variable, compared to national averages in almost every year since 2004 (with the highest price volatility in 2008.) Diesel prices had a similar trend as gasoline. Natural gas prices were as high as 60 percent more expensive in California prior to 1998. However, natural gas has consistently been cheaper in California compared to the U.S. average since 1998.

The case for electricity price is interesting because electricity prices in California have consistently been higher compared to the U.S. averages across all industries except for the transportation sector where California exerted lower prices. Figure 5.21 shows the boxplot of electricity price ratio variations (CA over U.S. averages) across different economic sectors.

Considering the average price ratios of 2015 to 2018, the numbers shown in Table 5.8 were used to convert prices from previous sections to account for differences in regional prices in California versus national averages.

Table 5.8. Price ratio of alternative fuels (California over U.S. averages)

CA/US Price Ratio (2015-18)			
ELEC	**NG**	**DSL**	**GAS**
0.934	0.913	1.162	1.256

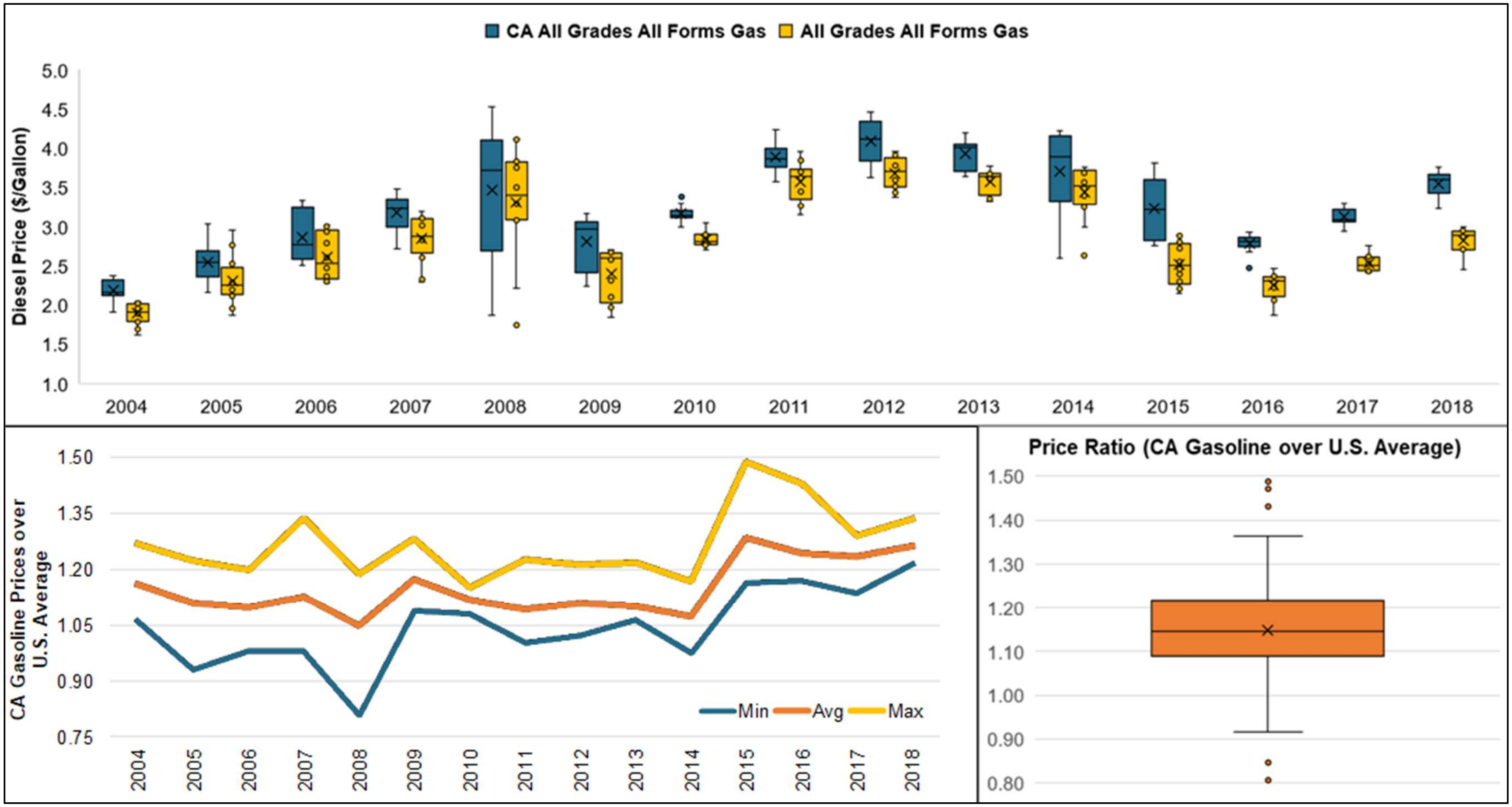


Figure 5.18: Comparison of gasoline prices between California and the U.S. average.

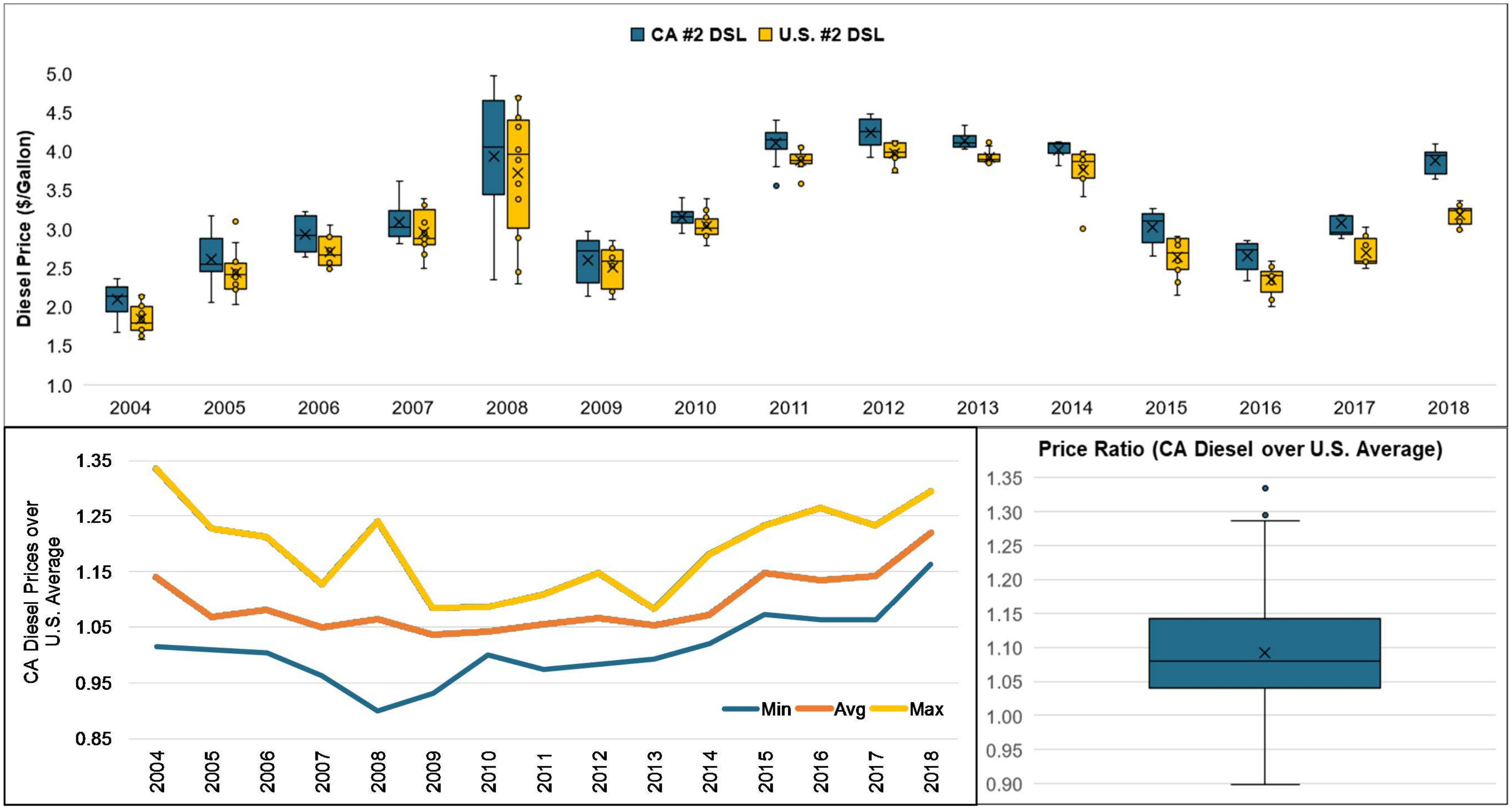


Figure 5.19: Comparison of diesel prices between California and the U.S. average (EIA webpage on Price of Petroleum and Other Liquids.)

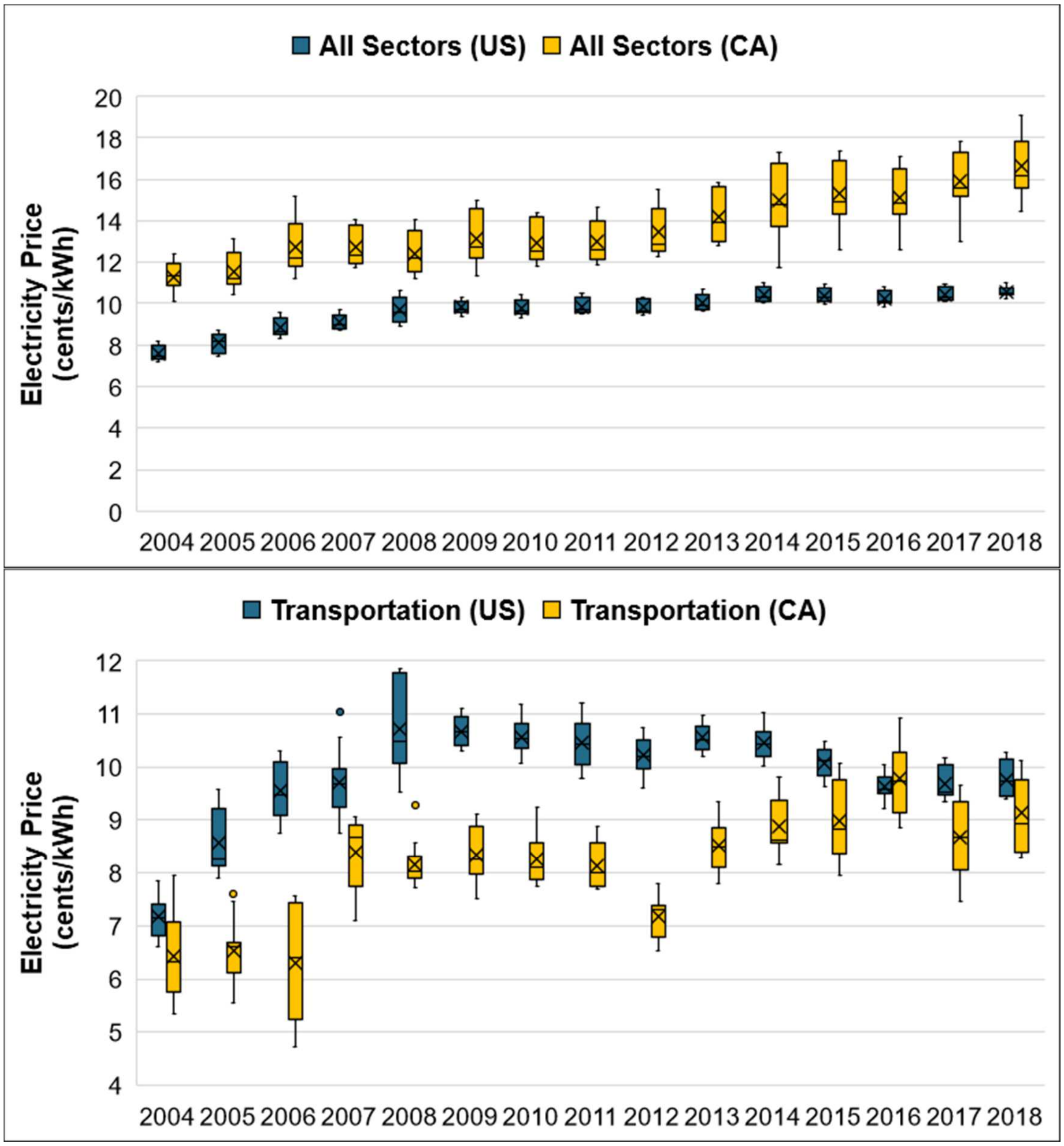


Figure 5.20: Comparison of electricity price in California versus the U.S. average, comparison of average price of all sectors on top and transportation sector prices in the bottom (EIA webpage on the Electricity Sector.)

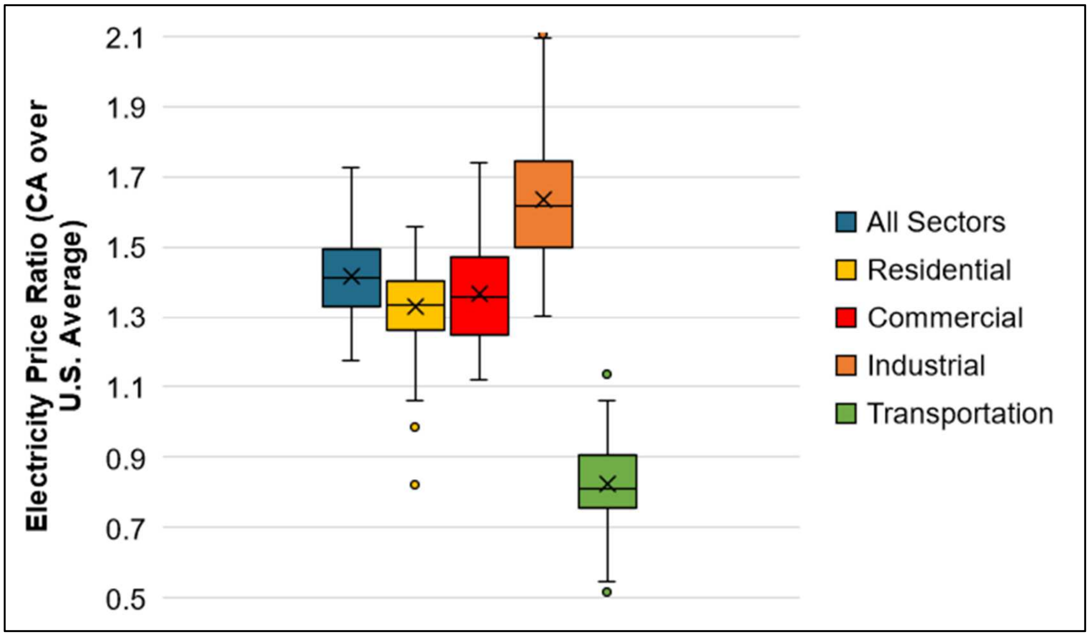


Figure 5.21: Variation in electricity price ratio (California over the U.S. average) across different economic sectors (EIA webpage on the Electricity Sector.)

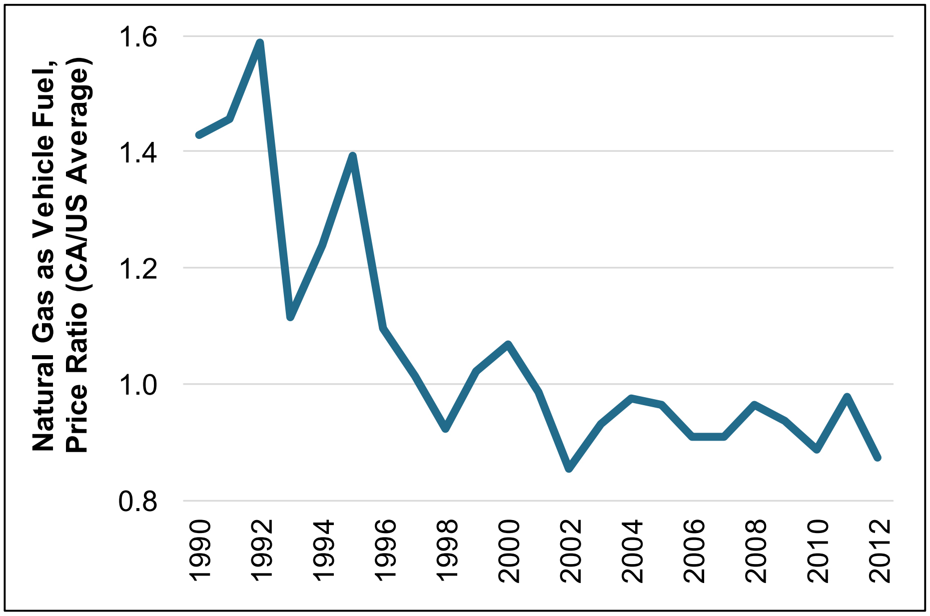


Figure 5.22: Natural gas price ratio (California over the U.S. average) by year (EIA webpage on Natural Gas.)

5.4.5. Vehicle Costs

5.4.5.1. Vehicle Purchase Price - Historical Data

The data collected from the DGS webpage for reporting years of 2011-14 provided historical data on vehicle purchase prices for all state agencies. Only the following data were selected from DB2011-14 and were used for the analysis conducted in this section:

- Data from the reporting year 2014,
- related to vehicles purchased after 2004,
- with purchase prices between $4k to $500K

The selected data were used to conduct linear regression and develop equations for vehicle price versus age for each of the vehicle types in the model. Average purchasing price by vehicle type is presented in Table 5.9. Table 5.10 shows the number of vehicles acquired and the minimum, average, and maximum purchase prices by fuel type.

Table 5.9. Average purchase price by vehicle and fuel type (DB2011-14)

Vehicle	Fuel	Avg Purchase Price
Auto-Comp	ELEC	$34,143
Auto-Comp	GAS	$19,276
Auto-Mid	E85	$19,619
Auto-Mid	GAS	$24,386
Auto-Mid	PHEV	$50,873
Auto-Full	E85	$17,461
Pickup-LD	GAS	$18,179
Pickup-MD	DSL	$52,214
Pickup-MD	E85	$22,604
Pickup-MD	GAS	$29,943
Pickup-MD	LPG	$27,726
SUV-LD	E85	$31,100
SUV-LD	ELEC	$52,178
SUV-LD	GAS	$23,626
Truck-LD	E85	$26,806
Truck-MD	CNG	$129,204
Truck-MD	DSL	$89,028
Truck-MD	GAS	$59,910
Truck-HD	CNG	$210,592
Truck-HD	DSL	$154,970
Truck-HD	GAS	$94,140
Van-LD	E85	$22,108
Van-LD	GAS	$27,084
Van-MD	E85	$40,916
Van-MD	GAS	$22,156

Table 5.10. Number of vehicles acquired, minimum, average, and maximum purchase price by vehicle type

Vehicle	Count of Vehicles Acquired	Min	Avg	Max
Auto-Sub	3	$28,221	$40,325	$47,250
Auto-Comp	1,024	$4,990	$13,941	$34,143
Auto-Mid	560	$4,853	$17,207	$25,721
Auto-Full	522	$5,400	$17,351	$28,024

Vehicle	Count of Vehicles Acquired	Min	Avg	Max
Pickup-LD	1,140	$3,441	$15,647	$43,031
Pickup-MD	6,084	$2,152	$26,680	$285,132
SUV-LD	767	$11,936	$25,188	$52,178
Van-LD	1,279	$2,047	$24,187	$255,237
Van-MD	49	$5,556	$39,767	$187,845
Truck-LD	15	$8,140	$33,350	$114,731
Truck-MD	1,934	$2,274	$55,379	$252,543
Truck-HD	3,276	$2,710	$109,433	$743,095

5.4.5.2. Vehicle Purchase Price – Projections

Price projections for every vehicle fuel combination used in this study were obtained from EIA (webpage on Vehicle Price Projections in AEO2018.) Figure 5.23 shows the average annual growth rate for vehicle prices between 2018 and 2050 (it should be noted that actual projections did not necessarily follow a linear pattern.)

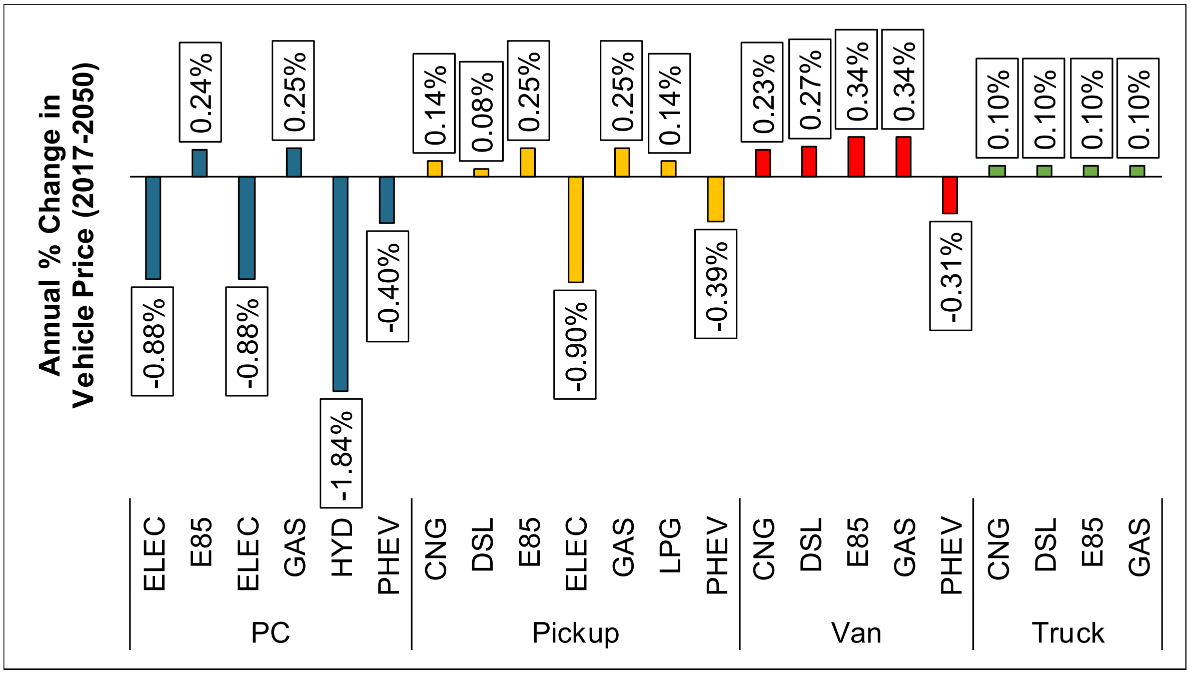


Figure 5.23: Average annual growth rate in vehicle price (EIA webpage on Vehicle Price Projections in AEO2018.

5.4.6. Fleet Replacement Schedule

There are two alternatives for designing the vehicle replacement schedule: 1) by evaluating the historical trends using the DB2011-14 data, 2) following the DGS policy. Both methods are discussed in this section.

5.4.6.1. Historical Trends of Vehicle Acquisition and Disposal in Caltrans fleet

Historical trends in acquiring new vehicles and disposal of old vehicles by Caltrans fleet were studied by using DB2011-14 data and the costs associated with historical acquisitions, and disposals were calculated. Figure 5.24

shows the number of vehicles purchased and disposed of by Caltrans in each year between 1997 and 2014. The net count of vehicles added each year to Caltrans fleet is shown in Figure 5.25, with the highest increase in the fleet size of 1,825 in 2000 and the highest decrease of 1,103 in 2014. The Caltrans fleet size decreased by 110 vehicles between 1997 and 2014.

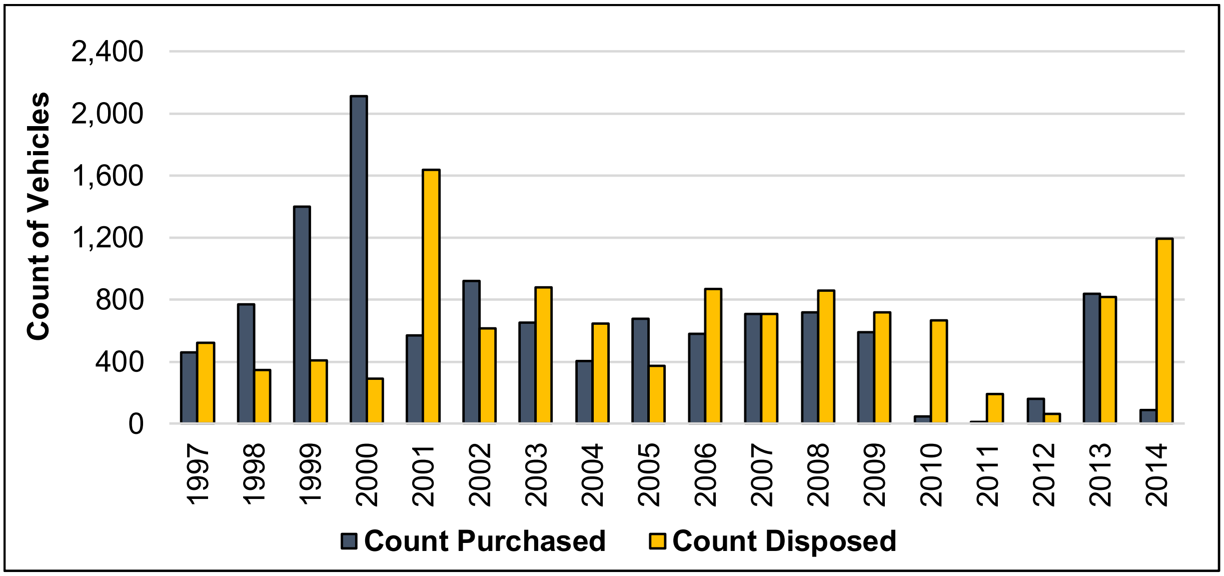


Figure 5.24: Count of vehicles Caltrans acquired and disposed each year between 1997 to 2014 (DB2011-14.)

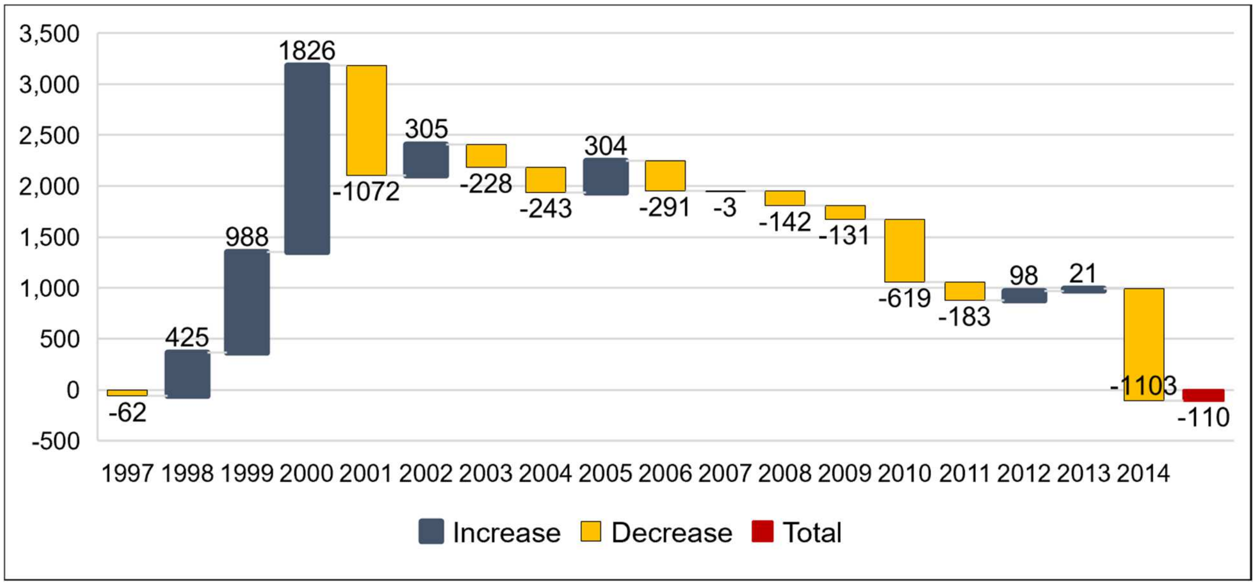


Figure 5.25: Changes in Caltrans fleet count per year between 1997 to 2014 (DB2011-14.)

Table 5.11 shows the average total miles driven and the average vehicle age when disposed of by Caltrans. Medium- and heavy-duty trucks had the highest “vehicle age when sold” of 17 years and highest “mileage when sold” was for medium-duty pickups and light-duty trucks with 173,957 and 163,485 miles, respectively. Figure 5.26 shows the average age of vehicles when sold, by vehicle type.

Table 5.11. Average age and miles of Caltrans' disposed vehicles, by vehicle type (DB2011-14)

Vehicle	Count in Database	Avg Miles per Year	Avg Total Miles	Avg Years in Use
Auto-Comp	1,313	13,972	125,770	9.3
Auto-Mid	861	14,225	130,507	9.5
Auto-Full	561	14,503	142,315	10.3
Pickup-LD	1,169	13,885	146,923	11.4
Pickup-MD	3,808	15,182	173,957	10.5
SUV-LD	552	16,226	168,599	11.1
SUV-MD	6	21,077	147,583	12.1
Van-LD	883	12,351	132,726	11.5
Van-MD	34	10,352	110,841	14.7
Truck-LD	11	10,778	163,485	15.8
Truck-MD	953	9,020	139,099	16.7
Truck-HD	1,625	10,135	161,366	17.1

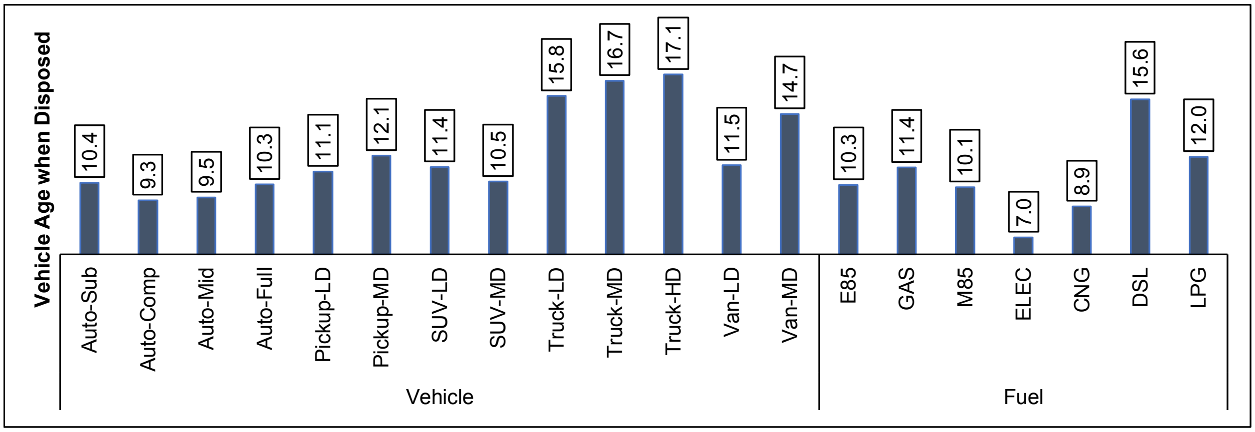


Figure 5.26: The average age of vehicles disposed of by Caltrans, by vehicle type and fuel type (DB2011-14.)

5.4.6.2. Current Policies for Acquiring and Disposal of Fleet Vehicles

DGS published a fleet replacement policy in 2017 for the age and mileage for replacing fleet vehicles based on vehicle type (whichever reach the threshold earlier.) The DGS policy is presented in Table 5.12.

Table 5.12. Current DGS policy for fleet replacement (CA DGS webpage on Vehicle Replacement Policy)

Vehicle	Age of Vehicle (in months)	Vehicle Mileage
GVWR* up to 8,500 Pounds		
Law Enforcement Vehicles	60	100,000
Sedans	72	65,000
Mini Vans	96	80,000
Cargo Vans	60	65,000
Pickup Trucks	60	65,000
Sport Utility Vehicles	84	85,000
GVWR of 8,501 – 16,000		
Law Enforcement Vehicles	60	100,000
All Trucks, Vans, and SUVs	72	70,000

Vehicle	Age of Vehicle (in months)	Vehicle Mileage
GVWR of 16,001 – 26,000		
All Trucks, Vans, and SUVs	132	115,000

5.4.7. *Salvage Value*

Regardless of the vehicle replacement schedule, there is salvage value in vehicles that are traded before the end of their useful service life. This salvage value needs to be accounted for, both in terms of monetary value and the environmental impact of vehicle cycle. It was assumed that a brand-new vehicle loses about 40 percent of its initial value within the first three years and the depreciation rate after three years was assumed to be linear through the typical average life of the vehicle.

Average useful lives (in VMT) for light-duty vehicles, pickup, and vans were taken from the GREET model (ANL webpage on GREET) and the values for trucks were taken from the EPA compliance and fuel economy data center (EPA webpage on Compliance and Fuel Economy.) These values were converted to average useful life (in years) by using average annual VMT of each vehicle category based on DB2017 data. The results are shown in Table 5.13.

Table 5.13. Average service life by vehicle type

Vehicle	Useful Life (VMT)	Avg Service Life (Years)
Auto-Sub	173,000	13
Auto-Comp	173,000	13
Auto-Mid	173,000	14
Auto-Full	173,000	13
SUV-LD	186,000	12
Pickup-LD	186,000	14
Pickup-MD	186,000	13
Van-LD	186,000	21
Van-MD	186,000	14
Truck-LD	110,000	9
Truck-MD	185,000	15
Truck-HD	435,000	33

5.4.8. *Life Cycle Environmental Impacts*

5.4.8.1. Vehicle Production Impacts (Vehicle Cycle Impacts)

Vehicle cycle impacts include all the energy consumption and emission due to vehicle production; from raw material extraction all the way to delivery of the brand-new vehicle to the end user. The processes at the end of the vehicle service life (either being dumped in a landfill or transported and recycled in a facility) should be included in this stage. The other items that are included in the vehicle cycle are fluids, batteries, and tires used during the vehicle life cycle. Almost all the data used for vehicle cycle impacts in this study were collected from the GREET model (ANL webpage on GREET), unless stated otherwise.

The vehicle cycle impacts are reported in four main categories: 1) Components, 2) Assembly, disposal, and recycling (ADR), 3) Batteries, and 4) Fluids.

The components category consists of the following items:

- Body
- Powertrain
- Transmission
- Chassis
- Traction Motor
- Generator
- Electronic Controller
- Hydrogen Storage

Figure 5.27 shows the GHG emissions of components for passenger cars. The bar chart on the left of the figure compares total GHG emissions due to components, across different vehicle technologies. Fuel cell vehicle (FCV) components have the highest GHG emissions, 8419 kg of CO_2e, while the other four major technologies, EVs, HEVs, ICEVs, and PHEVs, all have less than 5,000 kg CO_2e emission due to components. The bar chart on the right side of the same figure shows the breakdown of the GHG emissions between vehicle component items identified earlier.

The total GHG emissions due to the vehicle cycle are calculated by adding the other vehicle cycle categories: ADR, batteries, and fluids. FCVs have the highest vehicle cycle GHGs with 9,925 kg of CO2e per vehicle life cycle, followed by PHEVs, EVs, HEVs, and ICEVs in descending order, all having impacts of less than 7,600 kg of CO2e, as shown in the bar char on the left side of Figure 5.27.

The bar chart in the middle of Figure 5.28 shows the breakdown of vehicle cycle impacts between the four main categories identified earlier: components, ADR, batteries, and fluids. Batteries have the highest share of total emissions in EVs with 28 percent, among all vehicle technologies, followed by PHEVs and HEVs, with 16 and 12 percent, respectively.

To account for changes in vehicle weights during the 33-year analysis period of this study, weight projections by vehicle type were taken from the EIA webpage (EIA webpage on New Vehicle Attributes in AEO2018.) The bars on the right side of Figure 5.29 show vehicle weights in 2018 and their projected values in 2050 for different vehicle types. The right side of the figure shows average annual percent change in vehicle weights (note that weight projections do not necessarily follow a linear trend.)

However, there were two challenges to address: a) Vehicle cycle GHG emissions of trucks were not available in any major sources. b) EIA does not provide weight projections for different fuel technologies and only has data based on vehicle type.

The GREET model does not provide vehicle cycle data for trucks, nor does the AFLEET model which is a payback calculator developed based on GREET with data for extra combinations of light-duty vehicle and fuel combinations compared to GREET (ANL webpage of AFLEET.) The literature survey and online research did not yield reliable data sources for trucks. Therefore, a workaround was devised to develop data models for vehicle cycle impacts of light-, medium-, and heavy-duty trucks:

- First, the weight of light-duty vehicles of different fuel technologies were collected from AutoNomie webpage which is maintained by Argonne National Laboratory (AutoNomie webpage.) The collected data were compared to determine the percentage increase in vehicle weight compared to conventional ICEV for each of the vehicle fuel technologies. The results show that the electric option on average has a 39 percent increase in vehicle weight compared to the conventional gasoline option. The plug-in hybrid, hybrid, and diesel options have 26, eight, and four percent increases in vehicle weight compared to the gasoline option, respectively. Figure 5.30 and Figure 5.31 show the details of the calculations.
- Then it was assumed that a similar trend in weight increase exists for trucks with different fuel technologies.
- As CNG option was missing in the light-duty vehicle options, further literature survey was conducted to determine extra weight needed for CNG tanks that need to be added to the truck. Table 5.14, taken from a recent study by NHTSA (Reinhart, 2016) compares the weight of diesel and CNG options for the truck fuel tank at different capacities. Based on the collected data it was assumed that the CNG option for trucks on average add 6 percent to the truck weight compared to the diesel option (details of the calculations available in the main model.)

Table 5.14. Weight comparison of trucks fuel tank: diesel vs. CNG (Reinhart, 2016)

Diesel Gallon Equivalent (DGE)	Fuel Type	Empty Weight (lbs.)	Full Weight (lbs.)
40	CNG	578	820
40	Diesel	100	386
75	CNG	1,650	2,085
80	Diesel	180	752
116	CNG	2,080	2,750
160	Diesel	360	1,464

- The available vehicle-cycle GHG emissions data for light-duty vehicles were divided by vehicle mass to calculate vehicle cycle GHG intensity (in terms of CO_2e per kg of the vehicle), as shown in Table 5.15. The calculated GHG intensities were used to calculate vehicle cycle GHG emissions of trucks with various fuel technologies.

Table 5.15. Vehicle cycle GHG emissions by fuel type (kg CO_2e per kg of the vehicle)

Vehicle	Weight (lbs.)	GHG (kg CO2)	kg CO2e / kg Vehicle
CNG	3,500	6,547	4.12
DSL	3,308	6,188	4.12
DSL-B20	3,308	6,188	4.12
DSL-R100	3,308	6,188	4.12
E85	3,644	5,979	3.62
ELEC	3,324	7,234	4.80
GAS	3,183	5,996	4.15
HEV	3,429	6,401	4.12

Vehicle	**Weight (lbs.)**	**GHG (kg CO2)**	**kg CO2e / kg Vehicle**
HYD	3,644	9,925	6.00
LPG	3,500	6,547	4.12
PHEV	3,756	7,560	4.44

As stated earlier, the EIA does not differentiate between vehicle fuel technologies and only provides weight projections based on vehicle type. To address this issue and calculate vehicle cycle impacts for all the vehicle type and fuel combinations in the model, it was assumed that the vehicle weight change rate is the same for all vehicle technologies under the same category. Projections of the vehicle weight in the future were then multiplied by vehicle cycle GHG intensity (based on the vehicle technology) to calculate the vehicle cycle impact projections. It should be noted that this approach does not consider the changes in GHG intensity of vehicle materials, even though future reduction in vehicle weight is in part due to use of lighter materials that can have different GHG intensity than the current materials.

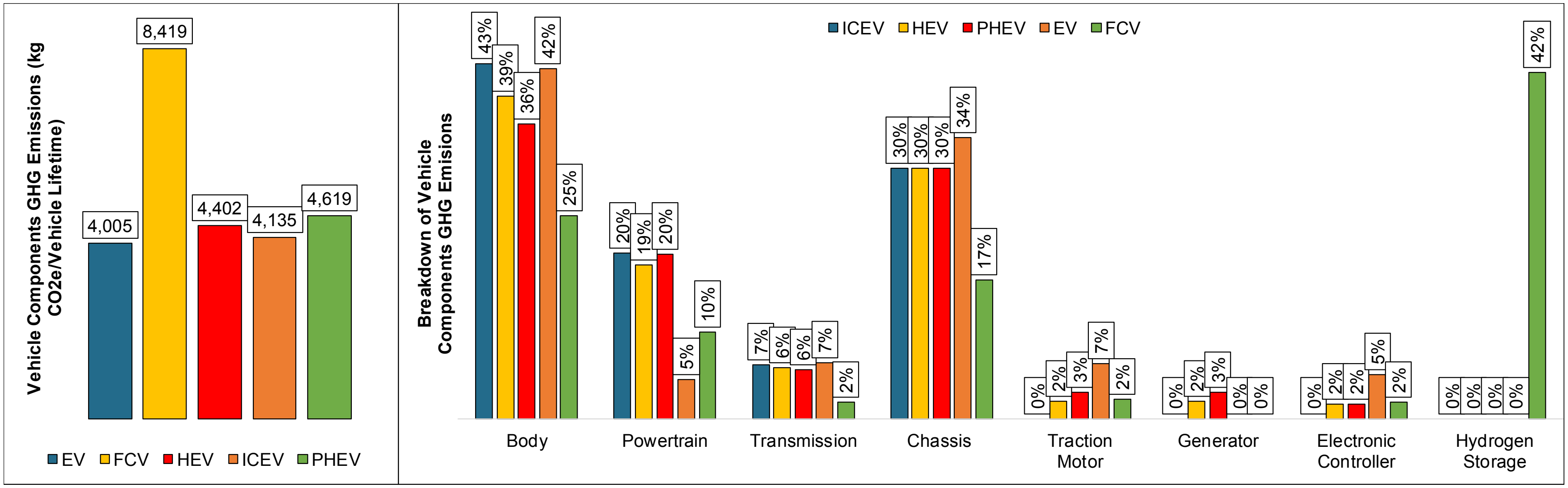
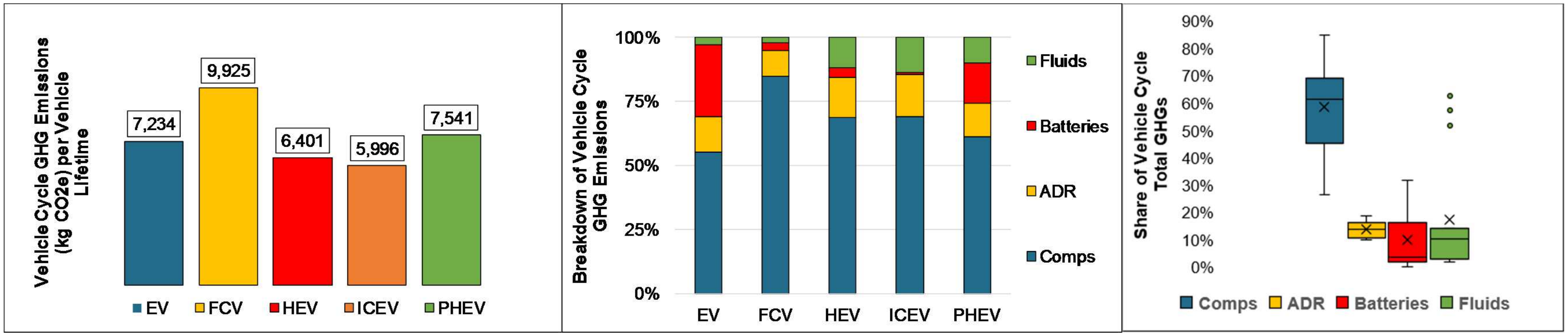


Figure 5.27: Comparison of components impacts across vehicle types, and breakdown of components impacts.



Comps: components, ADR: assembly, disposal, & recycling

Figure 5.28: Vehicle cycle GHG emissions in kg CO_2e per vehicle lifetime (left) Breakdown of vehicle cycle impacts by four main vehicle cycle items: fluids, batteries, ADR, and components (middle) Ranges of the share of total vehicle cycle impacts for each main vehicle cycle item across all vehicle types (right)

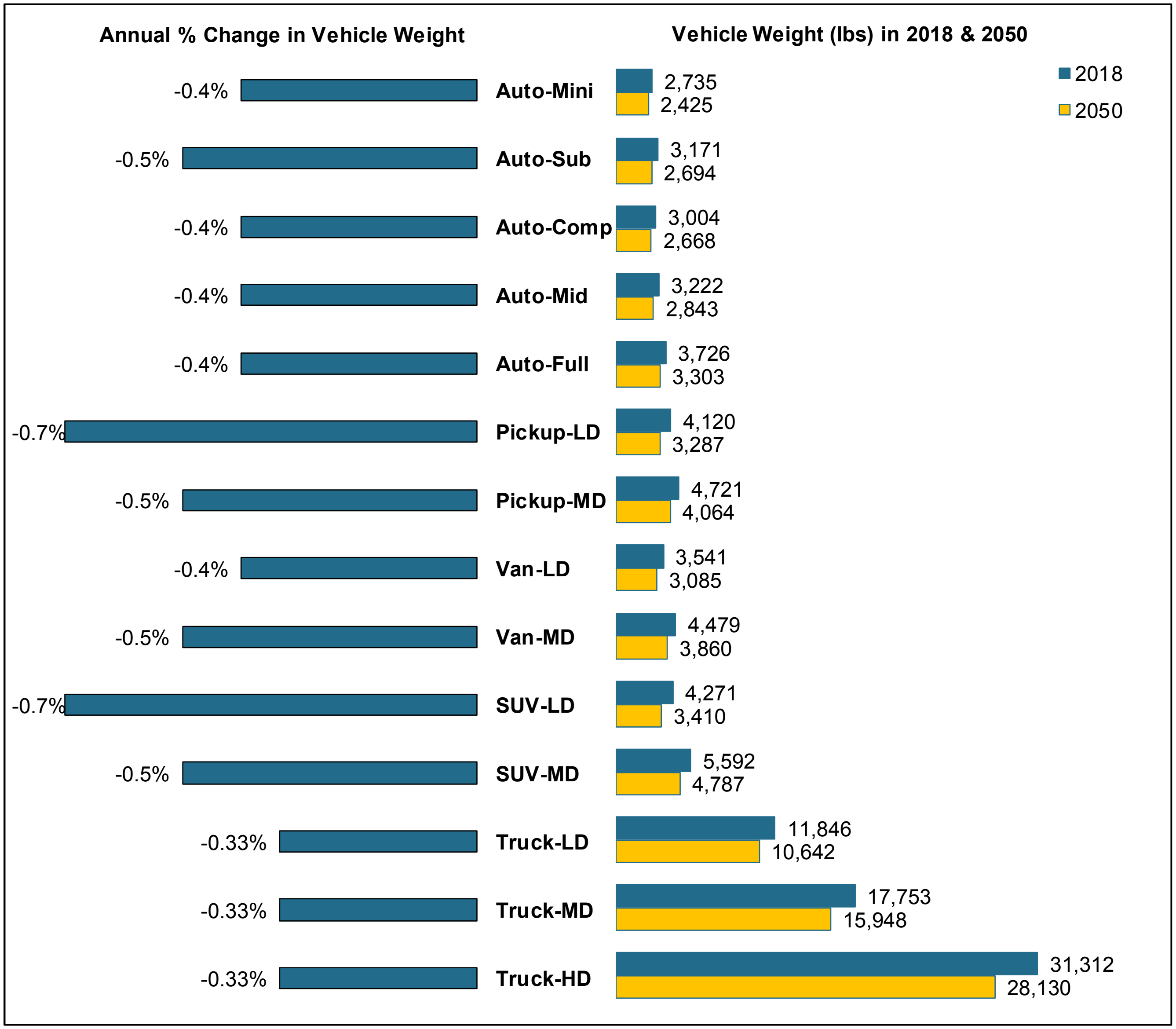


Figure 5.29: Annual percent change in vehicle weight and vehicle weight (lbs.) in 2018 and 2050 per vehicle type (EIA webpage on New Vehicle Attributes in AEO 2018.)

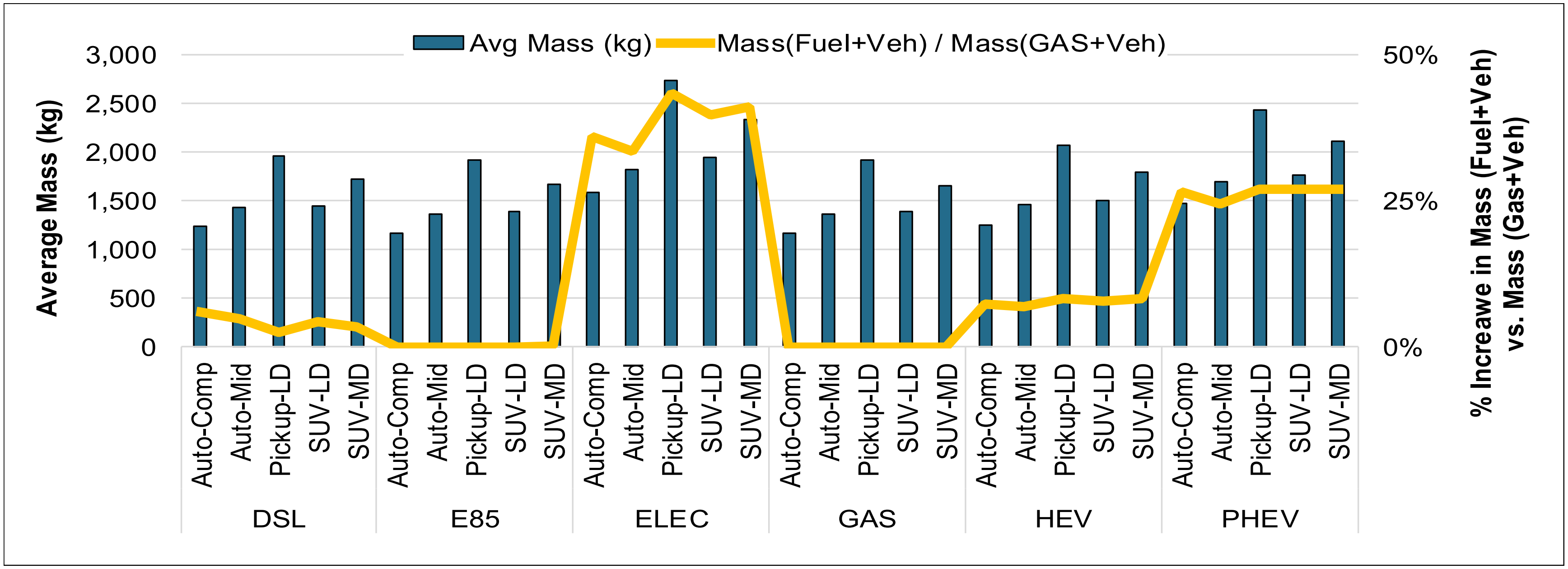


Figure 5.30: Average passenger vehicle weight by fuel type (EIA webpage on New Vehicle Attributes in AEO 2018.)

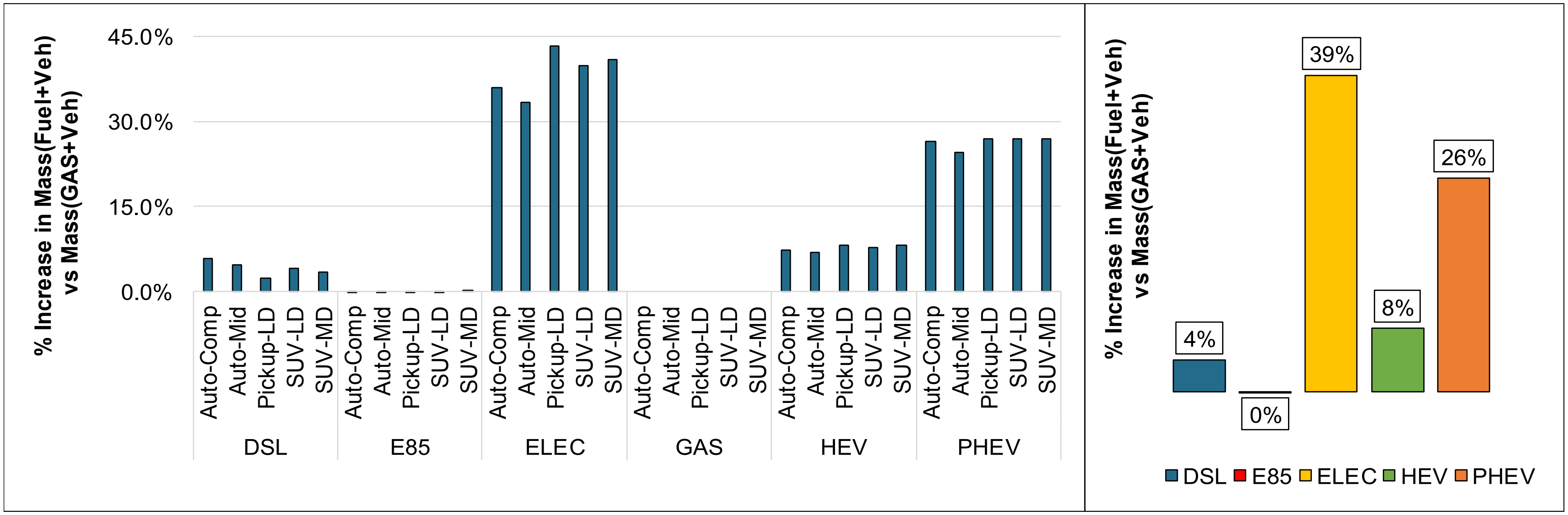


Figure 5.31: Percent increase in weight compared to conventional ICE vehicle (EIA webpage on New Vehicle Attributes in AEO 2018.)

5.4.8.2. Fuel Use Impacts [Well-to-Wheel (WTW) Impacts]

The second part of the environmental impacts of using vehicles is due to fuel use, which by itself consists of two separate stages:

- Fuel production stage impacts, which captures the energy consumption and environmental impacts of all the upstream processes that are conducted for producing the fuel and making it available at the pump, hence well-to-pump (WTP) impacts. The terminology was coined based on conventional petroleum-based fuels which originate from crude oil extracted through wells in the ground. However, it is not the case for all fuel pathways, at least not anymore.
- Fuel combustion in vehicles: which refer to the emissions due to fuel combustion during the in vehicles during the use stage. This stage is referred to as pump-to-wheel (PTW.)

The collective impacts of WTP and PTW are referred to as well-to-wheel (WTW) impacts. WTW impacts are expressed in grams of CO_2e per mile of travel. Figure 5.32 shows the boxplots of WTP, PTW, and WTW impacts for ICEVs, EVs, and FCVs. While EVs and FCVs have the highest WTP impacts, their zero tailpipe emissions during the use stage (zero PTW impacts) make them have lower impacts compared to ICEV, HEV, and PHEV when considering the full WTW impacts. The variability in GHG impacts of each vehicle technology shown in the boxplots of Figure 5.32 is due to alternative feedstocks/pathways available for each vehicle fuel technology. The high variabilities that are observed show how drastically WTW emissions of a vehicle fuel technology can change just by choosing a different feedstock/pathway. The figure does not cover all vehicle fuel technologies as the GREET database, which was used to create these boxplots, had very few entries for PHEVs and HEVs resulting in significantly lower variabilities for them compared to ICEV and EVs which would not make sense since they use similar fuel type.

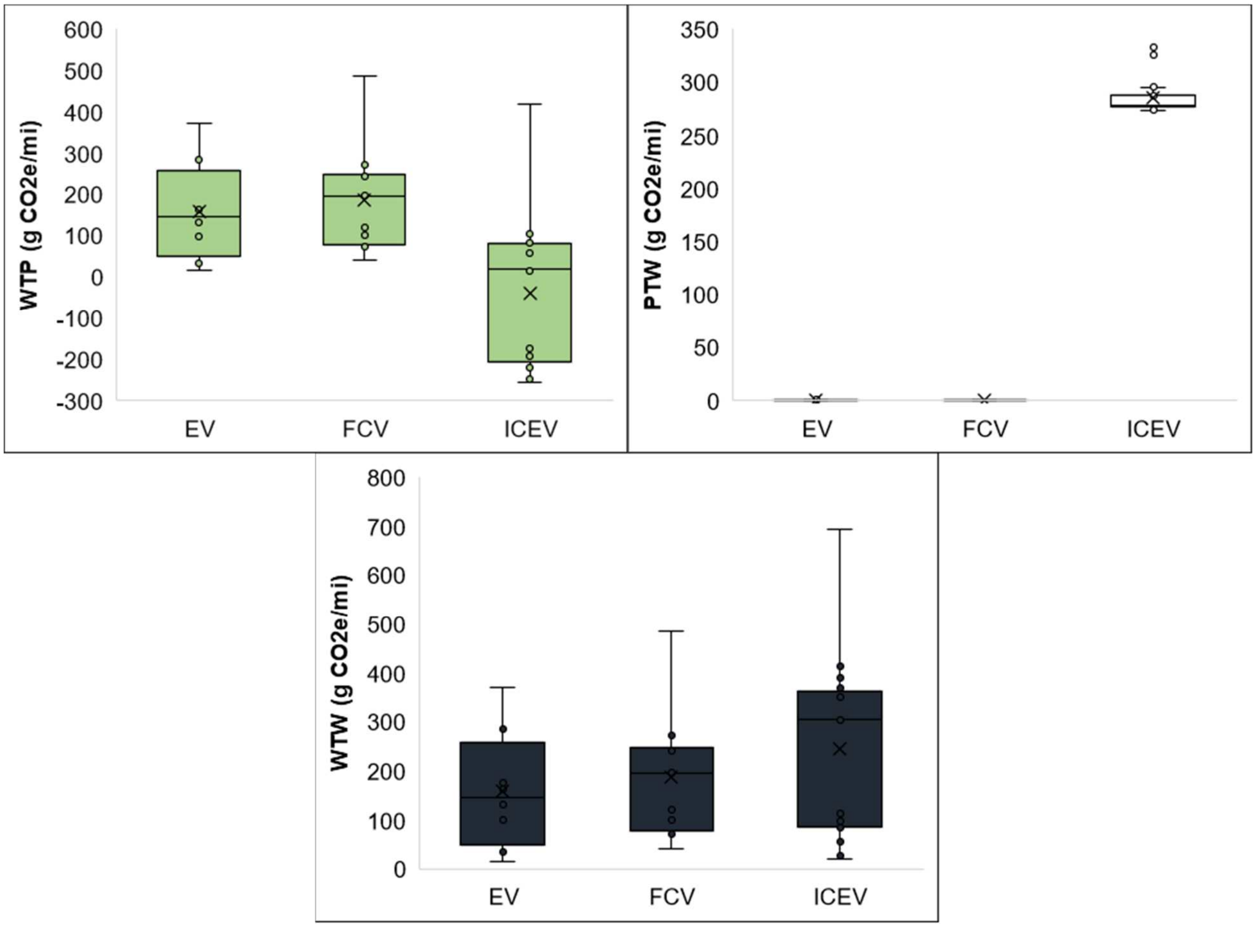


Figure 5.32: WTP, PTW, and WTW for different feedstocks of selected vehicle fuel technologies.

5.4.8.3. WTW and Vehicle Cycle Impact

The final data model that was used in the model quantifying vehicle cycle and fuel cycle impacts is presented in Table 5.16. Figure 5.33 is the graphical presentation of the results for light-duty vehicles as graphs. ICEVs have the highest total GHG emissions per mile, with 448 grams of CO_2e per mile followed by HEVs, FCVs, and PHEVs with 336, 307, and 268. EVs, running on California electricity, have the best performance with 233 grams of CO_2e per mile, a reduction of 48 percent compared to ICEVs. Vehicle operation constitutes the main portion of total GHGs for ICEVs, HEVs, and PHEVs, with 74.1, 71.5, and 42.4 percent, respectively, while this number is zero for EVS and FCVs as they have no tailpipe GHG emissions.

Table 5.16. Final dataset used in the model for WTP, WTW, and vehicle cycle GHG impacts

Vehicle	Fuel	Vehicle Cycle Impacts (kg CO2)	Fuel WTP (g CO_2e/mi)	Vehicle Cycle Impacts (g CO_2e/mi)	Vehicle Operation (g CO_2e/mi)	Total GHG Emissions (g CO_2e/mi)
Auto-Comp	ELEC	9,100	173	53	0	226
Auto-Comp	PHEV	7,643	111	44	114	269
Auto-Comp	HEV	6,045	59	35	241	334
Auto-Comp	GAS	5,659	81	33	332	446
Auto-Full	ELEC	11,285	173	65	0	239

Vehicle	Fuel	Vehicle Cycle Impacts (kg CO2)	Fuel WTP (g CO_2e/mi)	Vehicle Cycle Impacts (g CO_2e/mi)	Vehicle Operation (g CO_2e/mi)	Total GHG Emissions (g CO_2e/mi)
Auto-Full	PHEV	9,478	111	55	114	279
Auto-Full	E85	6,110	213	35	80	328
Auto-Mid	ELEC	9,758	173	56	0	230
Auto-Mid	PHEV	8,196	111	47	114	272
Auto-Mid	HYD	10,044	250	58	0	308
Auto-Mid	E85	5,284	213	31	80	323
Auto-Mid	GAS	6,068	81	35	332	449
Auto-Sub	ELEC	9,603	173	56	0	229
Auto-Sub	PHEV	8,066	111	47	114	271
Pickup-LD	ELEC	12,478	206	67	0	274
Pickup-LD	PHEV	10,481	155	56	192	403
Pickup-LD	E85	6,756	302	36	113	452
Pickup-LD	GAS	7,760	129	42	535	706
Pickup-MD	DSL-R100	8,831	-304	47	480	224
Pickup-MD	DSL-HPR	8,831	33	47	149	229
Pickup-MD	E85	7,281	-50	39	479	468
Pickup-MD	CNG	9,344	118	50	403	571
Pickup-MD	LPG	8,831	97	47	433	577
Pickup-MD	DSL-B20	8,831	34	47	497	578
Pickup-MD	GAS	8,359	119	45	487	651
Pickup-MD	DSL	8,831	110	47	495	653
SUV-LD	ELEC	12,936	197	70	0	267
SUV-LD	E85	7,004	224	38	84	345
SUV-LD	PHEV	10,865	135	58	156	350
SUV-LD	GAS	8,044	106	43	432	581
Truck-HD	DSL-R100	58,573	-853	135	1,343	625
Truck-HD	DSL-HPR	58,573	93	135	416	643
Truck-HD	GAS	55,440	250	127	1,016	1,393
Truck-HD	DSL-B20	58,573	95	135	1,389	1,619
Truck-HD	CNG	61,973	345	142	1,318	1,806
Truck-HD	DSL	58,573	310	135	1,386	1,831
Truck-LD	E85	19,426	-119	177	1,140	1,198
Truck-LD	CNG	24,362	268	221	1,033	1,522
Truck-MD	DSL-R100	33,208	-761	180	1,198	617
Truck-MD	DSL-HPR	33,208	83	180	371	633
Truck-MD	LPG	33,208	196	180	871	1,246
Truck-MD	GAS	31,432	241	170	981	1,392
Truck-MD	DSL	33,208	276	180	1,236	1,692
Truck-MD	CNG	35,136	238	190	805	1,234
Truck-MD	DSL-B20	33,208	100	180	1,621	1,900
Van-LD	DSL-R100	6,882	-304	37	480	214

Vehicle	Fuel	Vehicle Cycle Impacts (kg CO2)	Fuel WTP (g CO_2e/mi)	Vehicle Cycle Impacts (g CO_2e/mi)	Vehicle Operation (g CO_2e/mi)	Total GHG Emissions (g CO_2e/mi)
Van-LD	DSL-HPR	6,882	33	37	149	219
Van-LD	E85	5,806	-50	31	479	460
Van-LD	DSL-B20	6,882	34	37	497	567
Van-LD	PHEV	9,007	102	48	418	569
Van-LD	GAS	6,669	119	36	487	642
Van-LD	DSL	6,882	110	37	495	643
Van-MD	E85	6,909	-50	37	479	466
Van-MD	CNG	8,865	118	48	403	568
Van-MD	GAS	7,931	119	43	487	649

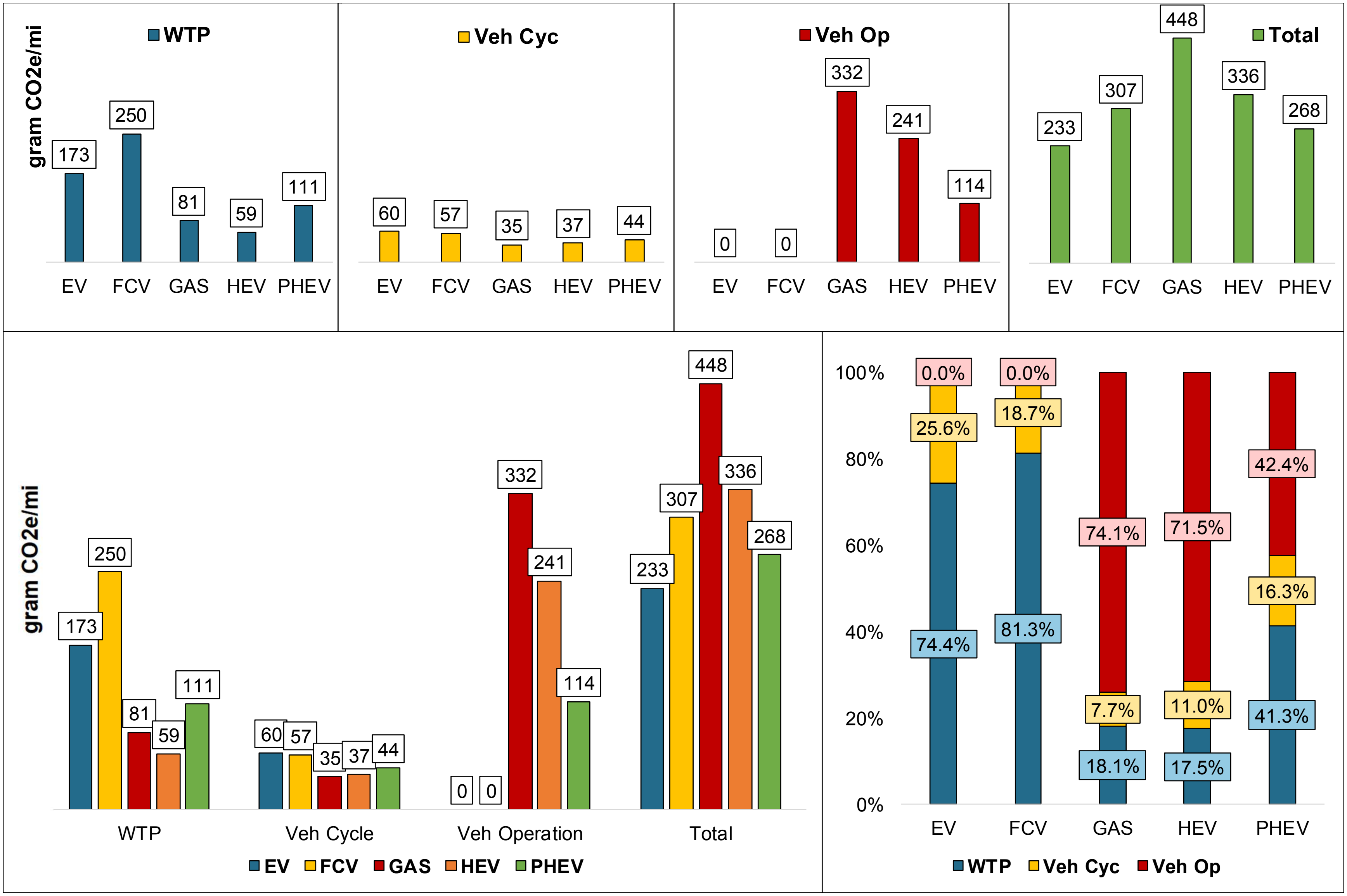


Figure 5.33: WTW and fuel cycle comparison of different light-duty vehicle types.

5.5. Data Sources and Data Quality

Table 5.17 shows the data sources used for developing the model in this study with quality assessment of each.

Table 5.17. Data sources used in this study and data quality assessment

Item	Data Sources	Geography	Time	Technology	Comp-leteness	Reprodu-cibility	Representativeness	Uncer-tainty
General								
Caltrans Fleet Mix and Average Miles Traveled per Year by Vehicle Type	Caltrans Fleet Database 2017@ DGS webpage	Excellent	Excellent	Excellent	Very Good	N	Excellent	Low
Historical MPG Values by Vehicle Type	USEPA	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Projections of MPG by Vehicle Type	EIA	Very Good	Excellent	Excellent	Excellent	N	Excellent	High
Depreciation Rate	DGS + Literature	Excellent	Excellent	Excellent	Excellent	Y	Excellent	Medium
LCA-Related								
Vehicle Cycle Impacts for Light-Duty Vehicles	GREET + AFLEET	Excellent	Very Good	Excellent	Excellent	Y	Excellent	Low
Vehicle Cycle Impacts for Trucks	Based on (GREET + AFLEET) Data	Excellent	Very Good	Good	Good	Y	Good	Medium
Fuel Impacts (WTP, PTW, and WTW)	GREET + AFLEET	Excellent	Excellent	Excellent	Excellent	Y	Excellent	Low
Projections of Vehicle Weight	EIA	Very Good	Excellent	Excellent	Excellent	N	Excellent	High
Cost-Related								
Energy Cost Comparison of CA vs U.S. Averages	EIA	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Historical Price of Alternative Fuels	AFDC	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Projections of Alternative Fuel Prices	EIA	Very God	Excellent	Excellent	Excellent	N	Very Good	High
Historical Price of Vehicle by Vehicle Type	Caltrans Fleet Database 2011-14@DGS webpage	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Projections of Vehicle Price by Vehicle and Fuel Technology Combination	EIA	Very Good	Excellent	Excellent	Excellent	N	Very Good	High
Registration Fees	CA DMV webpage	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low

Item	Data Sources	Geography	Time	Technology	Comp-leteness	Reproducibility	Representativeness	Uncer-tainty
Maintenance and Repair Cost per Vehicle Type	GREET + AFLEET	Very Good	Very Good	Very Good	Very Good	N	Excellent	High

5.6. Study Limitations and Gaps

The analysis presented in this chapter had the following limitations and gaps that need to be evaluated in future stages of this research:

- The study did not include the cost and environmental impacts of building and maintaining fueling infrastructure for any of the fuel types considered in the analysis.
- Maintenance and upkeep of parking spaces for the fleet were not included in the system boundary of the study.
- California is aggressively moving towards decarbonization/minimization of GHG emissions in all its economic sectors, specifically the electricity sector with measures such the Renewable Portfolio Standard (CPUC webpage on RPS) which mandates 50 percent renewable electricity in California grid mix by 2030. Therefore, one fuel pathway which is expected to have major reductions in WTP impacts is electricity. However, these expected reductions in WTP were not implemented in this study, mainly due to the limited scope of this initial study. However, the fact that more than 80 percent of the state fleet consists of medium-duty pickups and trucks for which an EV option is not currently available reduces the significance of this issue, at least for the immediate future.
- Due to current technological limitation for the range of EVs, conversion to EVs was not considered as an option for vehicles that had AVMT higher than typical current EV ranges. EV ranges are expected to increase in the future, however, it was not considered in this study due to uncertainty regarding the rate of range increase.

5.7. Results and Discussion

The results of the case studies are shown in Table 5.18 to Table 5.22 and Figure 5.34 and Figure 5.35. Figure 5.34 compares LCC across all four cases. Figure 5.35 focuses on GHG emissions at various stages of the vehicle and fuel cycles. Figure 5.36 compares the total fuel consumption during the analysis for each fuel. Figure 5.37 shows the WTW GHG emissions of the Caltrans fleet fuel consumption across four scenarios between 2018 and 2050.

The data in Table 5.18 show that the total life cycle costs of the BAU case, without considering the registration fees and insurance cots, have a net present value (NPV) of \$2.355 billion compared to \$2.512, \$2.425, and \$1.996 billion for DGS, All-at-Once, and Worst-Case Scenario, respectively which is equivalent to 7.4 and 3.3 percent increases versus BAU for the DGS and All-at-Once cases, and a 16.9 percent decrease for the Worst-Case Scenario.

Purchase of new vehicles was the largest portion of total net costs for all four cases, ranging between 59 to 83 percent of final net total costs.

Fuel costs were the second largest expense items for all cases, ranging between 30 to 35 percent of total net costs. Maintenance and repair on average made up about 24 percent of total net costs.

The salvage value for the DGS case was highest among all four cases, as the policy would require changing vehicles at far earlier ages compared to historical practice by Caltrans. The salvage value equaled -48 percent of total net costs for the DGS case because of the large number of vehicles bought in the last years of the analysis period, while for the other three cases this value was around 30 percent.

Looking at the GHG emissions data in Table 5.19 benchmarking of the fleet GHG emissions in the year 2017 show that WTW impacts are more than 69,000 metric tonnes of CO_2e. The total GHG emissions, including vehicle cycle impacts, could not be calculated as vehicle purchase data for the year 2017 were not available.

Total GHG emissions during the analysis period of 2018 to 2050 are projected to reach close to 1.46 million metric tonnes of CO_2e for the BAU case while the results for the DGS, All-at-Once, and Worst-Case scenarios were approximately 1.43, 1.32, and 2.25 million metric tonnes, which equate to savings of two and nine percent in total GHG emissions versus BAU for the DGS and All-at-Once scenarios.

The Worst-Case Scenario results show that consequences of inaction in the adoption of AFVs by Caltrans and maintaining the current mix of vehicle technology and fuel will result in a 54 percent increase in the GHG footprint of their fleet between now and the year 2050. The total fuel consumption by fuel type for each case is presented in Table 5.20.

The negative well-to-pump values over the analysis period shown in Table 5.19 are because of the use of AFVs, even in the BAU case. These values include the emissions from the production of electricity used in California, as well as the liquid fuels. The increasing use of bio-based diesel results in net carbon sequestration for WTP. Table 5.21 shows the breakdown of GHG emissions for cases with negative GWP values for WTP. The fuels in these cases are either E85 from corn or 100 percent renewable diesel from forest-residue and the negative GWP for WTP is only due to the fuel feedstock across all cases, after inclusion of processing and transportation to the pump. The values for fuel cycle presented in this table are taken directly from the 2018 Excel based model GREET 1. Use the fuel vehicle combinations in the fourth column of Table 5.21 to access the data by searching within the GREET 1 Excel file.

The assumptions and calculation details for LCA of each fuel are presented in separate tabs in the GREET main file. For the specific case of renewable diesel from forest-residue, the main reference used for the input data and assumptions was Jones et al., (2013.) The background, assumptions, and calculations methods used to calculate the fuel cycle impacts of all different vehicle fuel combinations provided in GREET and used in this study are available in Cai et. al (2017), Elgowainy et al., (2016) , Cai et al., (2015), and Elgowainy et al., (2010.)

Table 5.18. Comparison of life cycle cost (in million dollars) across cases

	BAU		DGS		All at Once		Worst-Case	
Cost Item	**Value**	**% of Net Cost**	**Value**	**% of Net Cost**	**Value**	**% of Net Cost**	**Value**	**% of Net Cost**
Fuel	1,323	35%	1,299	32%	1,322	34%	949	30%
Purchase of New Vehicle	2,263	59%	3,313	83%	2,400	62%	2,052	64%
Maintenance Repair	920	24%	923	23%	925	24%	827	26%
Salvage Value	-1,090	-29%	-1,916	-48%	-1,178	-31%	-1,022	-32%
Total Net Cost	3,417	90%	3,618	90%	3,469	90%	2,807	88%
Net Present Value	2,124	56%	2,281	57%	2,195	57%	1,765	55%
Change in NPV vs BAU	0.0	N/A	156.8	N/A	70.8	N/A	-358.7	N/A
Percent Change in NPV vs BAU	0.0%	N/A	7.4%	N/A	3.3%	N/A	-16.9%	N/A

Table 5.19. Comparison of total GHG emissions between 2018 and 2050 (Tonnes of CO_2e) and cost of GHG abatement (dollar per Tonne of CO_2e abated)

GHGs (Tonne CO_2e)	2017 Emissions	BAU	DGS	All at Once	Worst-Case
WTP	12,679	-1,110,670	-1,185,363	-1,289,950	352,826
PTW	56,885	2,218,095	2,179,817	2,245,951	1,570,324
WTW	69,564	1,107,425	994,454	956,001	1,923,150
Net Vehicle Cycle	N/A	384,514	461,520	401,785	353,849
Total GHG Emissions	69,564	1,459,127	1,433,508	1,321,527	2,245,997
Change in GHGs vs BAU	N/A	0	-25,619	-137,600	786,870
Percent Change vs BAU	N/A	0%	-2%	-9%	54%
Abatement Cost ($/Tonne CO2)	N/A	$0.0	$6,119	$514	N/A

Table 5.20. Comparison of total vehicle on-board liquid fuel consumption (in 1000 of gasoline or diesel gallon equivalent [GGE or DGE]) between 2018-2050 by fuel type across all cases

Fuel Type	BAU	DGS	All at Once (in 2018)	Worst-Case Scenario
CNG	306	184	85	2,216
DSL	0	0	0	0
DSL-B20	0	0	0	0
DSL-HPR	23,165	14,293	5,272	132,344
DSL-R100	193,487	201,675	216,699	0
E85	7,395	5,484	4,846	22,629
ELEC	6,247	6,729	6,998	182
GAS	13,893	7,572	2,494	70,794

Fuel Type	BAU	DGS	All at Once (in 2018)	Worst-Case Scenario
HEV	68	45	18	785
HYD	90	44	4	249
LPG	204	204	204	5,814
PHEV	1,950	1,856	1,782	743
Total	**246,805**	**238,085**	**238,401**	**235,757**
% Change vs BAU	**0.0%**	**-3.5%**	**-3.4%**	**-4.5%**

Table 5.21. Breakdown of GHG emissions for cases with negative WTP

Fuel	Fuel Full Title in GREET	Fuel + Vehicle Combinations in GREET Excel Model-1	Feedstock (g CO_2 / mile)	Fuel (g CO_2 / mile)	WTP (g CO_2 / mile)	PTW (g CO_2 / mile)	WTW (g CO_2 / mile)
DSL-R100	Forest Residue-based RDII 100	CIDI Heavy Heavy-Duty Vocational Vehicles: Forest Residue-based RDII 100	-1,263	410	-853	1,343	490
DSL-R100	Forest Residue-based RDII 100	CIDI Medium Heavy-Duty Vocational Vehicles: Forest Residue-based RDII 100	-1,126	365	-761	1,198	437
DSL-R100	Forest Residue-based RDII 100	CIDI Light Heavy-Duty Vocational Vehicles: Forest Residue-based RDII 100	-925	300	-625	985	360
E85	E85, Corn	SI Light Heavy-Duty Vocational Vehicles: E85, Corn	-563	443	-119	1,140	1,021
E85	E85, Corn	SI Medium Heavy-Duty Vocational Vehicles: E85, Corn	-475	375	-101	964	863
DSL-R100	Forest Residue-based RDII 100	CIDI Heavy-Duty Pick-Up Trucks and Vans: Forest Residue-based RDII 100	-449	146	-304	480	177
E85	E85, Corn	SI Heavy-Duty Pick-Up Trucks and Vans: E85, Corn	-235	185	-50	479	429

The abatement costs for each tonne of GHG reduced compared to BAU will cost Caltrans around $6,119 for DGS and $514 for All-at-Once. The reason for high cost of DGS is due to significant decrease in replacement mileage of vehicles (47 percent reduction on average across all vehicle types, ranging between 17 percent for medium duty trucks to 61 percent reduction for light duty pickup trucks.) Therefore, even though the all-at-once scenario replaces the whole fleet in the first year of the analysis, its life cycle cost is lower than implementing the gradual but more frequent schedule of DGS.

The information regarding the abatement potential calculations presented in this chapter is summarized in Table 5.22 for the 33-year analysis period.

Table 5.22. Abatement cost and potential for each case

Case	**35 Year Analysis Period**				**Average Annual over 35 Year Analysis Period**		
Scenario	**CO_2e Change (MMT)**	**Time Adjusted CO_2e Change (MMT)**	**Life Cycle Cost Change ($ million)**	**Benefit/Cost ($/tonne CO_2e reduced)**	**CO_2e Change (MMT)**	**Time Adjusted CO_2e Change (MMT)**	**Life Cycle Cost Change ($ million)**
BAU	0.000	0.00	0	N/A	0.00E+00	0.00E+00	0.00
DGS	-0.026	-0.03	157	$6,120	-7.76E-04	-7.76E-04	4.75
All-at-Once	-0.138	-0.14	70	$511	-4.17E-03	-4.17E-03	2.13
Worst-Case	0.787	0.79	-359	No Abatement	2.38E-02	2.38E-02	-10.89

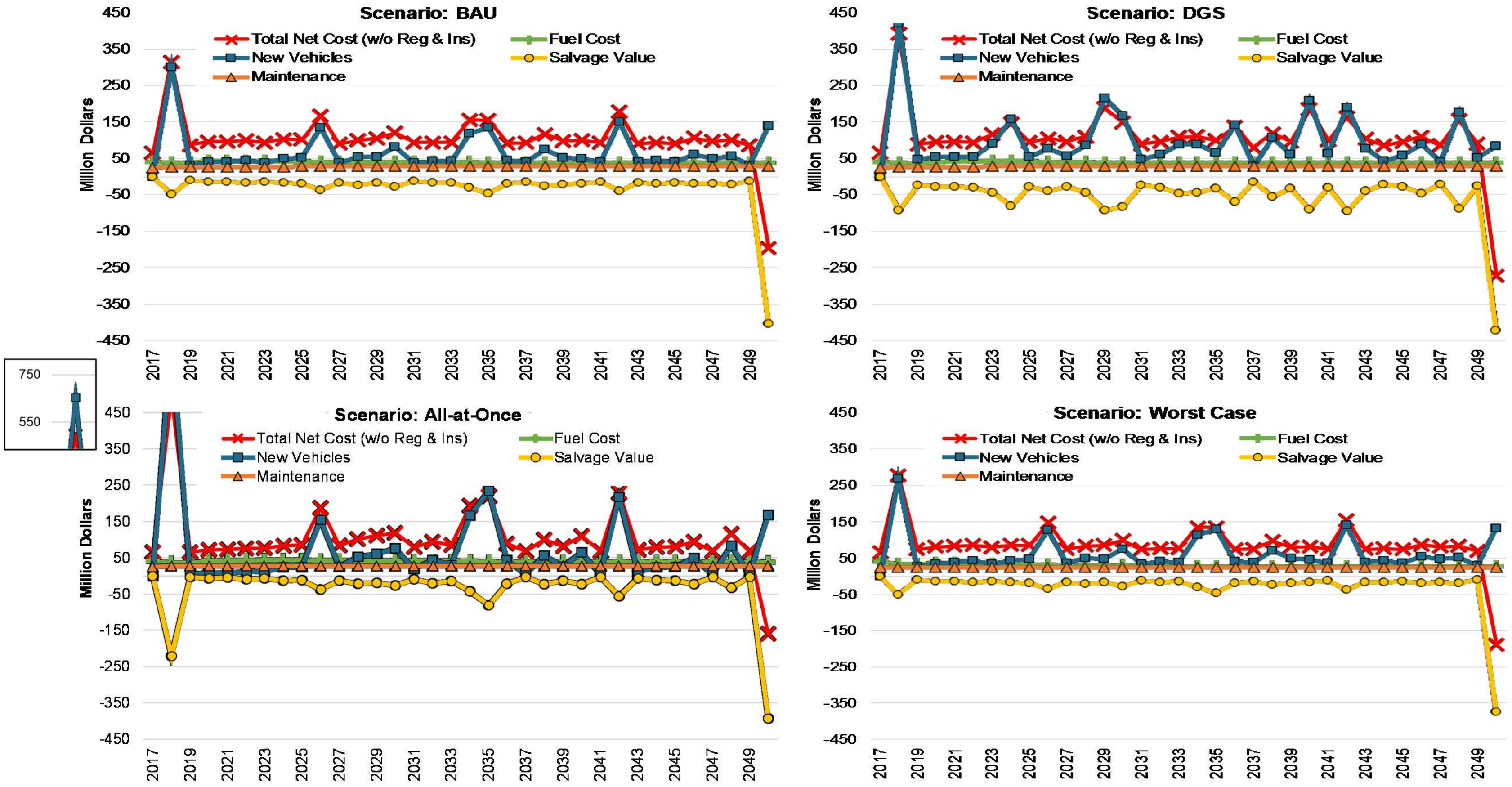


Figure 5.34: Comparison of life cycle cash flow across four scenarios.

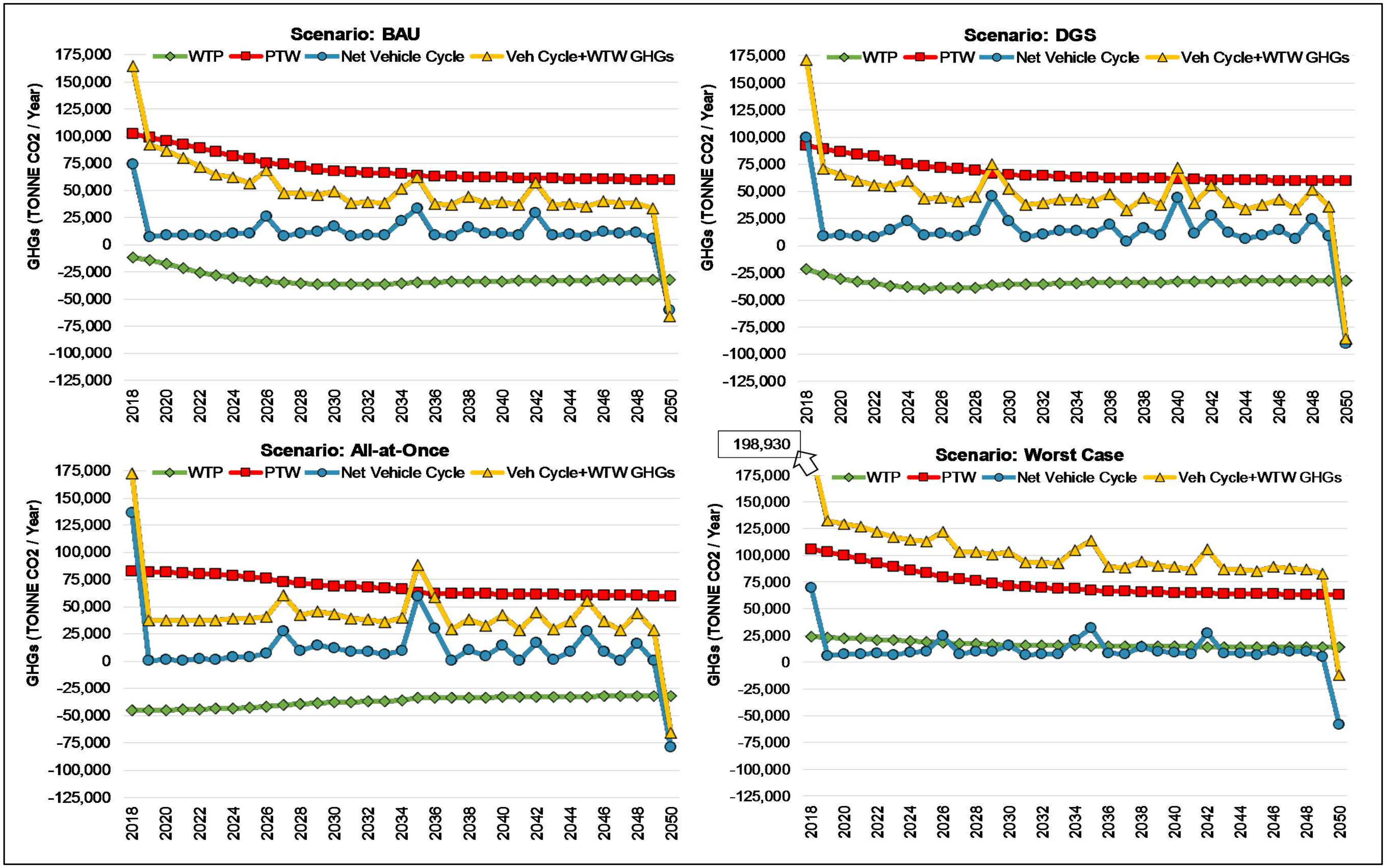


Figure 5.35: Comparison of GHG emissions across four scenarios: total GHG emissions, vehicle cycle emissions, and emissions due to various fuel life cycle stages (WTP, PTW, and WTW.)

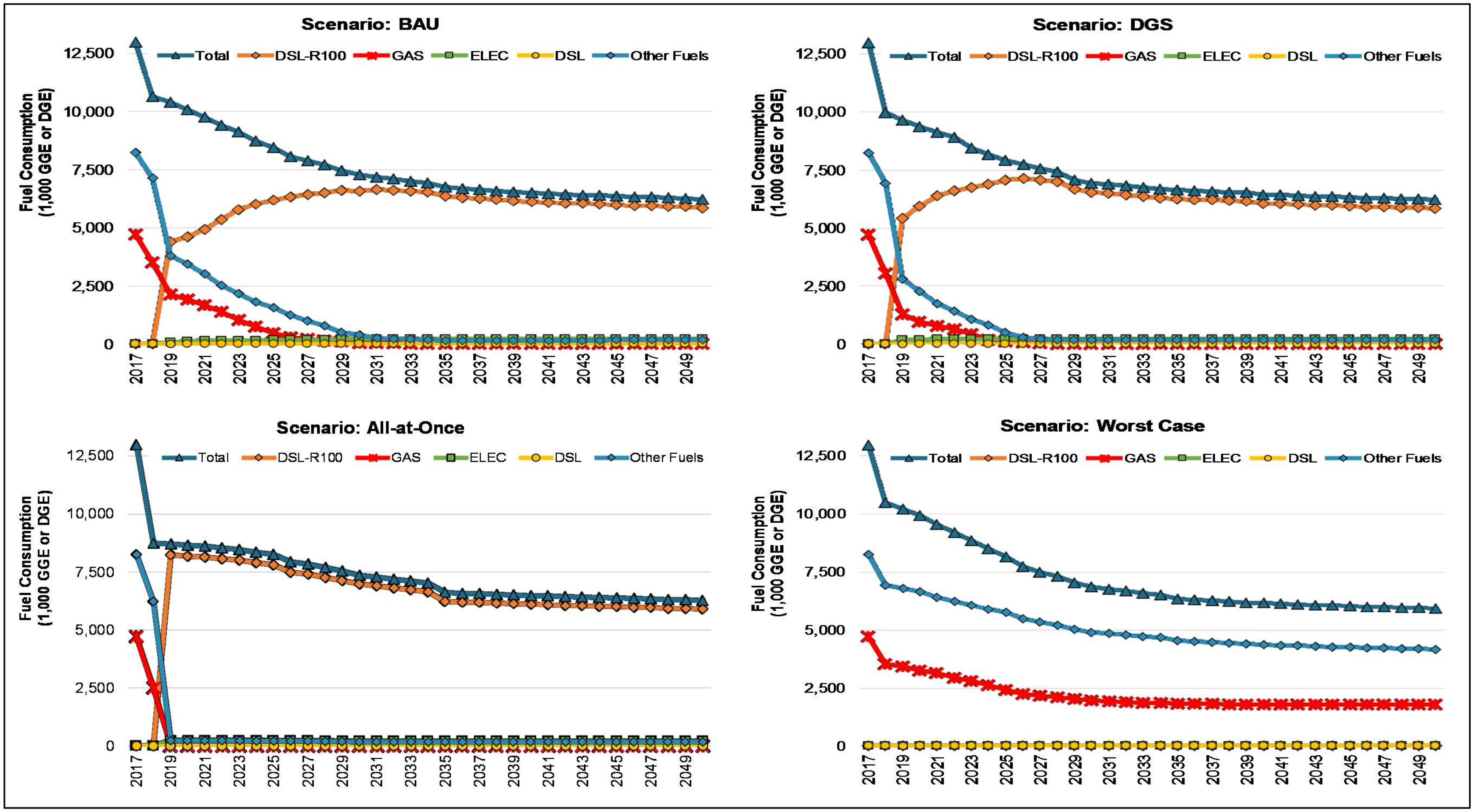


Figure 5.36: Comparison of total fuel consumption across all four cases.

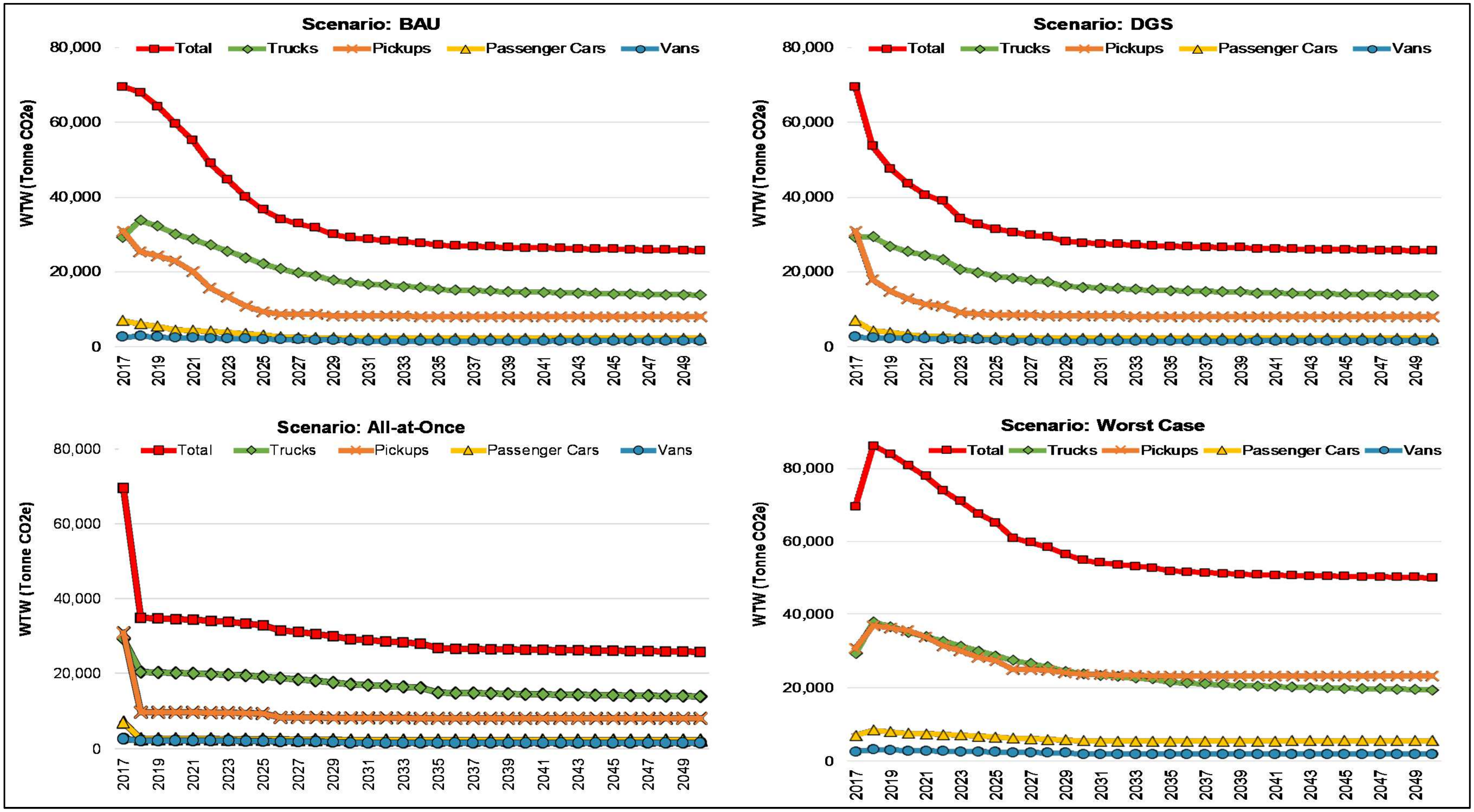


Figure 5.37: Comparison of WTW GHG emissions across cases.

CHAPTER 6. Evaluation of Increased Use of Reclaimed Asphalt Pavement in Construction Projects Considering Costs and Environmental Impacts

6.1. Introduction

Hot mix asphalt (HMA) is the surface type for approximately 75 percent of the state highway network and a widely used structural material in a number of different pavement applications. Rubberized hot mix asphalt (RHMA), which includes recycled used tires in the binder, is mandated for use for the surface layer of asphalt pavements. Reclaimed asphalt pavement (RAP) is old HMA that is milled off of existing pavement and can be used to partially replace virgin asphalt binder and aggregate in new HMA. RAP is not currently allowed in RHMA because it reduces the cracking resistance of RHMA, which is a key factor in the current approach for using RHMA as a surface material, and because the RAP binder displaces some of the waste tire rubber recycled into RHMA. Caltrans must meet a legislative mandate for recycling waste tires in all kinds of hot mix asphalt. Caltrans is currently developing technical approaches for increasing the percentage of RAP in HMA and allowing some RAP in RHMA without reducing the performance of these materials. This chapter evaluates the increased use of RAP in HMA compared with those from typical recent practice, without considering RHMA, by calculating changes in environmental impacts and costs.

6.2. Background

Caltrans has allowed contractors to use up to 15 percent RAP (by weight) in HMA without any additional engineering for a number of years (Caltrans, 2018c), which is considered as the baseline for this strategy in this chapter. Up to 25 percent RAP was allowed in the past several years, however, the specifications called for a very conservative approach to the engineering of the blended RAP/virgin binder and the use of expensive and time consuming testing that also required the use of highly regulated solvents, all of which essentially eliminated the use of more than 15 percent RAP. In 2018, the specifications were changed to allow up to 25 percent RAP without the need for the testing that was considered by industry to be onerous. Caltrans is working on developing approaches to include approximately 40 percent RAP in HMA in the future, and to begin to use up to 10 percent coarse RAP in RHMA. Coarse RAP consists of the larger particle sizes in the material and has low binder content, with the result that this strategy would be to replace virgin aggregate with little or no replacement of virgin binder. The use of RAP in RHMA was not considered in this study.

An important portion of Caltrans environmental impacts are due to projects awarded each year to contractors for maintaining nearly 50,000 lane-miles of state highway pavement infrastructure in California. Additional pavement infrastructure includes ramps, parking lots, turnouts, shoulders, rest areas, gore areas, drainage facilities, dikes, and curbs. The purpose of this case study was to assess how much Caltrans can reduce the environmental impacts due to the HMA materials used in these projects, specifically by increasing the amount of RAP to replace virgin materials.

There are many different types of materials used in pavement projects; however, this chapter only focuses on the increased use of recycled asphalt concrete in flexible pavements as a starting point. Similar evaluations should also be conducted for other transportation infrastructure materials such as portland cement concrete, metals, plastic polymers, and additives.

As noted, HMA and RHMA are used for the majority of the pavement surfaces in California (Caltrans 2015.) The use of up to 15 percent RAP in asphalt is a mature and common practice across the nation. Asphalt surface layers can be milled at the end of their service life and used as RAP in new construction or M and R activities by blending it with virgin asphalt binder and aggregate to create new HMA, hence reducing virgin materials (aggregate and binder) in the mix through replacement. The use of RAP provides cost savings to materials producers. This is particularly true for the RAP binder which is much less expensive than virgin binder. The replacement of part of the virgin binder in a new mix with aged asphalt binder left on RAP particles can be allowed and obtain similar performance with a mix that has only virgin binder if the residual binder in RAP is able to blend with the virgin binder in the new mix, and if the properties of blended binder are similar to those the 100 percent virgin binder that would have been used otherwise.

RAP binder is stiffer and more brittle the specified virgin binder for a given climate region and application. The properties of RAP binder vary considerably depending on the original properties it had before it was placed, the amount of aging, and later processing. RAP piles at asphalt plants also have RAP from multiple locations. Even if the RAP is milled from one location, it often has a mix of multiple asphalt layers placed over the years. RAP should be processed to create greater uniformity before being used in new mixes. How to measure and engineer the resultant properties of the blended binder, and also determine the degree of blending that occurs during mixing, are the technological challenges to using higher percentages of RAP. Higher percentages of RAP often require the use of a softer virgin binder for the portion of the total binder not replaced by the RAP binder and the addition of softening additives, called rejuvenators, to facilitate blending of the aged and the virgin binders. It is important that the mix containing the RAP have similar performance to a mix with virgin binder with respect to fatigue and low-temperature cracking and rutting or else any cost and/or environmental benefits are in jeopardy.

6.3. Goal and Scope Definition

The goal of this study is to calculate how much reduction in GHG emissions can be achieved by increasing the maximum RAP content in HMA mixes, going from 15, 25, 40, and 50 percent binder replacement, and scale these calculations to the use of HMA on the state network in California. The scope of this study considers all the impacts from materials extraction to transportation to plants, and all the processes conducted in the plant to prepare the final mix. This is an example of an LCA with a *cradle to gate* scope. It was assumed that the construction process and field performance of the mixes with higher RAP content is the same as the base scenario. Therefore, the construction stage, use stage, and end-of-life were excluded from the scope of this study. This assumption is not consistently valid and depends on the ability of the asphalt technology to adjust for the RAP properties, which is considered in this study, but it is sufficiently valid for this first-order analysis.

The functional unit for this study is defined to be the California highway network. The analysis period considered for this study is 33 years, from 2018 to 2050. Cost implications of these scenario changes were of interest so that comparison with other reduction strategies would be possible.

6.4. Assumptions and Modeling Approach

The framework used for conducting this analysis is shown in Figure 6.1. A major part of the effort in this study was spent on estimating the amount of materials used each year on the state highway network during the analysis period. For this purpose, two options were considered:

- Material quantity estimates projected over the analysis period based on programmed work in the Caltrans pavement management system (PaveM), or
- Projection of material quantities from historical data of construction projects published annually in the Construction Cost Data Book.

PaveM is an asset management tool used for project prioritization, timing of future maintenance and rehabilitation, and budget allocation. User inputs into PaveM include a multitude of decision-making factors such as available budget, network characteristics (climate, traffic, dimensions), and agency decision trees that trigger treatment based on current and predicted values of key performance indices such as cracking and surface roughness for each segment in the network.

The output of PaveM is the type of treatment applied to each network segment, or “do nothing” for each year during the analysis period within the defined budget limits. It also calculates the cost of each treatment applied. The treatments for asphalt concrete are defined as thin, medium, and thick overlays, and provide an indication of the thickness of the asphalt concrete treatment, which can be multiplied by the lane width and length of the segment to get a volume. The volume can be converted to mass units typically used for asphalt materials, using a typical density. The PaveM estimates will tend to be lower than the actual total amount of asphalt concrete used by Caltrans because it only considers the lanes in the travelled way. It does not consider any paving on shoulders, ramps, parking lots, gore areas, and other places where Caltrans uses this material.

The other approach would be to use the Contract Cost Data Book (Caltrans webpage on CCDB) which is published annually by Caltrans. All the cost items of projects undertaken during the last fiscal year in Caltrans projects are listed in the CCDB with the unit cost and the amount purchased across the year of each item, regardless of where it was used. The CCDB can be used to estimate the amount of each material type used in Caltrans projects in prior years and then use the historical data to project materials consumption in the future.

A PaveM run was conducted under the current default budgeting scenario which projected an expenditure of 267 million dollars in 2018 for asphalt paving materials. However, the data in the 2018 Construction Cost Data Book (items 390132, 390135, 390136, 390137, 390401, 390402, 395020, and 395040) shows 545 million dollars in the same year for the same items (Caltrans webpage on CCDB.) To address this discrepancy and calculate material consumption in each year during the analysis period, the tonnages of materials from the CCDB 2018 were multiplied in all years after 2018 by the ratio of CCDB purchases in 2018 divided by the PaveM projected purchases in 2018. This should account for the additional material used outside of the travelled way lanes. App-Table 25 in Appendix V shows HMA and RHMA use in tonnes/year that was used in this study.

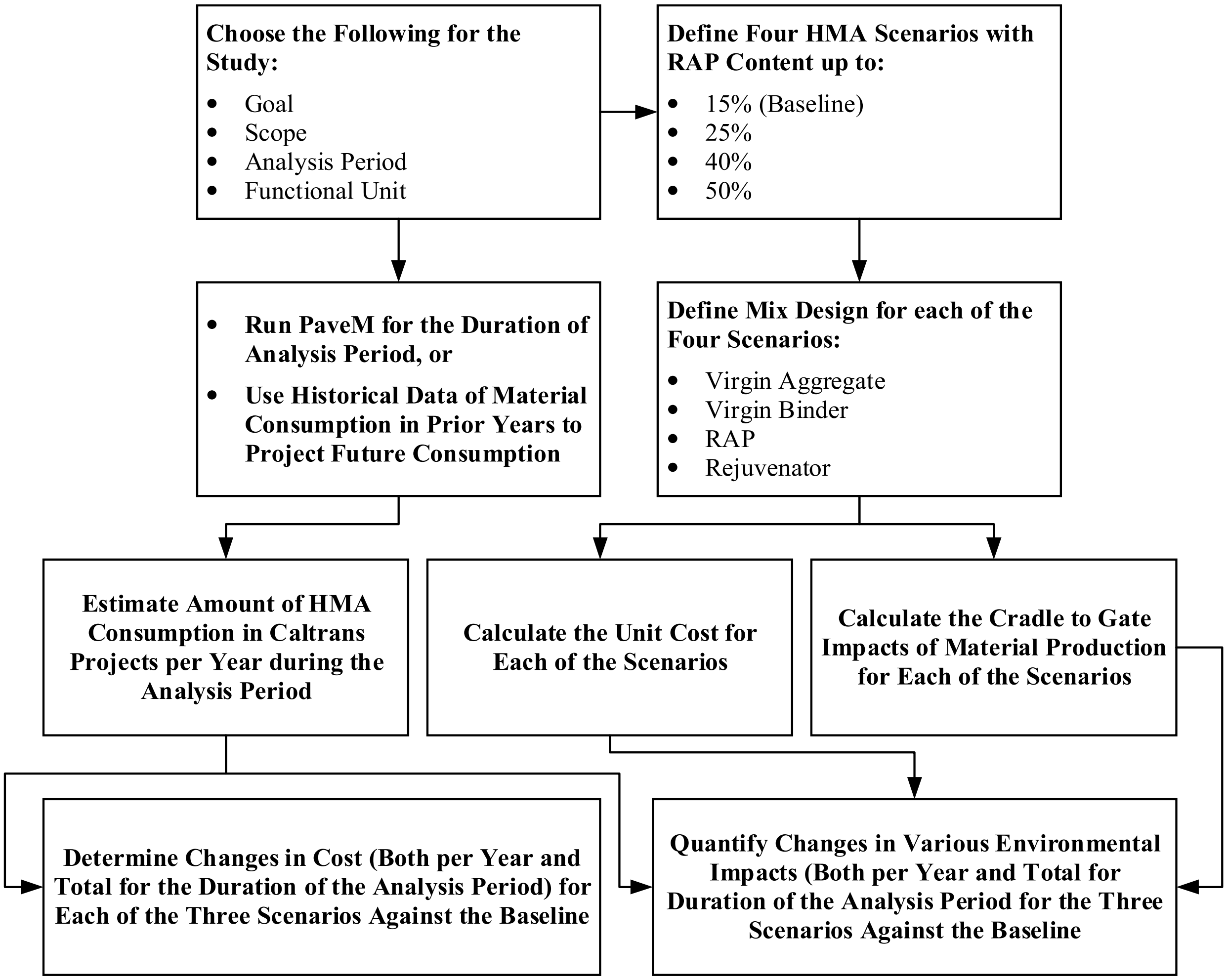


Figure 6.1: Flowchart of model development used for this study.

This study assumed that the current projected work plans to 2050 will not change considerably, and that current costs are representative of future costs. The study also assumes that current recycling strategies will not show much improvement. All of these assumptions are highly unlikely; however, they are reasonable for at least the next 5 to 10 years.

It should also be noted that northern California local agencies often follow Caltrans specifications, and any effects of Caltrans specification changes would be amplified by agencies in the northern counties following those specifications. Changes in local government practices were not considered in this study.

6.4.1. Material Consumption per Year

Figure 6.2 shows the amount of HMA and RHMA needed each year between 2018 and 2050 in Caltrans projects. The amount of materials was taken from PaveM. The current run provides data up to 2046. Due to lack of better alternative to estimate material need in 2046 to 2050, it was assumed that the average masses of HMA and RHMA used in the 10 years prior will be applied during that time period. Table D-1 in section 1 of Appendix V includes the details of the amount of HMA and RHMA needed per year per treatment type.

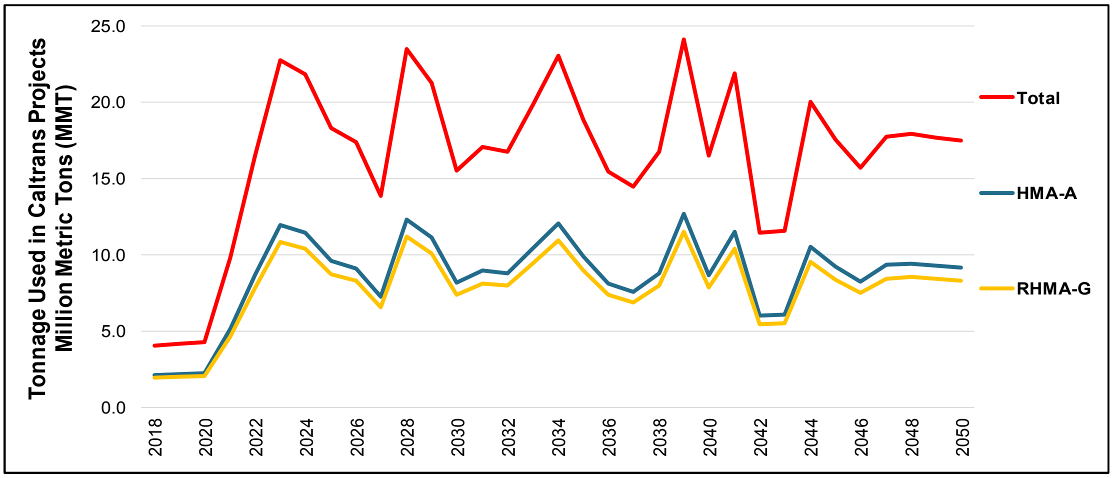


Figure 6.2: Materials needed per year between 2018-2050 based on PaveM outputs.

6.4.2. Mix Designs

The use of RAP in RHMA is not currently allowed in Caltrans projects. Therefore, four mixes with increasing maximum RAP content for HMA were considered as shown in Table 5-1. To avoid heating RAP to high temperatures, which can damage the residual binder in RAP, the heating temperature for RAP was limited to $350^oF\ (177^oC)$ while virgin aggregate were heated up to $500^oF\ (260^oC)$ to compensate and reach the required mixing temperature needed for the blended materials. These differences in temperature do not have any implications for the life cycle inventory of energy use for each mix because setting a fixed final mixing temperature for all mixes requires the same amount of heat for 1 kg mix of blended RAP and virgin materials, independent of the mass ratios of the two components. Increasing the RAP content will only result in higher temperatures needed for virgin aggregate materials to achieve the same mixing temperature for the blend.

Mixes with RAP content above 25 percent require a rejuvenating agent to be added to ensure reliable performance due to the higher percentage of aged binder recovered from RAP. Three common types of rejuvenating agents (RA) are aromatic extracts made from petroleum, bio-based RAs from made soy oil, and bio-based RAs made from tall oil that comes from trees. Another method for handling the issue of aged binder is to use softer virgin binder, which eliminates the need of rejuvenators, however, this method is only applicable for RAP contents up to 25 percent.

The models developed for this study are capable of considering the impact of rejuvenators and the user can modify the amount of rejuvenator in the mix design of each case. However, due to very limited information available regarding the materials in rejuvenating agents, developing LCA models in GaBi was not an option. It was eventually decided to use the LCI of a proxy, Aromatic BTX, as a placeholder for aromatic extracts and soy oil for bio-based RAs. This chapter reports the results for HMA with maximum of up to 25, 40, and 50 percent RAP with aromatic RA, bio-based RA, and with no RA (only for the scenario of up to 25 percent RAP.)

The actual virgin binder replaced in mixes by RAP binder is usually somewhat less than the specified limit in practice as contractor's work to meet a long list of other binder and mix requirements in the specifications. Also, high RAP mixes are replacing part of the virgin binder with rejuvenator, and future specifications will most likely consider rejuvenator as part of the RAP binder, and not part of the virgin binder, when allowing the maximum RAP content.

Table 6.1.The five scenarios considered for HMA for Caltrans projects across the entire network

Mix Title	Max RAP Content	Actual Binder Replacement	Virgin Binder Replaced by RAP	Virgin Binder Replaced by Rejuvenator
HMA (Max 15% RAP)	15%	11%	11%	0%
HMA (Max 25% RAP)	25%	20%	15%	5%
HMA (Max 25% RAP)	25%	20%	20%	0%
HMA (Max 40% RAP)	40%	35%	28%	7%
HMA (Max 50% RAP)	50%	42%	32%	10%

The baseline mix designs for HMA and RHMA were taken from the UCPRC Case Studies report (Wang et al., 2012) and are presented in App-Table 26 in Appendix V. It was also assumed that the RAP materials had a binder content of 5 percent by mass with a 90 percent binder recovery ratio, resulting in an effective RAP binder content of 4.5 percent. Therefore, the total binder content for HMA baseline is 4.7 percent (0.04 + 0.15 * 0.045 = 0.047.) The RHMA total binder content is 7.5 percent. These data combined with the information in Table D-2 were used to develop the mix designs for new HMA scenarios which are shown in Table 6.2.

Table 6.2. Mix design component quantities by mass of mix for HMA scenarios and RHMA used in this study

Mix	RAP	Rejuv	Virgin Binder	Virgin Agg	CRM	Extender Oil	Total Binder
HMA (Max 15% RAP)	11.5%	0.00%	4.18%	84.3%	0.00%	0.00%	4.70%
HMA (Max 25% RAP)	15.7%	0.24%	3.76%	80.3%	0.00%	0.00%	4.70%
HMA (Max 25% RAP, no Rejuvenator)	20.9%	0.00%	3.76%	75.4%	0.00%	0.00%	4.70%
HMA (Max 40% RAP)	29.2%	0.33%	3.06%	67.4%	0.00%	0.00%	4.70%
HMA (Max 50% RAP)	33.4%	0.47%	2.73%	63.4%	0.00%	0.00%	4.70%
RHMA-G	0.0%	0.00%	5.81%	92.5%	1.50%	0.19%	7.50%

6.4.3. LCA Calculations

The mix designs were then used to calculate the cradle to gate environmental impacts of for each mix using the LCA methodology. For this purpose, the LCI database created by the UCPRC (Saboori et al., 2020) was used. All the details of model development, data sources, and the assumptions made can be found in that reference.

Table 6.3 shows the LCI results for the main construction materials used in this study taken from the UCPRC LCI database. The electricity grid mix used for modeling the material production stage was based on the 2012 grid mix in California (CEC Webpage on Electricity Generation in CA.) Only the following impact categories and inventory items are reported in this study: Global Warming Potential (GWP), Smog Formation Potential, Particulate Matter 2.5 (PM 2.5), Primary Energy Demand (PED) which is reported as Total, Non-Renewable (NR) and Renewable (R.)

Table 6.3. LCI of the items used in this study

Item	Unit	GWP [kg CO_2e]	Smog [kg O_3e]	PM 2.5 [kg]	PED-Total [MJ]	PED-NR [MJ]	PED-R [MJ]
Electricity	1 MJ	1.32E-1	4.28E-3	2.54E-5	3.09E+0	2.92E+0	1.70E-1
Natural Gas (Combusted)	1 m3	2.41E+0	5.30E-2	1.31E-3	3.84E+1	3.84E+1	0.00E+0

Item	Unit	GWP [kg CO_2e]	Smog [kg O_3e]	PM 2.5 [kg]	PED-Total [MJ]	PED-NR [MJ]	PED-R [MJ]
Aggregate (Crushed, Virgin)	1 kg	3.43E-3	6.53E-4	1.59E-6	6.05E-2	5.24E-2	8.03E-3
Binder (Virgin)	1 kg	4.75E-1	8.09E-2	4.10E-4	4.97E+1	4.93E+1	3.40E-1
Crumb Rubber Modifier	1 kg	2.13E-1	6.90E-3	1.05E-4	4.70E+0	3.60E+0	1.10E+0
Reclaimed Asphalt Pavement	1 kg	7.16E-3	1.39E-3	2.70E-6	1.02E-1	1.02E-1	0.00E+0
Rejuvenator	1 kg	6.44E-1	1.57E-4	3.20E-2	4.78E+1	4.76E+1	2.18E-1
Rejuvenator, Bio-based (Soy Oil)	1 kg	3.00E-1	2.60E-2	1.73E-4	3.48E+0	3.48E+0	0.00E+0
Rejuvenator, Aromatic BTX	1 kg	6.44E-1	1.57E-4	3.20E-2	4.78E+1	4.76E+1	2.18E-1

Table 6.4 shows the material production impacts for 1 kg of each of the mixes in this study. The GWP for the mixes, expressed in kg CO_2e, are compared in a bar chart in Figure 6.3 and the breakdown of GWP by components for each mix is shown in Figure 6.4.

Table 6.4. Environmental impacts of material production stage for 1 kg of each of the mixes

Mix Title	Rejuvenator Type	Unit	GWP [kg CO_2e]	Smog [kg O_3e]	PM 2.5 [kg]	PED-Total [MJ]	PED-NR [MJ]	PED-R [MJ]
HMA (Max 15% RAP)	N/A	1 kg	4.95E-2	4.68E-3	3.25E-5	2.56E+0	2.54E+0	2.23E-2
HMA (Max 25% RAP)	Aromatic BTX	1 kg	4.91E-2	4.37E-3	1.06E-4	2.46E+0	2.44E+0	2.10E-2
HMA (Max 25% RAP)	Bio-Based (Soy Oil)	1 kg	4.83E-2	4.43E-3	3.12E-5	2.36E+0	2.34E+0	2.05E-2
HMA (Max 25% RAP)	No Rejuvenator	1 kg	4.78E-2	4.41E-3	3.09E-5	2.35E+0	2.33E+0	2.01E-2
HMA (Max 40% RAP)	Aromatic BTX	1 kg	4.69E-2	3.90E-3	1.33E-4	2.16E+0	2.15E+0	1.78E-2
HMA (Max 40% RAP)	Bio-Based (Soy Oil)	1 kg	4.58E-2	3.99E-3	2.87E-5	2.02E+0	2.00E+0	1.71E-2
HMA (Max 50% RAP)	Aromatic BTX	1 kg	4.64E-2	3.67E-3	1.77E-4	2.07E+0	2.05E+0	1.67E-2
HMA (Max 50% RAP)	Bio-Based (Soy Oil)	1 kg	4.48E-2	3.79E-3	2.76E-5	1.86E+0	1.85E+0	1.57E-2
RHMA-G	N/A	1 kg	6.00E-2	5.97E-3	1.00E-4	3.50E+0	3.46E+0	4.53E-2

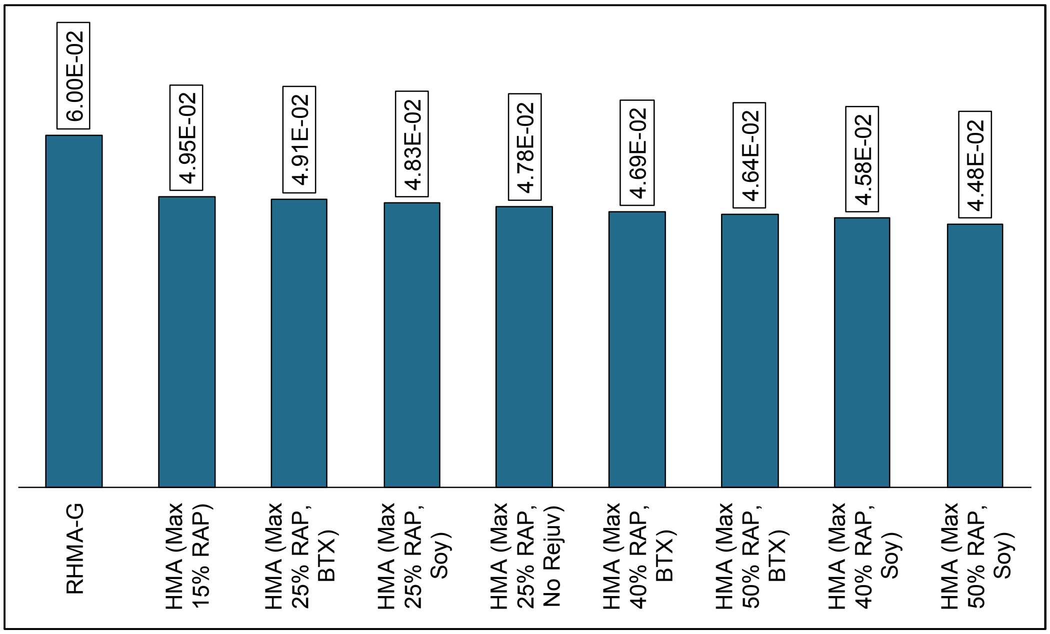


Figure 6.3: GWP (kg CO_2e) of material production stage for 1 kg of each of the mixes.

6.5. Data Sources and Data Quality

Table 6.5 summarizes the data sources for all the data used in this study and presents further details about the quality of the data used in this study.

6.6. Study Limitations and Gaps

The few limitations identified for this study are:

- This study was conducted assuming that the performance of mixes with higher RAP content are similar to mixes currently in use in Caltrans project. This assumption is currently being investigated and verified through research experiments, field studies, and pilot projects. All possible savings in the material production stage due to higher percentage of RAP use can be offset by possible reduced performance during the use stage as it results in more frequent maintenance and rehabilitation in the future.
- Recyclability and quality of materials recycled at the EOL of HMA with high RAP content is another issue that was not part of the scope in this study. Possible losses in quality after multiple rounds of recycling is an issue to consider in a more detailed study once research results in this area are available.

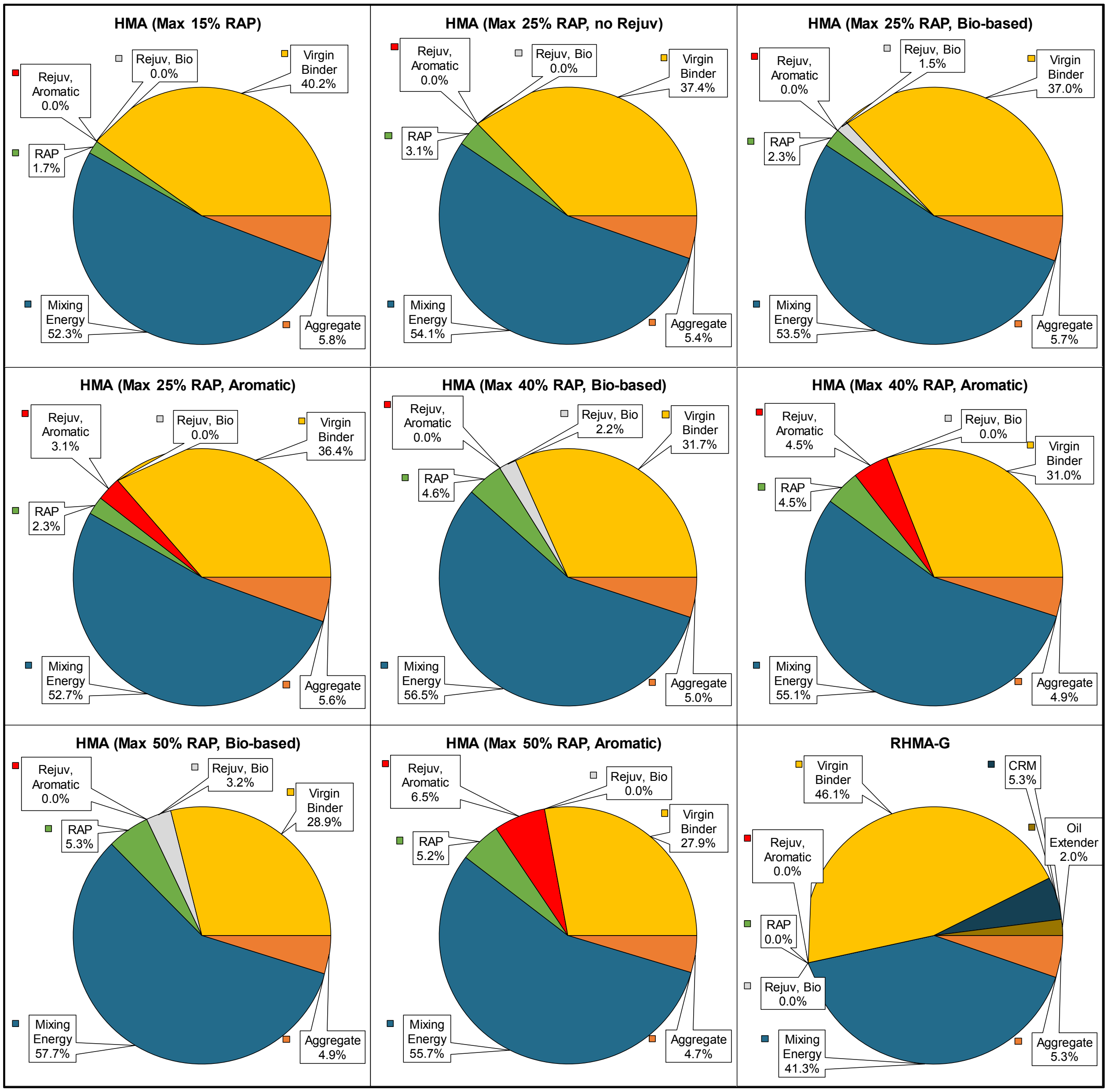


Figure 6.4. Breakdown of GWP between components across all mix designs considered in this study

Table 6.5. Data sources and data quality assessment

Item	Data Sources	Geography	Time	Technology	Complete-ness	Reproducibility	Representative-ness	Uncertainty
General								
HMA Usage per Year	*PaveM*	Excellent	Excellent	Excellent	Very Good	Y	Excellent	Low
LCA-Related								
Electricity	*GaBi/*	Good	Excellent	Excellent	Good	Y	Good	Low
Natural Gas (Combusted)	*GaBi*	Fair	Excellent	Good	Good	Y	Good	Low
Aggregate (Crushed)	*GaBi*/Lit.	Good	Good	Good	Good	Y	Good	Low
Bitumen	*GaBi*/Lit.	Good	Very Good	Good	Good	Y	Good	Low
Crumb Rubber Modifier	*GaBi*/Lit.	Good	Good	Good	Good	Y	Good	High
Extender Oil	*GaBi*	Fair	Good	Poor	Fair	N	Fair	High
RAP	*GaBi*/Lit	Fair	Excellent	Good	Good	Y	Good	Low
Rejuvenator Aromatic BTX	GaBi	Fair	Good	Good	Good	N	Good	High
Rejuvenator Bio-Based (Soy Oil)	GaBi	Fair	Good	Good	Good	N	Good	High
Wax	*GaBi*	Fair	Very Good	Good	Good	N	Good	Low
Cost-Related								
Material Costs	Caltrans	Excellent	Excellent	Excellent	Very Good	Y	Excellent	Low

6.7. Results and Discussion

6.7.1. GHG Emissions per Year

The total GHG emissions due to material production stage of HMA and RHMA mixes in Caltrans projects can be quantified by combining the amount of materials used each year and data in Table 6.3 (LCA results for unit mass of each mix.) Full results of the analysis are available in App-Table 27 of Appendix V.

The material production impacts of HMA in the entire analysis period of 33 years (2018 to 2050) results in close to 14.1 Million Metric Tonnes (MMT) of CO_2e for the baseline scenario. RHMA production impacts within the same time period is about 15.52 MMT CO_2e. RHMA is responsible for about 52 percent of the combined GHG emissions of HMA and RHMA and since use of RAP is currently not permitted in RHMA mixes, use of RAP in RHMA is a significant untapped area for cutting emissions if it becomes technically possible to obtain same performance and not reduce the amount of tire rubber recycled into pavement.

Increasing the RAP content from the original 11.5 percent (for the max 15 percent RAP baseline) by 8.5, 23.5, and 30.5 percent can result in 96, 729, and 870 thousand metric tonnes of CO_2e savings compared to the baseline, respectively, during the 33-year analysis period, when using aromatic BTX RAs. These reductions are equivalent to 0.7, 5.2, 6.2 percent reductions in GHG emissions compared to the baseline. These results are presented in Table 6.6 as well.

These numbers change to 326, 1,052, and 1,331 thousand metric tonnes of CO_2e when bio-based RA is utilized, which results in 2.3, 7.4, and 9.4 percent reductions compared to the baseline. For the case of RAP with maximum of 25 percent RAP, not using any RAs and choosing a softer virgin binder, can result in 470 thousand metric tonnes of CO_2e savings compared to the base case, or a 3.3 percent reduction.

Table 6.6. Total changes in GHG emissions compared to the baseline for the analysis period (2018 to 2050)

Metric	Total GHGs (Tonne CO2e)	CO2e Reductions (Tonne CO2e)	Percent Reduction in GHGs vs Baseline (%)
Max 15%, no Rejuv	14,125,517	0	0.00%
Max 25% RAP, BTX	14,029,843	-95,674	-0.70%
Max 25% RAP, Soy Oil	13,799,359	-326,158	-2.30%
Max 25% RAP, no Rejuvenator	13,655,723	-469,794	-3.30%
Max 40% RAP, BTX	13,396,501	-729,016	-5.20%
Max 40% RAP, Soy Oil	13,073,824	-1,051,693	-7.40%
Max 50% RAP, BTX	13,255,578	-869,939	-6.20%
Max 50% RAP, Soy Oil	12,794,611	-1,330,906	-9.40%

6.7.2. Cost Considerations

Table 6.7 shows cost per year for each of the treatment types included in this study, assuming that RA is used for all cases and the price of RA is the same as asphalt binder. The information in this table are taken from PaveM and the values are corrected as previously described in the Major Assumptions section.

Table 6.7. Annual tonnage of material, and costs

Year	HMA (Tonne)	RHMA (Tonne)	Cost (Billion $)	NPV (Billion $)
2018	2.11	1.91	0.55	0.55
2019	2.19	1.98	0.56	0.54
2020	2.24	2.03	0.58	0.53
2021	5.14	4.66	1.33	1.18
2022	8.69	7.87	2.24	1.92
2023	11.90	10.79	3.07	2.53
2024	11.43	10.36	2.95	2.33
2025	9.59	8.69	2.48	1.88
2026	9.10	8.25	2.35	1.72
2027	7.26	6.58	1.87	1.32
2028	12.32	11.17	3.18	2.15
2029	11.13	10.09	2.87	1.87
2030	8.13	7.37	2.10	1.31
2031	8.93	8.09	2.31	1.39
2032	8.76	7.94	2.26	1.31
2033	10.37	9.40	2.68	1.49
2034	12.07	10.94	3.12	1.66
2035	9.86	8.94	2.55	1.31
2036	8.11	7.35	2.09	1.03
2037	7.56	6.85	1.95	0.93
2038	8.76	7.94	2.26	1.03
2039	12.64	11.46	3.27	1.43
2040	8.66	7.85	2.24	0.94
2041	11.47	10.40	2.96	1.20
2042	5.99	5.43	1.55	0.60
2043	6.07	5.50	1.57	0.59
2044	10.49	9.51	2.71	0.98
2045	9.19	8.32	2.37	0.82
2046	8.23	7.46	2.13	0.71
2047	9.30	8.43	2.40	0.77
2048	9.40	8.52	2.43	0.75
2049	9.26	8.39	2.39	0.71
2050	9.16	8.30	2.37	0.67
Total	**285.51**	**258.76**	**73.75**	**40.16**

6.7.3. RAP Cost Savings

Using RAP will lower the amount of virgin aggregate and binder in the mix, which results in cost savings. Using the data extracted from Caltrans Construction Procedure Directive (CPD16-8), Attachment 7 (Caltrans 2016), the data shown in Table 6.8 were selected as the price of virgin aggregate and binder (per ton which was later converted into metric tonnes, 1 tonne = 1.10231 ton.)

Table 6.8. Cost ($/ton) of virgin binder and aggregate

Item	Material	Trucking	Subtotal	Markup 15%	Total
Aggregate	$7.0	$3.0	$10.0	$1.5	$11.5
Virgin Binder	$400.0	$18.0	$418.0	$62.7	$480.7

The cost of rejuvenator was assumed to be similar to the cost of the virgin binder, therefore, to calculate the cost savings due to increased use of RAP, the amount of virgin binder and virgin aggregate replaced only by RAP materials were calculated and multiplied by the estimates shown in Table 6.9, per instructions of CPD16-8. Table 6.9 shows the cost-saving results per tonne of HMA for each of the three scenarios of higher RAP content versus the baseline.

Table 6.9. Cost savings for each mix ($ per tonne of HMA)

Mix Title	Mix Design		Material Savings vs. Baseline HMA (percent)		Cost Savings vs. Baseline HMA ($/tonne of HMA)		
	RAP Content	Binder from RAP	Virgin Aggregate	Virgin Binder	Virgin Aggregate	Virgin Binder	Total Mix
HMA (Max 15% RAP)	11.5%	0.52%	0.0%	0.0%	$0.00	$0.00	$0.00
HMA (Max 25% RAP)	15.7%	0.71%	4.2%	0.2%	$0.53	$1.00	$1.53
HMA (Max 25% RAP)	20.9%	0.94%	9.4%	0.4%	$1.19	$2.24	$3.43
HMA (Max 40% RAP)	29.2%	1.32%	17.8%	0.8%	$2.25	$4.23	$6.48
HMA (Max 50% RAP)	33.4%	1.50%	21.9%	1.0%	$2.78	$5.23	$8.01

App-Table 26 in Appendix V shows the cost savings per year across the whole network alongside the GHG emission savings for each of the scenarios versus the baseline of HMA with up to 15 percent RAP. Using high percentage of RAP can result in 237 to 1,245-million-dollar savings (NPV) during the 33-year analysis period. These cost savings correspond to 95.6 thousand to 1.33 million metric tonnes of CO_2e reductions which equals 0.7 to 9.4 percent reduction compared to the baseline. Figure 6.5 shows the amount of savings in total GHG emissions between 2018 and 2050 compared to the baseline for HMAs with higher RAP content, and Figure 6.6 shows the percent change in emissions for each scenario versus the baseline.

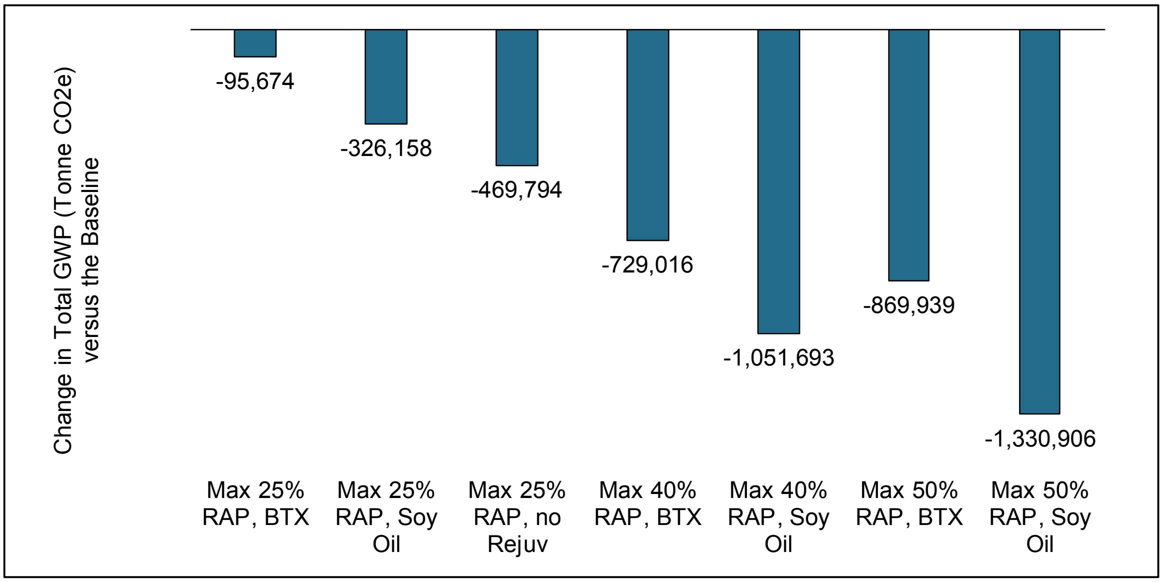


Figure 6.5: Change in total GHG emissions between 2018-2050 compared to the baseline for the three scenarios with higher RAP content.

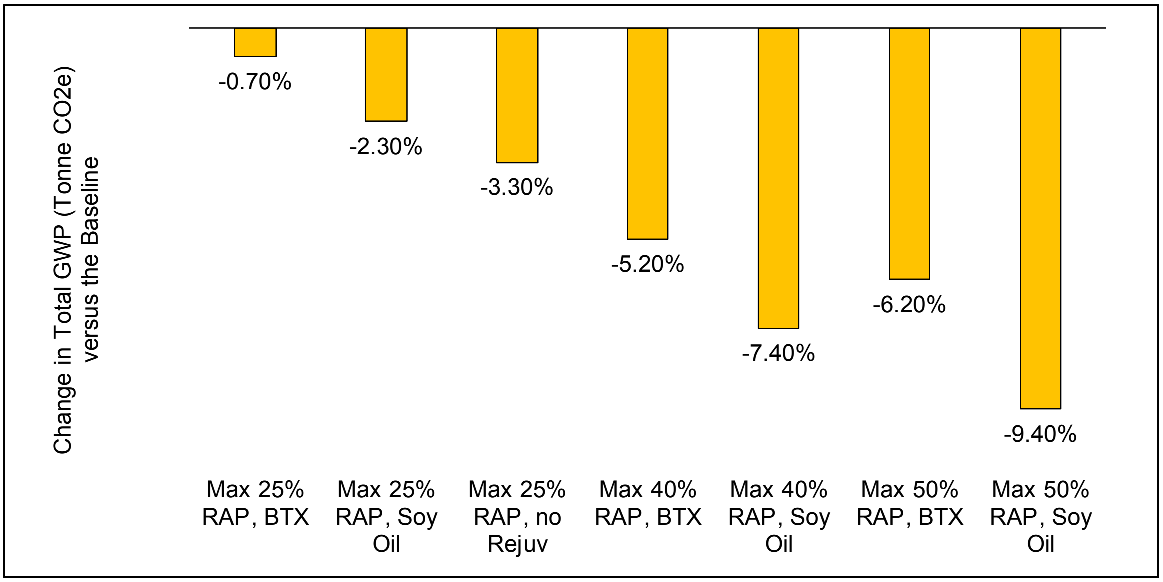


Figure 6.6: Percent change in GHG emissions compared to the baseline for mixes with higher RAP content.

6.7.4. Discussion

Increasing the amount of RAP in HMA mixes used by Caltrans in their projects can result in reductions in GHG emissions and cost savings. As shown in previous sections, RHMA production is also as significant as HMA production in terms of environmental impacts (annual RHMA impacts are about 67 percent of HMA impacts.) However, Caltrans currently does not allow RAP to be used in RHMA which signifies a major untapped area for further reducing the GHG emissions of material production in Caltrans projects.

There are concerns, however, regarding the performance of HMA with higher RAP content. This study was conducted assuming similar performance during the use stage across all the scenarios. Decreases in performance can result in more frequent maintenance and rehabilitation needs in the future. Higher surface roughness due to poor performance can cause in an increase in vehicle fuel consumption. These issues can result in not only offsetting the original savings due to use of higher RAP content, but also causing higher environmental impacts compared to the base scenario.

Therefore, further research is needed for investigating the performance of HMA with higher than 15 percent RAP content, and also RHMA with RAP. The research findings would allow design guidelines to be developed and unintended consequences, that can arise from good intentions, to be avoided.

The information regarding the abatement potential calculations presented in this chapter is summarized in Table 6.10 for the 33-year analysis period.

Table 6.10. Summary of abatement potential for increased RAP use in asphalt pavements in California

	CO$_2$e Change (MMT)			Average Annual over 33 Year Analysis Period	
Mix	**CO$_2$e Change (MMT)**	**Life Cycle Cost Change (\$ million)**	**Benefit / Cost (\$/tonne CO$_2$e reduced)**	**CO$_2$e Change (MMT)**	**Life Cycle Cost Change (\$ million)**
Max 25% RAP, BTX	-0.10	-237	-2,479	-0.003	-7.188
Max 25% RAP, Soy Oil	-0.33	-237	-727	-0.010	-7.188
Max 25% RAP, no Rejuv	-0.47	-534	-1,136	-0.014	-16.173
Max 40% RAP, BTX	-0.73	-1,008	-1,383	-0.022	-30.549
Max 40% RAP, Soy Oil	-1.05	-1,008	-959	-0.032	-30.549
Max 50% RAP, BTX	-0.87	-1,245	-1,431	-0.026	-37.737
Max 50% RAP, Soy Oil	-1.33	-1,245	-936	-0.040	-37.737

6.8. The Issue of Allocation in LCA of Recycled Materials

As discussed earlier in Chapter Two, the issue of allocation is present in many aspects of pavement LCA studies. ISO 14040 (2006) defines allocation as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems." Systems that produce co-products, by-products, or recycled materials are areas of concern for allocation. Allocation of recycled materials has been an area of discussion in all the three international symposiums on pavement LCA (Davis, CA 2010, Nantes, France 2012, and Davis, CA 2014) and three different approaches have been suggested (Harvey et al., 2010; Van Dam, 2015):

- Cut-off method: all impacts of using recycled materials go to the downstream project (pavement 2 is responsible for R1, all impacts of original production of material to be recycled assigned to pavement 1 with no reductions for reductions in use of virgin material in pavement 2)
- 50/50 method: half the impacts to the second pavement and half to the first pavement
- Substitution method: The first pavement is given the full benefits (the impacts that are avoided by substituting virgin materials in pavement 2)

Asphalt pavements can be recycled at the end of their service life as RAP and can be used in a new construction as part of a closed loop system. With the increased popularity of using RAP in flexible pavements, the issue of allocation has become more important. This section is aimed at providing a better understanding of the impact of the allocation methodology used in LCA of HMA with RAP in different contexts.

To address the goal of this study a comparison was made of the LCI of RAP and HMA under two allocation methodologies while assuming a factorial of cases for the major input parameters. The system boundary is cradle-to-laid (material production, transportation, and construction.) To achieve the goal, a factorial of possible values for main input parameters affecting RAP and HMA LCI is assumed and the LCI results are compared under the two allocation methodologies to better understand the impact of allocation method in different contexts (combination of input parameters.)

A functional unit of 1 ln-km was selected for this comparison with a lane width of 3.7 m, a milling depth of 6 in., and specific gravity of 2.6 for RAP materials. Two allocation methods were considered as follows:

- Cut-off: Milling and hauling impacts are assigned only to RAP and the upstream project is responsible for all the impacts of virgin material production. No part of the reduction in environmental impacts are allocated to the upstream project for the material recycling at the pavement EOL.
- 50/50: The total impacts of virgin material production, milling at the EOL, and hauling to the plant are summed up and divided 50/50 between the upstream and downstream projects. Only the portion of binder that is recovered is included though and the virgin aggregate that will be replaced (downstream project does not take 50 percent of the impacts for the unrecovered binder in the original material.)

The following were the major input parameters considered in the factorial of cases defined under this study:

- Mix Design Binder Content
- Average RAP Binder Content
- RAP Binder Recovery
- Binder Replaced by RAP/Rejuvenator (two types: Aromatic and Bio-based)
- RAP Hauling Distance

Table 6.11. Factorial of cases considered for the main input parameters in evaluating the impact of allocation methodology on RAP LCI

Input Parameter	Value
Mix Design Binder Content	4.5% 5.0% 5.5% 6.0%
Binder Replaced by RAP (Rejuvenator)	11% (0%) 15% (5%) 20% (0%) 28% (7%) 32% (10%)
Average RAP Binder Content	4.0% 4.5% 5.0% 5.5%
RAP Binder Recovery	50% 60% 75% 90%
Hauling Distance (mi)	0 25 50 100

A total of 2,048 cases were run using the factorial of input parameters defined in this section. Details of LCA modeling of the milling process, virgin material production, and RAP and HMA LCA modeling are provided earlier in Chapter Three of this document. In this section only changes in the LCI of HMA due to changes in 5 main input parameters and the allocation methodology used are investigated. Table 6.12 shows selected LCI and LCIA items for the background items needed to conduct this analysis.

Table 6.12. LCI of background items used

LCI of Background Items	Functional Unit	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Ren) [MJ]	Feedstock Energy [MJ]
Heavy Truck (24 Tonne)	1000 kg-km	7.8E-2	1.2E-2	2.5E-5	1.1E+0	1.1E+0	0.0E+0
Diesel Burned	1 gallon	1.2E+1	5.3E+0	9.4E-3	1.6E+2	1.6E+2	0.0E+0
Aggregate - Crushed	1 kg	3.4E-3	6.5E-4	1.6E-6	6.0E-2	5.2E-2	0.0E+0
Bitumen	1 kg	4.8E-1	8.1E-2	4.1E-4	5.0E+1	4.9E+1	4.0E+1
Rejuvenator, Bio	1 kg	3.0E-1	2.6E-2	1.7E-4	3.5E+0	3.5E+0	0.0E+0
Rejuvenator, Aromatic	1 kg	6.4E-1	1.6E-4	3.2E-2	4.8E+1	4.8E+1	2.2E-1
Milling of RAP	1 ln-km	1.3E+3	5.8E+2	1.0E+0	1.8E+4	1.8E+4	0.0E+0
Transportation of RAP (after milling to plant)	1 ln-km of RAP hauled 50 miles	9.2E+3	1.5E+3	2.9E+0	1.3E+5	1.3E+5	0.0E+0
Milling of RAP	1 kg	8.9E-4	3.9E-4	7.0E-7	1.2E-2	1.2E-2	0.0E+0
Transportation of RAP (after milling to plant)	1kg for 50 mi	6.3E-3	1.0E-3	2.0E-6	9.0E-2	9.0E-2	0.0E+0

For the HMA, it was assumed that the mix design only includes virgin binder, virgin aggregate, RAP, and rejuvenator.

The GWP results in this section are presented for 1 kg of HMA with different RAP contents, with the goal of understanding the impact of the allocation methodology on the GWP and also the sensitivity of the GWP to the major input parameters identified earlier under each allocation method. The results are presented as boxplots plotted side by side of the ratio of GWP for HMA with RAP versus HMA with no RAP for each allocation methodology. This was done to compare the results between allocation methodologies and to also provide an understanding of how the GWP of HMA changes with changes in major input variables such as RAP content, RAP binder content and so forth.

Figure 6.7 shows the GWP ratio of 1 kg of HMA using RAP over using only virgin materials. Each set of graphs has two series of boxplots, blue ones for data using the cut-off method for calculating the impacts of HMA with RAP, and yellow ones for data calculated using the 50-50 method.

GWP of HMA with RAP using cut-off method is consistently lower compared to GWP HMA with RAP using the 50-50 method. The trend observed in all the boxplots is consistent between the cut-off and the 50-50 except for two graphs: the one plotted against mix binder content, and the one plotted against binder replaced by rejuvenators. The first graph shows similar boxplot for cut-off method regardless of mix binder content, which is expected as binder content does not play a role in calculating HMA LCI using the cut-off method. The other graph shows no trend in boxplots of the 50-50 method; this is because the impacts of virgin binder and rejuvenator are not much different, resulting in similar GWP for HMA using the 50-50 method.

Increased RAP hauling distances results in increased GWP of HMA under both allocation methods compared to HMA with virgin materials, with a more dramatic increase when the cut-off method is used. For hauling distances above 50 miles, there are cases where GWP of 1 kg of HMA with RAP will be higher than HMA with virgin materials, depending on the values of other input parameters. Thirty-six cases with the cut-off method resulted in higher GWP for HMA with RAP versus HMA with virgin materials (GWP ratio of higher than one.) The cases where the use of virgin materials results in less GWP compared to the use of RAP for the cut-off method all have hauling distance of 100 miles with RAP binder recovery of 50 or 60 percent. The number of these cases for the 50-50 method is 361 and for them, the following combinations of RAP binder recovery ratios and hauling distance are observed: 75% + 100, 60% + 100, 50% + 100, 50% + 50, 50% + 25.

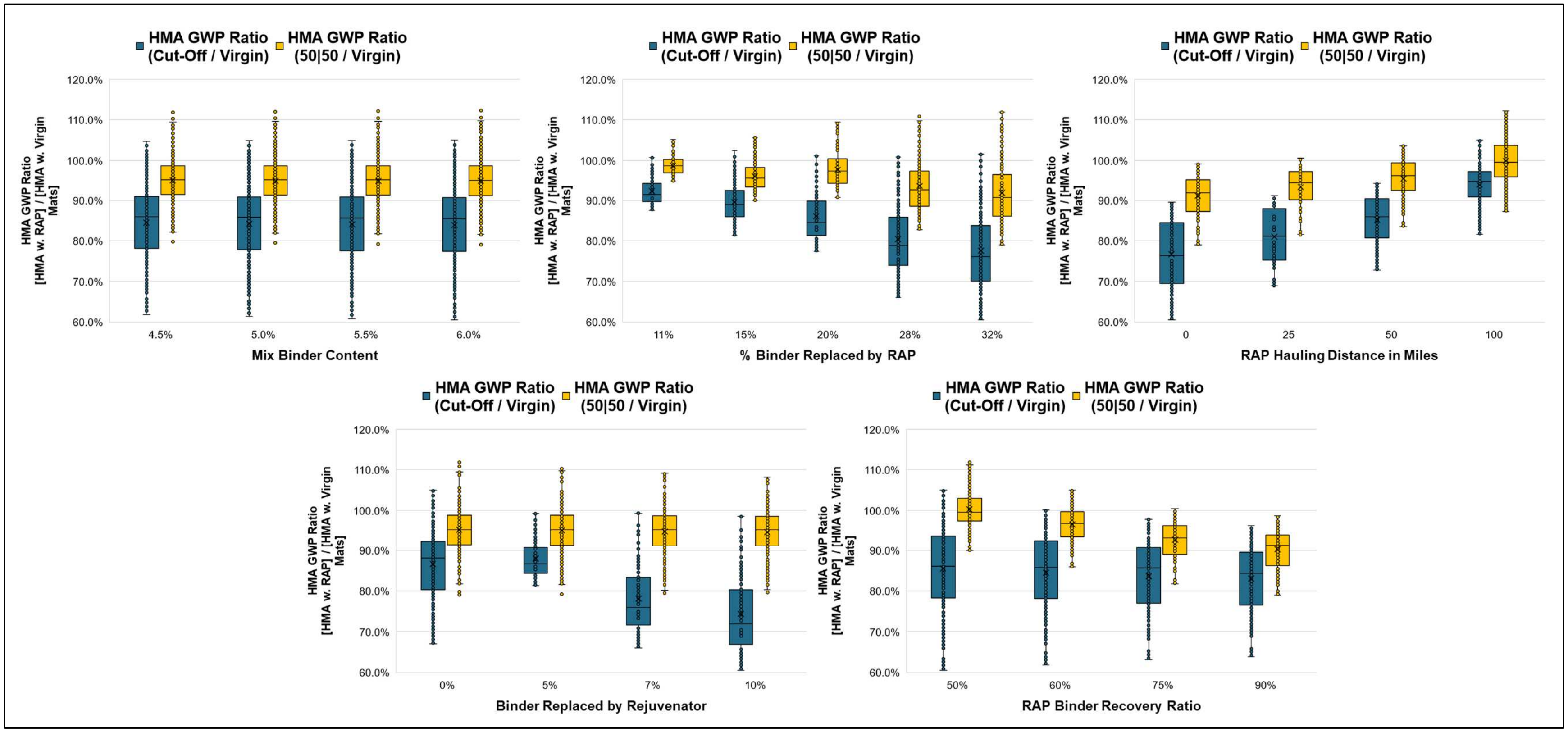


Figure 6.7: Ratio of GWP of 1 kg of HMA (using RAP over using virgin materials, under two allocation methods.)

CHAPTER 7. Cradle-to-Laid LCA Benchmarking and Comparison of Currently Available Alternatives for End of Life Treatment for Flexible Pavements in California

7.1. Introduction

Sustainability is an integral part of the Caltrans mission statement: “Provide a safe, sustainable, integrated, and efficient transportation system to enhance California’s economy and livability” which has resulted in Caltrans pursuing innovative materials and construction processes in their projects for many years. As pavements reach their end-of-life (EOL), there are multiple options available and recycling has become increasingly popular due to the general perception of recycling as a more sustainable alternative than other alternatives. This has also been driven by cost considerations for virgin versus reclaimed asphalt binder, and virgin versus recycled aggregate. Virgin aggregate has become scarcer in California near locations of greatest use which is another contributing factor to the recent trends observed. It is widely believed that recycling will always lead to significant environmental benefits, to the point that many pavement engineers exclusively associate the term sustainability for pavements with recycling. Objective quantification of the environmental impacts of recycling alternatives throughout their full life cycle is needed to have a better understanding of the performance of different alternatives in terms of sustainability.

This chapter utilizes LCA methodology for benchmarking and comparison of the environmental impacts of the current methods in practice for in-place recycling (IPR) or reclamation of flexible pavements at their EOL. The methods considered in this study for in-place recycling are cold in-place (CIR) and full depth reclamation (FDR) with different stabilizers and wearing courses on top of the recycled or reclaimed layer, and the primary current practices of asphalt overlay and mill-and-fill (remove part of the asphalt and then overlay.)

In this chapter background information on in-place recycling methods for flexible pavements is presented followed by the framework for conducting the “cradle-to-laid” LCA for each treatment. The framework is described in detail including goal and scope definition, life cycle inventory development, impact assessment methodology to use, followed by interpretation. The chapter is concluded with a summary of findings and recommendations for the next stage of this study, which is development of performance models that are needed for a full life cycle LCA comparison of alterative EOL options. Such an approach is needed for unbiased, quantified, and objective decision-making which helps transportation planners avoid unintended consequences and situations in which reducing emissions in construction stage results in such extra impacts during other life cycle stages that the net result is worse than conventional options.

The main objectives of this chapter and the next are to:

- Develop models to quantify the environmental impacts of EOL alternatives for flexible pavements, using the practice in California as the case study.
- Develop performance prediction models for sections built using in-place recycling techniques to understand how their roughness and structural deterioration progress with time. These predictive models for roughness and cracking are needed in the use stage to estimate fuel consumption in vehicles and frequency of maintenance and rehabilitation based on cracking performance.

To achieve the project objectives, the following questions are addressed in this chapter:

- What are the environmental impacts of the EOL strategies for flexible pavements in California considering only the material production, construction and EOL stages and without considering the use stage performance?
- How much does each life cycle stage contribute to the total impacts (without considering the use stage)?
- How do current alternative EOL strategies for flexible pavements in California compare with each other, in terms of cradle-to-laid impacts?
- How much does haul distance of materials contribute to the differences observed? What is the transport distance for new materials (for FDR, CIR, and overlays) at which the different environmental impacts are the same?

The following chapter on performance prediction models will address the following questions:

- How do sections built using IPR perform in the field? How quickly do cracks appear on the surface? How does surface roughness vary with time under traffic?
- How do sections built using IPR and conventional strategies compare in terms field performance during the use stage? Is the difference significant enough to warrant more frequent maintenance and rehabilitation, resulting in more environmental impacts and costs?

7.2. Overview of In-Place Recycling of Flexible pavements

There are three different options available at the end of a flexible pavement’s service life, which can be applied to either the entire pavement structure above the subgrade or layers within the structure:

- Removal of materials and disposal in landfills,
- Continued use (referred to here as reuse) in place as an underlying layer in its state at the end of life of the pavement, or
- Pavement material recycling or reclamation either in place or at a recycling plant.

Recycling pavement materials (sometimes referred to as reclaiming depending on the technology), either in place or at a plant from other projects and either full- or partial-depth, will displace use of virgin aggregates and binders (particularly asphalt but others such as residual hydraulic cement as well) and therefore eliminate the impacts of producing virgin materials. However, there are still emissions and energy consumption related to demolition, processing, stabilization, and transportation of the recycled materials to an offsite processing plant or transportation of stabilizing and additional virgin materials when recycling on site.

7.3. In-Place Recycling Technologies for Flexible Pavements

All in-place recycling technologies require that any drainage problems be addressed for the treatment to be successful.

CIR is an in-place rehabilitation technique that is typically used when there is surface cracking, particularly top-down cracking that has not proceeded all the way through the asphalt layers, and oxidation. It is not used for heavily cracked pavement, pavement with deep moisture damage, or where the extensive cracks extend through all asphalt layers. The CIR process includes milling the surface of the pavement, mixing the recycled material with asphalt emulsion and often a small amount of cement, compacting it, and placing an asphalt overlay or a chip seal as a wearing surface. The depth of asphalt pavement recycled with CIR is typically not less than 50 mm (2 in) or more than 100 mm (4 in) and there must be additional existing asphalt pavement below this depth to support the milling machine, making CIR a partial-depth recycling process.

FDR is an in-place rehabilitation technique in which all the HMA layer and at least 0.17 ft (50 mm, 2 in) of the base/sub-base materials are pulverized and an asphalt overlay, or a chip seal is placed as a wearing surface. FDR is used where there is extensive cracking of the HMA, and the cracks extend through all the HMA layer. It is also used where there is extensive delamination of the HMA layers and where there is extensive moisture damage in the HMA. The pulverized materials are mixed with or without stabilizing agents and are graded, placed, and compacted back in place providing an improved base layer before placing the wearing HMA overlay or a surface treatment.

In some states, the term CIR includes all cold in-place recycling, including both partial-depth and full-depth. In other states, such as California, the term CIR only refers to partial cold in-place recycling and the term CIR is not applied to any FDR processes. In the remainder of this chapter, the term CIR is used to refer to partial-depth recycling that is done in-place and leave some existing asphalt. FDR is used to refer to full-depth reclamation.

The benefits of in-place recycling, according to a study conducted by NCHRP in 2011, are as follows (Stroup-Gardiner, 2011):

- Reduction in use of natural resources
- Elimination of materials generated for disposal or landfilling
- Reduction in fuel consumption primarily due to reduction in transportation of new materials
- Reduction in greenhouse gas
- Reduction in lane closure times
- Safety improvement by increasing friction, widening lanes, and eliminating overlay edge drop-off
- Reduction in costs of preservation, maintenance, and rehabilitation
- Improving base support with minimum overlay thickness

This section provides a review of the construction process and the materials used in each of the in-place recycling techniques which serves as the basis of modeling the construction process in the next chapter for estimating the environmental impacts.

7.3.1. Construction Processes and Materials for Cold In-Place Recycling

Figure 7.1 shows the construction process and the equipment used for a typical CIR project. The Asphalt Recycling and Reclaiming Association (ARRA) recommends that the equipment used for CIR should be capable of the following (ARRA, 2014):

- Milling of the existing roadway
- Sizing the resulting RAP
- Mixing the RAP with the stabilizer designated in the mix design, which are typically portland cement and asphalt emulsion or foamed asphalt

- Meeting the required gradation and sizing with either the milling process or with additional sizing equipment
- Producing a homogenous and uniformly coated mixture by mixing RAP and additives in the milling machine or in an additional mixing chamber
- Placement and compaction according to the specifications

These requirements can be achieved through a set of equipment consisting of (not all the equipment may be needed for every project):

- Pavement cold planer (milling machine) with a minimum 3.75 m (12.5 ft) cutter and a means for controlling the depth of milling and the cross-slope or pulverization machine
- Crushing and sizing equipment
- Mixing and proportioning equipment
- Cement and asphalt emulsion or foamed asphalt storage and supply equipment
- Mixing and spreading equipment for dry cement
- Mixing and spreading equipment for corrective aggregate
- Paving equipment
- Water truck
- Broom truck
- Compaction equipment
- Fog sealing and sand spreading equipment

The construction process starts with roadway preparation in which the contractor should identify the location of all utilities within the project site, clean and remove any dirt or obstacle, reference the profile and cross slope, cold mill along cross walks and gutters to prepare for the final overlay, and correct all areas known to have soft or yielding subgrades.

CIR construction is recommended to be allowed to proceed only when the RAP temperature is above 50°F (10°C) and the previous overnight temperature was above 35°F (2°C.) A control strip with a minimum length of 1000 ft (300 m) should be constructed on the first day of the project to show that the construction process meets the specifications. The optimal rates of stabilizer and the rolling pattern to achieve the optimum field density should be identified from the control strip.

The existing pavement should be milled to the depth required by the plan or the specifications and the recycled materials should be crushed and sized to the maximum particle size specified (ARRA, 2014.) The incorporation of recycling additive or stabilizing agent can be in the form of applying mechanical, chemical, or bituminous stabilizer or a combination of all. Mineral stabilization is defined as the addition of imported granular materials to reach the desired characteristics in terms of gradation. Mechanical stabilization consists of compaction to desired density, which improves stiffness, strength, rutting and fatigue properties, and decreases water permeability. Chemical stabilization is achieved by adding one or a combination of portland cement, fly ash, calcium chloride, magnesium chloride, and lime, with portland cement being the most commonly used chemical stabilizer. These materials only stabilize if they create pozzolonic cementing action. Bituminous stabilization consists of adding asphalt emulsion or foamed asphalt. Common practice in many states for partial-depth recycling is to use a combination of bituminous stabilization with emulsions or more recently using foamed asphalt and chemical stabilization. Mechanical stabilization in the form of compaction is used for all treatments, and addition of imported granular materials is used if the existing in-place materials do not provide a satisfactory gradation (Van Dam et al., 2015.) Cement or lime slurry may be directly added to the mixing chamber or sprayer over the cutting teeth of the milling machine. If dry cement or corrective aggregate is needed, it can be spread on the existing surface ahead of the milling operation (ARRA, 2014.) The CIR milling and mixing process can be accomplished with a single-unit machine or a multi-unit train.

The placement of the recycled materials is conducted either with conventional asphalt pavers or cold mix pavers, followed by compaction. The time between material placement and start of compaction is determined by the contractor. Compaction (initial/breakdown, intermediate, and final compaction) is one of the main factors affecting the future performance of the section. The type and number of compactors depend on many factors such as the degree of compaction required, material properties of the pulverized mix, support capabilities of the underlying layers, and the needed productivity. In general, the characteristics of the recycled mix determine the type of roller needed and the thickness of the layer, and the required compaction dictates the weight, amplitude, and frequency of the compactors. In any case, the contractor is responsible for determining the compaction plan that meets the specified densities. The compaction should be monitored using nuclear density testing in accordance with ASTM D2950, or the owner agency approved method (ARRA, 2014.)

For materials stabilized by chemical and bituminous materials, curing is a critical step and is needed to assure that adequate strengths have been achieved for opening to traffic, prevent raveling, and facilitate placement of the final wearing course. The curing rate depends on multiple factors, particularly if traditional asphalt emulsions are used because the water that makes up 40 to 60 percent of the emulsion must be evaporated. The factors affecting curing include the nature of the stabilization, temperature, humidity, moisture content of the mix, compaction level, and drainage characteristics of the section and it is best to keep the traffic off the pavement until sufficient curing has occurred to achieve adequate opening strengths.

For stabilization with traditional asphalt emulsions the curing period depends on the type and quality of the agent, moisture content of the pulverized mix, mix level of compaction, aggregate characteristics, stabilizer (cement or lime), and ambient conditions. The addition of cement along with asphalt emulsion helps provide faster strength for earlier paving of the overlay and opening to traffic. ARRA (2014) states that for CIR a curing period of at least 3 days and the moisture content of less than 3 percent should be required before proceeding to secondary compaction or opening to traffic. ARRA recommends secondary compaction if the recycling agent is emulsified asphalt with no chemical stabilizers added. If secondary compaction is planned, a separate rolling pattern should be established during the control strip and the density of the recycled materials after secondary compaction should be checked to verify compliance. ARRA suggests that secondary compaction be done with pneumatic and double drum vibratory at temperatures above 80 °F (27 °C.) As materials are better understood and contractors gain more experience, practice for local governments in many locations with light vehicles moving at slow speeds is often to open within hours of construction, and to follow with re-compaction and overlay several days later.

In the final step, a wearing course is usually laid on top. For low traffic roads, a single or double chip seal might be enough but in sections with higher traffic levels, an HMA overlay is needed. The overlay thickness is dependent on the specifics of the project, the agency's policies, anticipated traffic, climate, economics, stabilizing agent, and structural requirements. For HMA or Warm Mix Asphalt (WMA) overlays, ARRA recommends applying a tack coat of either CSS-1h or SS-1h emulsified asphalt at the minimum rate of 0.05 gal/yd2 before applying the wearing course.

7.3.2. Construction Processes and Materials for Full Depth Reclamation

The FDR construction process is like CIR, with the main difference being that the whole thickness of the existing HMA layer and a predetermined thickness of the underlying layer are pulverized and mixed together, which requires different equipment than what is used for CIR, as shown in Figure 7.2. The FDR pulverization equipment uses larger teeth than is used by the CIR milling equipment, and the FDR equipment can operate on granular materials while CIR milling machines need sufficient HMA material below them to support their weight. FDR can recycle pavement depths up to 12 in. (300 mm) (Van Dam et al., 2015.)

The FDR process can vary between projects depending on the project specifics, owner/agency needs, and the requirements of the section after recycling. Common practice for many agencies is to use a combination of foamed asphalt and chemical stabilization (typically cement) or only chemical stabilization or only asphalt emulsion stabilization with FDR.

The UCPRC has been conducting extensive research on in-place recycling since 2000. These projects were mainly focused on comparing various design and construction methods, both in the lab and on the field using heavy vehicle simulator (HVS) with the objective of developing best practice methods for the state of California.

In a comprehensive study on FDR with foamed asphalt for Caltrans (Jones et al., 2009), results of extensive literature survey and a mechanistic sensitivity analysis was used to formulate a work plan for laboratory and field studies to understand and to address issues specific to recycling thick asphalt pavements. The results showed that FDR with foamed asphalt combined with a cementitious filler should be considered as a rehabilitation option on thick, cracked asphalt pavements on highways with an annual average daily traffic volume not exceeding 20,000 vehicles. The technology is particularly suited to pavements where multiple overlays have been placed over relatively weak supporting layers, and where cracks reflect through the overlay in a relatively short time. However, the report emphasized that project selection, mix design, and construction should be strictly controlled to ensure that optimal performance is obtained from the rehabilitated roadway.

Later UCPRC published comprehensive guidelines for project selection, design, and construction of sections with FDR and a combination of foamed asphalt and an active filler, typically portland cement or lime. The main topics covered in the guideline are project selection, mix design, structural design, construction design, and construction (Jones et al., 2009.)

The research on FDR at UCPRC continued with a study comparing the performance of four different full-depth pavement reclamation strategies, namely pulverization with no stabilization (FDR-NS), stabilization with foamed asphalt and portland cement (FDR-FA), stabilization with portland cement only (FDR-PC), and stabilization with engineered asphalt emulsion (FDR-EE.) The first stage of this study was finished in 2014 focusing on literature review, the test track layout and design, stabilization and asphalt concrete mix designs, test track construction, and collection and analysis of results of HVS and laboratory testing (Jones et al., 2014.) The second stage of the study included accelerated pavement testing, full-scale field testing, and additional laboratory testing. The results showed that FDR-FA and FDR-PC sections performed very well under both dry and wet conditions. The FDR-NS sections tested performed acceptably. Due to problems associated with construction, no conclusions could be drawn from the test results. Figure 7.3 shows the construction methodology that was used in this study (Jones et al., 2016.)

7.4. Life Cycle Assessment Framework

This section summarizes the framework used for conducting LCA for each of the cases. First, the goal and scope of the study is described and then the modeling effort for developing the life cycle inventory database is explained in detail for each of the three life cycle stages. The models developed under this study and other LCA efforts at UCPRC have undergone a 3rd party critical review according to the requirements of ISO 14040 (2006.) The summary results for the LCI and LCIA for each stage are presented at the end of each section. The final phase of LCA, the interpretation, is presented in the next chapter.

7.4.1. Goal and Scope Definition

The goal of this LCA study is to quantify the environmental impacts of the current EOL treatments in use for flexible pavements through a benchmark study. The intended application is to provide an estimate of how different alternatives perform in terms of the environmental impacts during material production, transportation, construction, and the EOL of each section. As this range does not cover the full life cycle of the alternatives, comparison between the LCA of treatments shall not be used as a basis for selecting between alternatives, because without the performance models the number of maintenance and rehabilitation treatments needed for each alternative during the use stage cannot be determined. For this stage of the study, attributional LCA was conducted on a matrix of possible treatments for EOL of flexible pavements to identify the hot spots within the cradle-to-laid period of each alternative. Table 7.1 shows the EOL treatments considered in this study.

Table 7.1. The EOL treatments considered in this study

Case #	Description
Case 1	CIR (10 cm (0.33 ft) Milled + 1.5% FA + 1% PC) w. Chip Seal
Case 2	CIR (10 cm (0.33 ft) Milled + 3% FA + 2% PC) w. 2.5 cm (0.08 ft) of HMA OL
Case 3	FDR (25 cm (0.82 ft) Milled + Mech. Stab.) w. 6 cm (0.2 ft) RHMA OL
Case 4	FDR (25 cm (0.82 ft) Milled + 4% AE + 1% PC) w. 6 cm (0.2 ft) RHMA OL
Case 5	FDR (25 cm (0.82 ft) Milled + 3% FA + 1% PC) w. 6 cm (0.2 ft) RHMA OL
Case 6	FDR (25 cm (0.82 ft) Milled + 2% PC) w. 6 cm (0.2 ft) RHMA OL
Case 7	FDR (25 cm (0.82 ft) Milled + 4% PC) w. 6 cm (0.2 ft) RHMA OL
Case 8	FDR (25 cm (0.82 ft) Milled + 6% PC) w. 6 cm (0.2 ft) RHMA OL
Case 9	HMA Overlay (7.5cm (0.25 ft))
Case 10	HMA Mill & Fill (10 cm (0.33 ft))

AE: asphalt emulsion
FA: foamed asphalt
OL: overlay
PC: portland cement
RHMA: rubberized hot mix asphalt
Stab.: stabilization

The location of use is limited to the state of California and the functional unit of the study is one ln-km of pavement. The physical boundary only includes the main lanes and not the shoulders. As the system boundary only includes material production and the construction stage, the analysis period is selected to be one year.

For the functional unit of one ln-km, the LCI of each of the rehabilitation techniques includes the following life cycle stages without considering the M&R activities during the use stage:

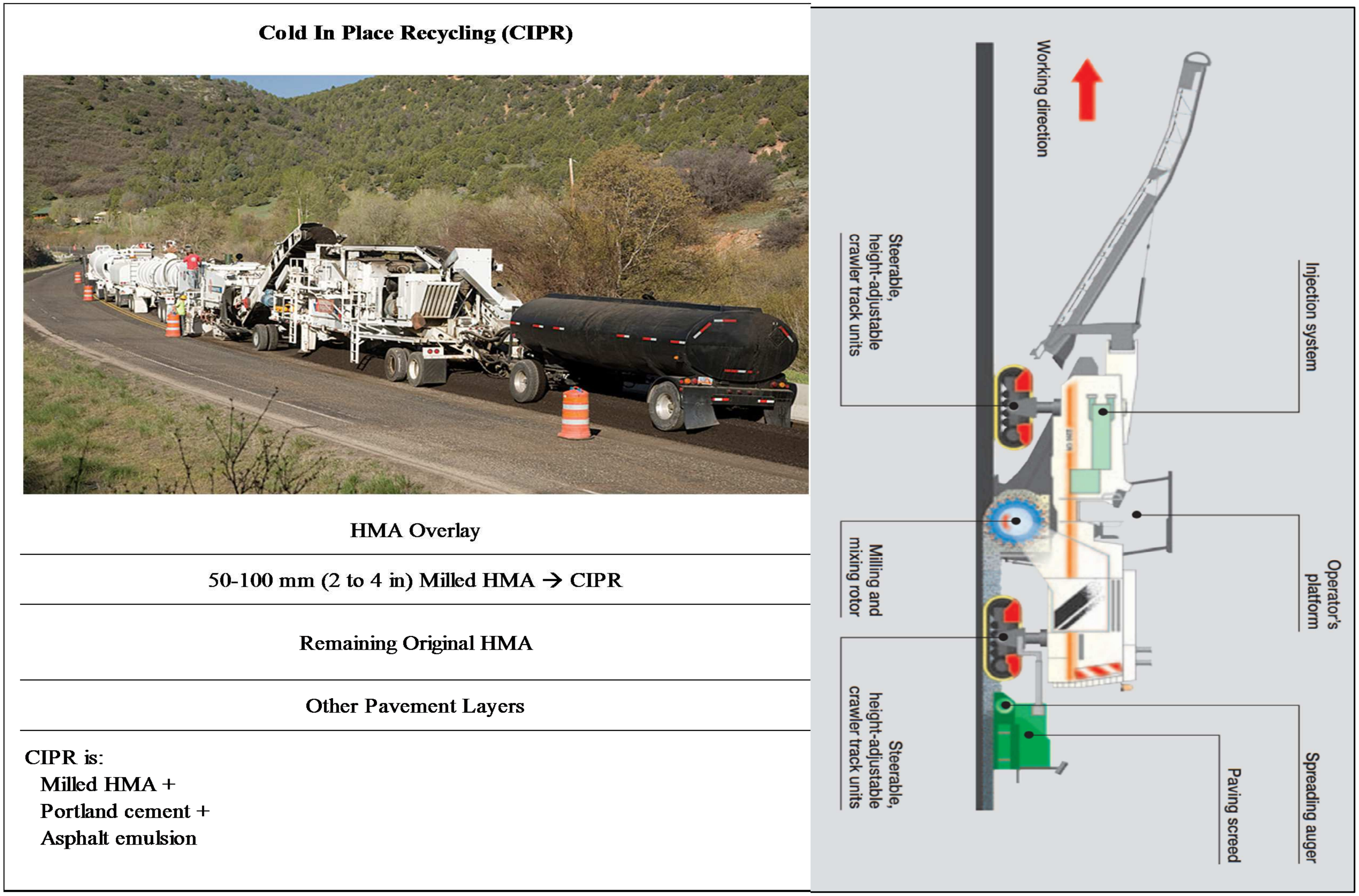
- Material production
- Transportation of the materials to the site
- Construction activities
- EOL milling and hauling to recycling plants or landfills

The material production stage inventories are cradle-to-gate for all the materials used in the construction. This means that the LCI includes the energy consumption and emissions of all the processes: raw material acquisition from the ground, transportation to the plant, and further processing of the raw materials in the plant until they are ready to be shipped at the gate. The models represent the conditions, technologies, and practices used in local plants and construction processes in California, but which are generally applicable to much of the world. For each of the construction materials, models were developed in GaBi, an LCA software, and energy sources in the model were calibrated to represent the local conditions in terms of electricity grid mix and fuel type used in plant.

This study follows US EPA's TRACI 2.1 methodology (Bare, 2012) for impact assessment. Main areas of concern are primary energy demand (PED) separated into PED used as an energy source and PED for materials not used as an energy source, global warming potential (GWP), and air quality. Air quality is assessed using two impact categories: Photochemical Ozone Creation Potential (POCP) which measures smog formation, and Particulate Matters smaller than 2.5 micrometers (PM 2.5.) Table 7.2 shows the LCI and LCIA items that are reported in this study. Primary energy is reported as three numbers: total PED, PED non-renewable, and non-fuel PED (or feedstock energy: the amount of energy left in the material and is not consumed when converting to useable energy.)

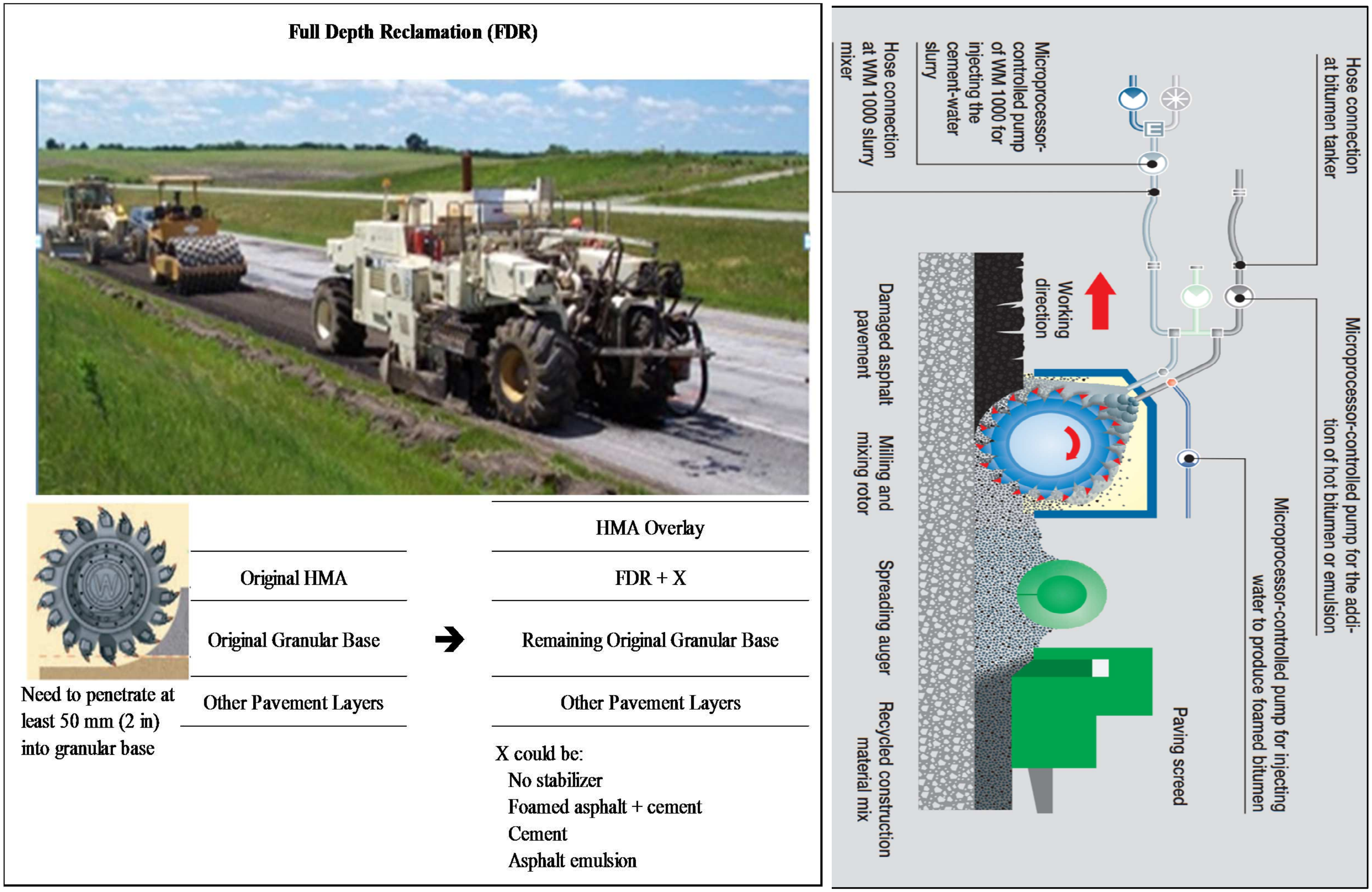
Table 7.2. Impact categories and inventories reported in this study

Impact Category/Inventory	Abbreviation	Unit
Global Warming Potential	GWP	kg of CO_2-e
Photochemical Ozone Creation (Smog) Potential	POCP	kg of O3-e
Particulate Matter less than 2.5 µm	PM2.5	Kg
Total Primary Energy Demand from renewable & non-renewable resources, (net calorific value)	PED (Total)	MJ
Primary Energy Demand from fuels and energy sources (net calorific value)	PED (Fuel)	MJ
Primary Energy Demand from materials that are not used as source of energy but do contain feedstock energy, non-fuel (net calorific value)	PED (Non-Fuel)	MJ



(a) *(b)*

Figure 7.1: CIR process: (a) construction (Van Dam et al., 2015); (b) CIR equipment (Wirtgen, 2012)



(a) (b)

Figure 7.2: FDR process: (a) construction (Van Dam et al., 2015); (b) FDR equipment (Wirtgen, 2012.)

(1) (2) (3) (4) (5) (6)

Figure 7.3: FDR+FA construction process in the field (Jones et al., 2016.)
The process consists of: (1) Spreading cement on old asphalt surface; (2) Recycling train; (3) Uniform mix behind; (4) Padfoot roller compaction on uniform mix; (5) Steel wheel compaction showing tightly bound surface; (6) Final compaction.

7.4.2. Life Cycle Inventory and Impact Assessment

In this section, the modeling process for developing the LCI and LCIA is presented. The modeling was conducted in GaBi software and the electricity grid mix and plant fuels for the material production stage were calibrated to represent the California grid mix and regulations for plant fuels. The results of the LCI were then converted to impact indicators using the US EPA impact assessment methodology, TRACI 2.1. (Saboori et al., 2020.)

7.4.3. Mix Designs for CIR and FDR Alternatives

As shown earlier in Table 7.2, this study is comparing 10 different alternatives for EOL of flexible pavements. Eight in-place approaches (2 CIR and 6 FDR) and 2 conventional methods (mill-and-fill, overlay.)
For the CIR cases, it was assumed that only milling is conducted (10 cm [0.33 ft]) of milling) without any stabilizers or additives. The CIR sections are topped with a wearing course that could be a chip seal or a 2.5 cm (0.08 ft) asphalt overlay. The mix designs of the wearing courses will be discussed shortly in this section.

For the FDR sections, the thicknesses were the same across all 6 cases; 25 cm (0.82 ft) of pulverization with stabilizers and then a 6 cm (0.2 ft) of rubberized asphalt on top. The type and amount stabilizers were the variables across all the FDR cases, starting with no stabilizer (mechanical stabilization) to various amount and combinations of asphalt emulsion and portland cement.

For the conventional methods, two cases were considered. One case was doing a 10 cm (0.33 ft) mill-and-fill and the other was a 7.5 cm (0.25 ft) HMA overlay.

There are three different wearing courses in the matrix of possible EOL treatments explained above, chip seal, hot mix asphalt, and rubberized hot mix asphalt. The rest of this section explains the mix design that was used to develop LCI for each of the wearing courses. The summary table at the end of this section only presents the impacts of material production for each of the wearing courses and does not include transportation and construction stages as these will be added later.

7.4.3.1. Chip Seal

It was assumed that the chip seal is constructed with 0.4 gal/sy (1.81 liter/m^2) of asphalt emulsion and 0.35 lb/sy (0.19 kg/m^2) of aggregate. The construction process consists of sweeping, application of binder, aggregate application, rolling with pneumatic and a final round of sweeping. Aggregate are assumed to be angular and crushed for better interlock.

7.4.3.2. Hot Mix Asphalt

The mix design was taken from UCPRC Case Studies (Wang et al., 2012) which represents a typical mix used by Caltrans for their rehabilitation projects, Table 7.3 is the mix design considered. The cut-off method was used as the allocation methodology for RAP. Only the impacts of milling off the old asphalt and transportation to the plant with a hauling distance of 50 miles (80 km) was assigned to RAP.

Table 7.3. HMA with RAP mix design

Item	% by Weight
Aggregate:	81
• Coarse	38
• Fine	57
• Dust	5
Asphalt	4
RAP	15

7.4.3.3. Rubberized HMA (RHMA)

The mix design, presented in Table 7.4, was taken from UCPRC Case Studies report (Wang et al., 2012) which represents a typical rubberized asphalt used by Caltrans in its rehabilitation projects.

Table 7.4. RHMA mix design

Item	% by Weight
Aggregate	92.5
• Coarse	68
• Fine	27
• Dust	5
Asphalt Binder	7.5
• Asphalt	77.5
• CRM	20
• Extender Oil	2.5
RAP	0

7.4.3.4. Summary

Table 7.5 shows the LCI and LCIA for the mixes that are used as the wearing course. Section thicknesses and length were used to calculate the volume of materials which were then converted to mass assuming a density of 2400 kg/m^3 for both conventional and rubberized asphalt concrete. Mass of chip seal was calculated based on the mix which was expressed in terms of kg of material per unit area.

Table 7.5. Summary of LCI and LCIA for the mixes used as the wearing course

Item	Functional Unit	Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Fuel) [MJ]	PED (Non-Fuel) [MJ]
Chip Seal	20.8	kg/m^2	9.8E-01	1.6E-01	7.9E-04	9.3E+01	2.1E+01	7.3E+01
Conventional Asphalt Concrete	1.0	kg	4.8E-02	4.4E-03	3.2E-05	2.5E+00	8.5E-01	1.6E+00
Rubberized Asphalt Concrete	1.0	kg	6.2E-02	6.1E-03	4.1E-05	4.0E+00	1.2E+00	2.8E+00

7.4.4. Transportation of Materials to Site

For all the treatments, an 80 km (50 mi) transportation distance was assumed for the materials to the site. It was assumed that heavy trucks (24 tonnes) are used for transporting the materials and Table 7.6 shows the LCI and

LCIAs used in this study which were taken from GaBi and are based on the well to wheel impacts of the fuel used by trucks without considering the vehicle cycle.

Table 7.6. LCI and LCIA of transportation

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Fuel) [MJ]	PED (Non-Fuel) [MJ]
Heavy Truck (24 Tonne)	1000 kg-km	7.79E-02	1.24E-02	2.49E-05	1.11E+00	1.11E+00	0.00E+00

7.4.5. Construction Activities

Table 7.7 lists the main EOL treatments that are considered in this study. The impacts of the construction stage are caused by construction activities which include fuel combusted in the construction equipment plus the electricity and other energy sources used on site. To capture the energy consumption and emissions of the construction activities, models were developed for the construction process for each of the in-place recycling and the conventional rehabilitation methods. Mobilization of workers and equipment to and from the site were not included.

Figure 7.4 shows the flowchart for developing the construction activity LCI models. Table 7.7 shows the details of the construction process considered for each of the treatments in this study. This was done to determine the total fuel consumption for one functional unit of each of the treatments (one ln-km of surface rehabilitation.) The results were multiplied by the emission factor of burning one gallon of fuel,

Table 7.8 taken from GaBi software, shows the impacts of diesel combustion in equipment. The LCI flows presented in this table are "well to wheel" (includes impacts of fuel extraction from ground, processing, transportation to pump, and its combustion in cars' engine. Combining the total fuel combustion for each treatment and the well-to-wheel impacts of diesel combustion gives the impacts of the construction activities for 1 ln-km of each treatment which are shown in Table 7.9..

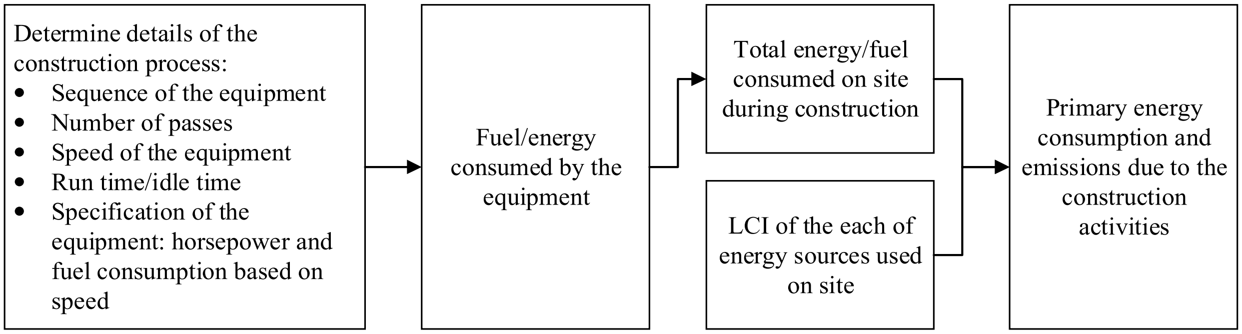


Figure 7.4: Flowchart used for developing LCI and LCIA of the construction activities.

Table 7.7. Construction details for each of the EOL treatments for 1 ln-km

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	# of Passes	Fuel Used (gal)	Total Fuel Used (gal)
CIR w. Stabilizer	Milling (Recycler & Water Tanker)	700	20.0	10	0.18	5.5	1	109.4	312

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	# of Passes	Fuel Used (gal)	Total Fuel Used (gal)
& Chip Seal	Stabilizer Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	Rolling (Pneumatic)	120	4.9	25	0.46	2.2	3	32.2	
	Rolling (Vibratory)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Static)	150	8.1	25	0.46	2.2	3	53.1	
	Emulsion Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	Aggregate Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	Rolling (Pneumatic)	120	4.9	25	0.46	2.2	3	32.2	
	Sweep (Truck)	80	2.0	100	1.83	0.5	2	2.2	
CIR w. Stabilizers & 25 mm HMA OL	Milling (Recycler & Water Tanker)	700	20.0	10	0.18	5.5	1	109.4	389
	Stabilizer Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	Rolling (Pneumatic)	120	4.9	25	0.46	2.2	3	32.2	
	Rolling (Vibratory)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Static)	150	8.1	25	0.46	2.2	3	53.1	
	Prime Coat Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	HMA Laydown (Paver)	250	10.6	15	0.27	3.6	1	38.6	
	Rolling (Vibratory)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Static)	150	8.1	25	0.46	2.2	3	53.1	
FDR (AE & Cement Stab.) w. Overlay	Milling (Recycler & Water Tanker)	1000	28.6	10	0.18	5.5	1	156.2	455
	Rolling (Padfoot)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Vibratory)	120	4.9	25	0.46	2.2	3	32.2	
	Leveling (Grader)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Rubber Tire)	150	8.1	25	0.46	2.2	3	53.1	
	Prime Coat Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	HMA Laydown (Paver)	250	10.6	15	0.27	3.6	1	38.6	
	Rolling (Vibratory)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Static)	150	8.1	25	0.46	2.2	3	53.1	
Conventional Asphalt Concrete (Mill & Fill)	Milling	700	20.0	10	0.18	5.5	1	109.4	284
	Prime Coat Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	
	HMA Laydown (Paver)	250	10.6	15	0.27	3.6	1	38.6	
	Rolling (Vibratory)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Pneumatic)	120	4.9	25	0.46	2.2	3	32.2	
	Rolling (Static)	150	8.1	25	0.46	2.2	3	53.1	
Conventional Asphalt Concrete (Overlay)	Prime Coat Application (Truck)	350	7.2	25	0.46	2.2	1	15.7	175
	HMA Laydown (Paver)	250	10.6	15	0.27	3.6	1	38.6	
	Rolling (Vibratory)	150	8.1	25	0.46	2.2	2	35.4	
	Rolling (Pneumatic)	120	4.9	25	0.46	2.2	3	32.2	
	Rolling (Static)	150	8.1	25	0.46	2.2	3	53.1	

Table 7.8. Well-to-wheel impacts of burning 1 gallon of diesel in the equipment

Item	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Fuel) [MJ]	PED (Non-Fuel) [MJ]
Diesel Combusted (1 gallon)	1.19E+01	5.27E+00	9.36E-03	1.64E+02	1.64E+02	0.00E+00

Table 7.9. Summary of LCI and LCIA of the construction activities for 1 ln-km

Item	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Fuel) [MJ]	PED (Non-Fuel) [MJ]
CIR with Stabilizer and Chip Seal	3.72E+03	1.97E+03	3.50E+00	6.14E+04	6.14E+04	0.00E+00
CIR with Stabilizer and Overlay	4.64E+03	2.05E+03	3.64E+00	6.40E+04	6.40E+04	0.00E+00
FDR with Stabilizer and Overlay	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
Hot Mix Asphalt (Mill & Fill)	3.40E+03	1.50E+03	2.67E+00	4.68E+04	4.68E+04	0.00E+00
Hot Mix Asphalt (Overlay)	2.09E+03	9.23E+02	1.64E+00	2.88E+04	2.88E+04	0.00E+00

7.4.6. End of Life

For this study EOL was handled using available methods without considering repeated recycling and impacts on quality. As mentioned earlier, questions remain regarding the number of times that aggregate can be recycled, and the impact of multiple recycling on quality and field performance, these issues will be addressed in the next stage of this research.

Regarding allocation, there are two common ways for handling it: the cut-off method where the virgin material production impacts are assigned to the upstream project and the impacts of in-place recycling are applied to the downstream project. The other method is the 50-50 method in which the total impacts (material production plus EOL in-place recycling) are divided equally between the upstream and downstream projects. For this study the cut-off method was selected assigning the impacts of milling the old asphalt, transportation to the plant, and any further recycling activities to the RAP. It was also assumed that at the EOL of the downstream project, all the overlay that was initially laid will be milled and then transported to a landfill or a recycling plant at similar distances assumed for virgin materials. For reporting purposes, the EOL impacts were added to transportation and construction impacts and were reported as part of them.

7.5. Final Results and Interpretation

In previous sections, environmental impacts of material production, transportation to site, construction, and EOL were calculated for one application of each of the EOL treatments. In this section, the total impacts for each treatment are provided and the share of different initial material production, transportation, and construction life cycle stages in total impacts, excluding the use state, are discussed. Table 7.10 is the breakdown of the total impacts for each treatment in detail based on life cycle stages included in this study. Table 7.11 shows the percentage share of each initial material production, transportation, and construction life cycle stage in total impacts. Bar charts of the results are also presented in Figure 7.5 and Figure 7.6.

The goal of this part of the project was to benchmark the cradle to laid environmental impacts of common EOL treatments for flexible pavements at their end of service life in California considering only a single EOL. This study cannot serve as a comparative study between treatments as the system boundary and scope of the study does not include the use stage.

Considering total initial materials and construction impacts, as shown in Figure 7.5, CIR with 1.5 percent FA and 1 percent portland cement has the lowest total impacts. All the FDR cases with stabilizer have higher total impacts compared to the conventional options of mill-and-fill and HMA overlay. The results also show that the total amount of stabilizer added (which depends on percent stabilizer and the layer thickness) has a significant impact on the total impacts. The FDR option with highest cement content (6 percent) consistently had the highest impacts in GWP, PM2.5, and PED (Fuel), while the FDR option with 4 percent asphalt emulsion and 1 percent portland cement had the highest impacts in POCP and PED categories. It must be kept in mind that there is potential energy kept unused in asphalt that is not lost and can be recovered if need be, that is reported in the table as PED (non-fuel), although the burning of RAP as an energy source is probably not cost-effective and has a number of practical challenges.

Considering the share of each cradle to laid life cycle stage in total impacts calculated in this phase of study, as shown in Figure 7.6 and Table 7.11, the material production stage is dominant in all impact categories for all treatments. For all the CIR treatments, transportation has the least contribution to total impacts in all categories. However, for all FDRs and the conventional overlay case, transportation is the second contributor to total impacts in GWP and PED (Total and Fuel.) For conventional mill-and-fill, transportation is the second contributor in all impact categories.

Between the treatments, GWP for 1 ln-km of treatment ranged between 2.50E+04 to 1.66E+05 kg of CO_2e, out of which 75 to 92 percent was caused during the material production stage, two to 19 percent during transportation, and three to 15 percent during construction. In material production, FDR with six percent portland cement (Case 8), had the highest percentage of the material production stage to total GWP impacts with 92 percent and case one, CIR with chip seal had the lowest share with 75 percent. In transportation, conventional mill-and-fill had the highest share in total impacts with 19 percent and CIR with HMA overlay and CIR with chip seal had the lowest share with two percent. In construction, the highest share in total GWP, 15 percent, was for CIR with chip seal, and the lowest with three percent, was for FDR with six percent Portland cement.

Photochemical ozone creation potential, an indicator of smog formation, varied between 4.87E+3 to 1.71E+4 kg of O_3e per lane-km of treatment, and the share of material production in total emissions in this category ranged between 55 and 78 percent.

PM2.5 emissions for all the treatments was mainly due to material production, ranging from 19 to 97.8 kg for 1 ln-km of treatment and a range of 81 percent to 93 percent share in the total. For the CIR treatments, construction activities had the largest share of the total among all treatments.

Total primary energy demand excluding material feedstock energy, PED [Fuel], for all treatments ranged between 3.89E+5 to 1.97E+6 MJ for 1 ln-km of pavement and was mainly due to material production, with shares of 79 to 90 percent of the total impacts across all treatments.

Table 7.10. Cradle-to-laid impacts by life cycle stage for one application for each of the EOL treatments for 1 ln-km

Treatment	Life Cycle Stage	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Fuel) [MJ]	PED (Non-Fuel) [MJ]
Case 1. CIR (10 cm (0.33 ft) Milled + 1.5% FA + 1% PC) w. Chip Seal	Material	2.07E+04	2.81E+03	1.53E+01	1.36E+06	3.18E+05	1.04E+06
	Transport	6.19E+02	9.86E+01	1.98E-01	8.85E+03	8.85E+03	0.00E+00
	Construction	3.72E+03	1.97E+03	3.50E+00	6.14E+04	6.14E+04	0.00E+00
	Total	2.51E+04	4.87E+03	1.90E+01	1.43E+06	3.89E+05	1.04E+06
Case 2. CIR (10 cm (0.33 ft) Milled + 3% FA + 2% PC) w. 2.5 cm (0.08 ft) of HMA OL	Material	4.19E+04	4.92E+03	2.92E+01	2.28E+06	6.09E+05	1.67E+06
	Transport	3.32E+03	5.30E+02	1.06E+00	4.76E+04	4.76E+04	0.00E+00
	Construction	4.64E+03	2.05E+03	3.64E+00	6.40E+04	6.40E+04	0.00E+00
	Total	4.98E+04	7.50E+03	3.39E+01	2.39E+06	7.21E+05	1.67E+06
Case 3. FDR (25 cm (0.82 ft) Milled + No Stab.) w. 6 cm (0.2 ft) RHMA OL	Material	3.61E+04	3.72E+03	2.45E+01	2.42E+06	6.96E+05	1.72E+06
	Transport	6.65E+03	1.06E+03	2.12E+00	9.51E+04	9.51E+04	0.00E+00
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
	Total	4.82E+04	7.18E+03	3.09E+01	2.59E+06	8.66E+05	1.72E+06
Case 4. FDR (25 cm (0.82 ft) Milled + 4% AE	Material	1.00E+05	1.26E+04	7.26E+01	7.07E+06	1.78E+06	5.29E+06
	Transport	8.03E+03	1.28E+03	2.57E+00	1.15E+05	1.15E+05	0.00E+00

Treatment	**Life Cycle Stage**	**GWP [kg CO_2e]**	**POCP [kg O_3e]**	**PM2.5 [kg]**	**PED (Total) [MJ]**	**PED (Fuel) [MJ]**	**PED (Non-Fuel) [MJ]**
+ 1% PC) w. 6 cm (0.2 ft) RHMA OL	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
	Total	1.14E+05	1.63E+04	7.94E+01	7.26E+06	1.97E+06	5.29E+06
Case 5. FDR (25 cm (0.82 ft) Milled + 3% FA + 1% PC) w. 6 cm (0.2 ft) RHMA OL	Material	8.71E+04	1.07E+04	6.28E+01	5.86E+06	1.46E+06	4.40E+06
	Transport	7.76E+03	1.24E+03	2.48E+00	1.11E+05	1.11E+05	0.00E+00
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
	Total	1.00E+05	1.44E+04	6.96E+01	6.05E+06	1.64E+06	4.40E+06
Case 6. FDR (25 cm (0.82 ft) Milled + 2% PC) w. 6 cm (0.2 ft) RHMA OL	Material	7.48E+04	6.95E+03	4.66E+01	2.68E+06	9.60E+05	1.72E+06
	Transport	7.20E+03	1.15E+03	2.30E+00	1.03E+05	1.03E+05	0.00E+00
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
	Total	8.75E+04	1.05E+04	5.32E+01	2.86E+06	1.14E+06	1.72E+06
Case 7. FDR (25 cm (0.82 ft) Milled + 4% PC) w. 6 cm (0.2 ft) RHMA OL	Material	1.14E+05	1.02E+04	6.87E+01	2.95E+06	1.22E+06	1.72E+06
	Transport	7.76E+03	1.24E+03	2.48E+00	1.11E+05	1.11E+05	0.00E+00
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
	Total	1.27E+05	1.38E+04	7.55E+01	3.13E+06	1.41E+06	1.72E+06
Case 8. FDR (25 cm (0.82 ft) Milled + 6% PC) w. 6 cm (0.2 ft) RHMA OL	Material	1.52E+05	1.34E+04	9.09E+01	3.21E+06	1.49E+06	1.72E+06
	Transport	8.31E+03	1.32E+03	2.66E+00	1.19E+05	1.19E+05	0.00E+00
	Construction	5.44E+03	2.40E+03	4.27E+00	7.49E+04	7.49E+04	0.00E+00
	Total	1.66E+05	1.71E+04	9.78E+01	3.41E+06	1.68E+06	1.72E+06
Case 9. HMA Overlay (7.5 cm (0.25 ft))	Material	3.51E+04	3.44E+03	2.34E+01	1.94E+06	6.28E+05	1.31E+06
	Transport	8.31E+03	1.32E+03	2.66E+00	1.19E+05	1.19E+05	0.00E+00
	Construction	3.40E+03	1.50E+03	2.67E+00	4.68E+04	4.68E+04	0.00E+00
	Total	4.68E+04	6.27E+03	2.88E+01	2.10E+06	7.94E+05	1.31E+06
Case 10. HMA Mill & Fill (10 cm (0.33 ft))	Material	4.58E+04	4.43E+03	3.04E+01	2.48E+06	8.16E+05	1.67E+06
	Transport	1.11E+04	1.77E+03	3.54E+00	1.59E+05	1.59E+05	0.00E+00
	Construction	2.09E+03	9.23E+02	1.64E+00	2.88E+04	2.88E+04	0.00E+00
	Total	5.90E+04	7.12E+03	3.56E+01	2.67E+06	1.00E+06	1.67E+06

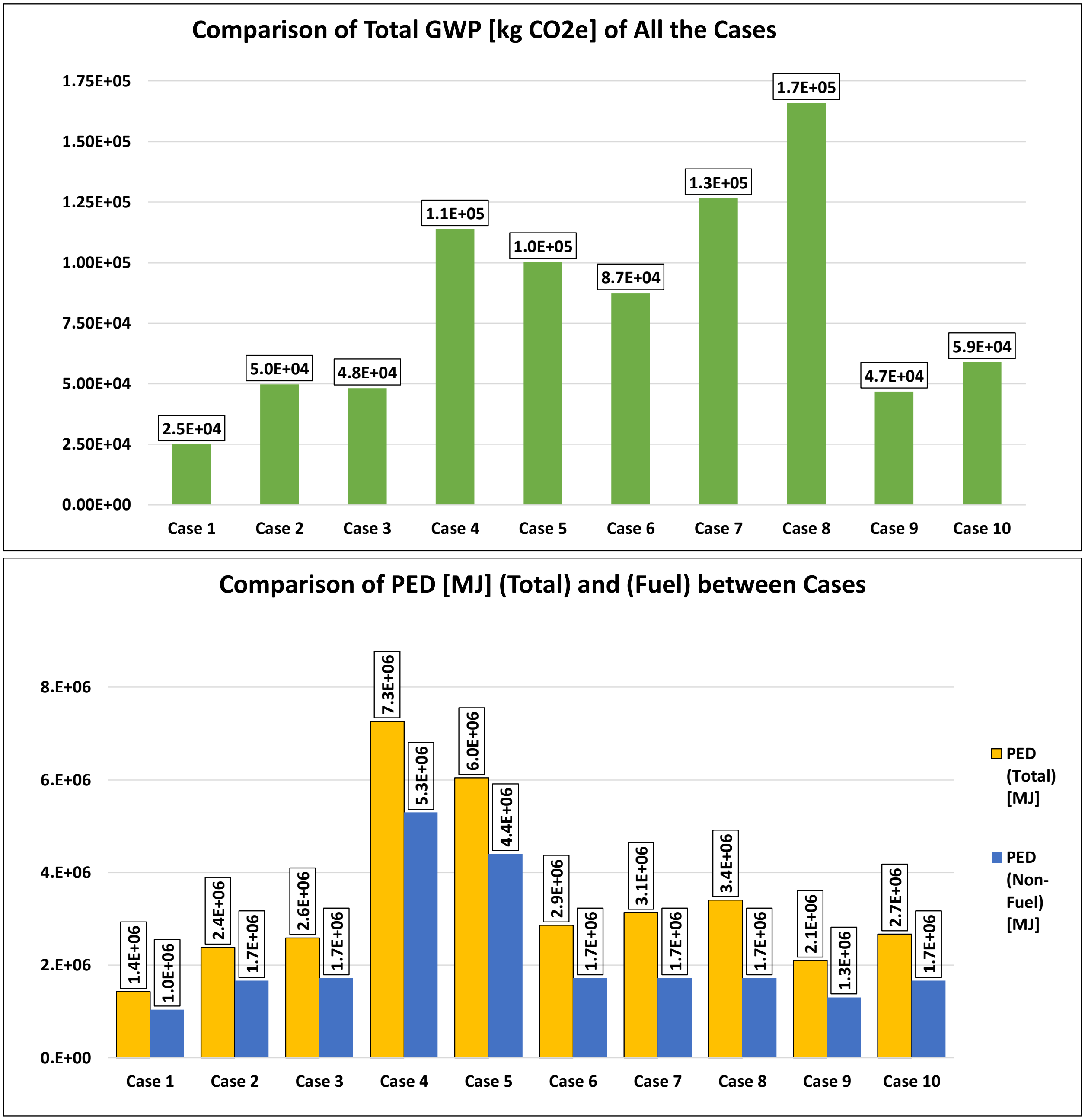
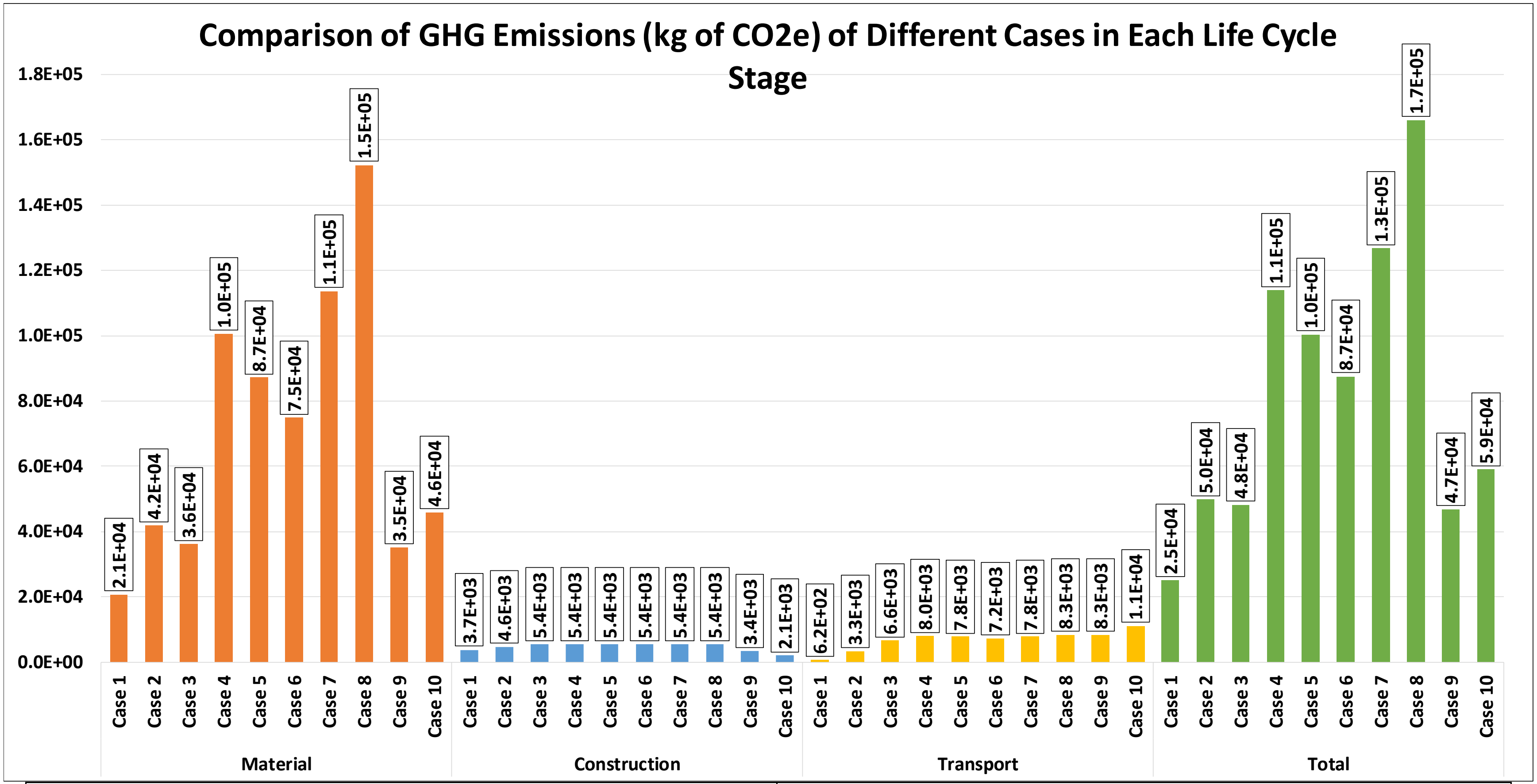


Figure 7.5: Comparison of total cradle to laid GHG and PED between all cases.



Case 1	CIR (10 cm (0.33 ft) Milled + 1.5% FA + 1% PC) w. Chip Seal	Case 6	FDR (25 cm (0.82 ft) Milled + 2% PC) w. 6 cm (0.2 ft) RHMA OL
Case 2	CIR (10 cm (0.33 ft) Milled + 3% FA + 2% PC) w. 2.5 cm (0.08 ft) of HMA OL	Case 7	FDR (25 cm (0.82 ft) Milled + 4% PC) w. 6 cm (0.2 ft) RHMA OL
Case 3	FDR (25 cm (0.82 ft) Milled + Mech. Stab.) w. 6 cm (0.2 ft) RHMA OL	Case 8	FDR (25 cm (0.82 ft) Milled + 6% PC) w. 6 cm (0.2 ft) RHMA OL
Case 4	FDR (25 cm (0.82 ft) Milled + 4% AE + 1% PC) w. 6 cm (0.2 ft) RHMA OL	Case 9	HMA Overlay (7.5cm (0.25 ft))
Case 5	FDR (25 cm (0.82 ft) Milled + 3% FA + 1% PC) w. 6 cm (0.2 ft) RHMA OL	Case 10	HMA Mill & Fill (10 cm (0.33 ft))

Figure 7.6: Comparison of GWP (kg CO_2e) of treatments across cradle to laid life cycle stages.

Table 7.11. Percentage of the total impacts for each of the cradle to laid life cycle stages for each of the EOL treatments

Case	Treatment	Life Cycle Stage	GWP	POCP	PM2.5	PED (Total)	PED (Fuel)	PED (Non-Fuel)
1	CIR (10 cm (0.33 ft) Milled + 1.5% FA + 1% PC) w. Chip Seal	Material	83%	58%	81%	95%	82%	100%
		Transport	2%	2%	1%	1%	2%	0%
		Construction	15%	40%	18%	4%	16%	0%
2	CIR (10 cm (0.33 ft) Milled + 3% FA + 2% PC) w. 2.5 cm (0.08 ft) of HMA OL	Material	84%	66%	86%	95%	85%	100%
		Transport	7%	7%	3%	2%	7%	0%
		Construction	9%	27%	11%	3%	9%	0%
3	FDR (25 cm (0.82 ft) milled + No Stab.) w. 6 cm (0.2 ft) RHMA OL	Material	75%	52%	79%	93%	80%	100%
		Transport	14%	15%	7%	4%	11%	0%
		Construction	11%	33%	14%	3%	9%	0%
4	FDR (25 cm (0.82 ft) milled + 4% AE + 1% PC) w. 6 cm (0.2 ft) RHMA OL	Material	88%	77%	91%	97%	90%	100%
		Transport	7%	8%	3%	2%	6%	0%
		Construction	5%	15%	5%	1%	4%	0%
5	FDR (25 cm (0.82 ft) milled + 3% FA + 1% PC) w. 6 cm (0.2 ft) RHMA OL	Material	87%	75%	90%	97%	89%	100%
		Transport	8%	9%	4%	2%	7%	0%
		Construction	5%	17%	6%	1%	5%	0%
6	FDR (25 cm (0.82 ft) milled + 2% PC) w. 6 cm (0.2 ft) RHMA OL	Material	86%	66%	88%	94%	84%	100%
		Transport	8%	11%	4%	4%	9%	0%
		Construction	6%	23%	8%	3%	7%	0%
7	FDR (25 cm (0.82 ft) milled + 4% PC) w. 6 cm (0.2 ft) RHMA OL	Material	90%	74%	91%	94%	87%	100%
		Transport	6%	9%	3%	4%	8%	0%
		Construction	4%	17%	6%	2%	5%	0%
8	FDR (25 cm (0.82 ft) milled + 6% PC) w. 6 cm (0.2 ft) RHMA OL	Material	92%	78%	93%	94%	88%	100%
		Transport	5%	8%	3%	3%	7%	0%
		Construction	3%	14%	4%	2%	4%	0%
9	HMA Overlay (7.5 cm (0.25 ft))	Material	75%	55%	82%	92%	79%	100%
		Transport	18%	21%	9%	6%	15%	0%
		Construction	7%	24%	9%	2%	6%	0%
10	HMA Mill & Fill (10 cm (0.33 ft))	Material	78%	62%	85%	93%	81%	100%
		Transport	19%	25%	10%	6%	16%	0%
		Construction	4%	13%	5%	1%	3%	0%

7.6. Further Analysis on Transportation Distance

Besides avoiding use of virgin materials, reduction of hauling distance in the construction project is usually one of the main advantages mentioned for in-place recycling as it results in fuel savings. In this section, the transportation stage is further investigated. A sensitivity analysis was conducted on travel distance to see how it affects the final results.

Regarding the sensitivity to transportation distance, the model was run under two scenarios for the two-way transportation distance: 80 km (50 mi) and 160 km (100 mi.) The percent increase in each impact category was calculated for all EOL treatments and the results are shown in Table 7.12. As the results show, the total impacts of conventional treatments are more sensitive to transportation distance than in-place methods. This was expected because more materials are transported in conventional treatments. The increase in total impacts with doubled transportation distance can be as high as 25 percent increase in POCP category for HMA overlays.

Table 7.12. Increase in total cradle to laid impacts as the two-way transportation distance is increased from 80 to 160 km

Surface Treatment	GWP	POCP	PM 2.5	PED (Total)	PED (Fuel)
CIR (10 cm (0.33 ft) Milled + 1.5% FA + 1% PC) w. Chip Seal	2%	2%	1%	1%	2%
CIR (10 cm (0.33 ft) Milled + 3% FA + 2% PC) w. 2.5 cm (0.08 ft) of HMA OL	7%	7%	3%	2%	7%
FDR (25 cm (0.82 ft) Milled + Mech. Stab.) w. 6 cm (0.2 ft) RHMA OL	14%	15%	7%	4%	11%
FDR (25 cm (0.82 ft) Milled + 4% AE + 1% PC) w. 6 cm (0.2 ft) RHMA OL	7%	8%	3%	2%	6%
FDR (25 cm (0.82 ft) Milled + 3% FA + 1% PC) w. 6 cm (0.2 ft) RHMA OL	8%	9%	4%	2%	7%
FDR (25 cm (0.82 ft) Milled + 2% PC) w. 6 cm (0.2 ft) RHMA OL	8%	11%	4%	4%	9%
FDR (25 cm (0.82 ft) Milled + 4% PC) w. 6 cm (0.2 ft) RHMA OL	6%	9%	3%	4%	8%
FDR (25 cm (0.82 ft) Milled + 6% PC) w. 6 cm (0.2 ft) RHMA OL	5%	8%	3%	3%	7%
HMA Overlay (7.5cm (0.25 ft))	18%	21%	9%	6%	15%
HMA Mill & Fill (10 cm (0.33 ft))	19%	25%	10%	6%	16%

The second issue of interest was the transportation distance for virgin materials below which a conventional treatment would have less cradle to laid impacts compared to a similar in-place recycling treatment. For this purpose, the CIR case with stabilizers and overlay was compared to HMA overlay, and HMA mill-and-fill was compared to three cases of FDR (cases five to eight.) These results should not be used to choose one treatment over the other because performance life has not been considered but are intended to provide an indication of the sensitivity of selection to transportation distance. The question is posed in terms of the distance at which it does not matter, in terms of environmental impacts, which option is selected.

The results are shown in Table 7.13. As the FDR cases already had higher total impacts compared to conventional mill-and-fill option, virgin materials should have significantly larger transport distances so that FDR options have the same impacts as mill-and-fill. The only case worthy of notice is CIR with stabilizer and HMA overlay for which up to 80 miles two-way transport distance for virgin materials resulted in conventional overlay having less GWP than CIR. After the 80 miles two-way threshold, CIR with stabilizers and HMA overlay becomes less impactful.

Table 7.13. Minimum two-way transport distance (miles) for in-place recycling and conventional treatments to have the same cradle to laid initial treatment total impacts

Case	GWP	POCP	PM2.5	PED (Fuel)
CIR, Case 2	80	127	212	NA
FDR, Case 4	951	998	2,297	1,158
FDR, Case 5	671	733	1,648	724
FDR, Case 6	417	324	758	171
FDR, Case 7	1,069	683	1,926	476
FDR, Case 8	1,982	1,185	3,561	904

7.7. Conclusions

This study was conducted to benchmark the environmental impacts of several common EOL treatments used in California for flexible pavements at their end of service life. The system boundary consisted of material production, transportation to the site and construction activities that together make up the EOL treatment for the initial application of the treatment and not considering the maintenance and rehabilitation sequence over a life cycle. The system boundary also did not include other life cycle stages such as use stage, and traffic delays during construction activities. Twelve treatments were studied, consisting of ten in-place recycling alternatives (CIR and FDR with different stabilization methods and wearing courses on top) and two conventional treatments (HMA overlay and HMA mill-and-fill.) The conclusions drawn from the results presented in this study are:

- There are large differences between the initial impacts of the treatments in each impact category but as discussed earlier, due to limited scope of this stage and the fact that the system boundary does not include all life cycle stages, comparison of the results shall not be used as basis for decision making and selecting between alternatives.
- The material production stage is dominant in all impact categories for all treatments. The results also show that the total amount of stabilizer added (which depends on percent stabilizer and the layer thickness) has a significant impact on the total impacts.
- HMA overlay and HMA mill-and-fill have lower impacts compared to all the FDR options with stabilizers across all impact categories.
- The FDR option with highest cement content (6 percent) consistently had the highest impacts in GWP, PM2.5, and PED (Fuel), while the FDR option with 4 percent asphalt emulsion and 1 percent portland cement had the highest impacts in POCP and PED (Total and Non-Fuel.)
- Material production share in total impacts ranged between 75 to 92 percent for GWP, 52 to 78 percent for POCP, 79 to 93 for PM 2.5, 92 to 97 percent for PED (Total), and 79 to 90 percent for PED (Fuel.) Binder and stabilizer production caused more than 90 percent of the total impacts of the material production across all cases.
- Share of material transportation to site in total impacts ranged between two to 19 percent for GWP, two to 25 percent for POCP, one to 10 percent for PM 2.5, one to six percent for PED (Total), and two to 16 percent for PED (Fuel.)
- Construction activities impacts caused three to 15 percent of total impacts for GWP, 13 to 40 percent in POCP, four to 18 percent in PM 2.5, one to four percent of PED (Total), and three to 16 percent of PED (Fuel)
- Changing transportation distance has the most drastic effect on total impacts of conventional treatments. This was already expected, as conventional treatments require the largest amount of materials transported.
- Comparing the CIR with stabilizers and HMA overlay with the conventional treatment of an HMA overlay shows that total GWP of the two options are close (5.0E+4 versus 4.7E+4, respectively) with the conventional treatment performing slightly better. This remains true up to transport distance of 80 miles (two-way) for the virgin materials, at which the impacts of both two options become equal and after that distance the CIR outperforms the conventional treatment.
- Similar comparison of FDRs with conventional mill-and-fill resulted in very long transport distances for virgin materials at which the impacts of the two treatments become equal. The transport distances were all above 150 miles.

CHAPTER 8. Performance Prediction Models for In-Place Recycling for Quantification of Use Stage Impacts

8.1. Introduction

Environmental impacts of the pavement use stage are due to: 1) excess fuel consumption (EFC) of vehicles traveling on the section, and 2) maintenance and rehabilitation (M&R) activities, including the initial in-place recycling or reclamation treatment, that are applied to the pavement to restore structural capacity and ensure safety and serviceability. This chapter is focused on the development of predictive models for performance indices (roughness and cracking) that are used to forecast the frequency of future M&R activities for sections built using in-place recycling methods.

EFC is defined as fuel used beyond what is needed to travel on an "ideal" pavement, defined as being smooth, having the required macrotexture to provide safe friction, and producing minimal energy consuming pavement structural response. Surface roughness, measured by the International Roughness Index (IRI), is the mechanism considered in this study. To be able to estimate excess vehicle fuel consumption from in-place recycling, or reclamation of asphalt pavements along with an asphalt overlay as a wearing course, models were developed to predict surface roughness with time and truck traffic. These models can be used with vehicle-pavement interaction (PVI) models to calculate EFC caused by pavement roughness.

Agencies normally use decision trees to determine the frequency of future M&R activities based on comparison of pavement condition indices with threshold values for those indices that trigger M&R activities. These decision trees are usually based on perception of optimality for cost-effectiveness of the timing of the treatment and previous experience in managing the network and are implemented subject to budget availabilities.

To determine M&R frequencies, wheel path cracking (WPC) is a commonly used performance index, although some agencies also trigger treatment based on IRI. These indices were used to help address some of the questions needed by decision makers regarding in-place reclamation and recycling such as the following:

- What are the changes in environmental impacts of pavement reclamation and recycling compared to conventional methods of mill and fill with respect to roughness progression during the use stage
- How do sections built using in-place recycling perform compared to sections treated with conventional treatments in terms of the frequency of future M&R needs during the use stage

Modeling the use stage includes determining the timing of future maintenance and rehabilitation, estimating service life of each treatment used, and prediction of surface roughness progression with time, to be able to model vehicle fuel consumption that is using the section. To be able to achieve such goal, performance prediction models are needed so that level of cracking and surface roughness can be estimated. At this point, the effect of recycling treatments on performance of pavement sections is not fully understood. Figure 8.1 shows how prediction models should be used for conducting a full life cycle comparative LCA between EOL treatments and the LCA study itself should follow the flowchart presented in Figure 8.2.

As shown in Figure 8.1, performance prediction models are critical in estimating the impacts of the transportation infrastructure during the use stage. Currently, there are no performance prediction models available for sections built using in-place recycling methods. Such predictive models are needed for a fair comparison between the in-place recycling methods and conventional treatments such as mill-and-fill or overlays. The goal of this chapter is to develop predictive performance models for sections built using in-place recycling. Since similar models are available for conventional treatments, the results in this chapter address this gap in the knowledge and allow conducting a full life cycle comparison between the EOL alternatives, according to Figure 8.2. However, conducting case studies on the full life cycle comparison of alternatives is not part of the scope of this chapter.

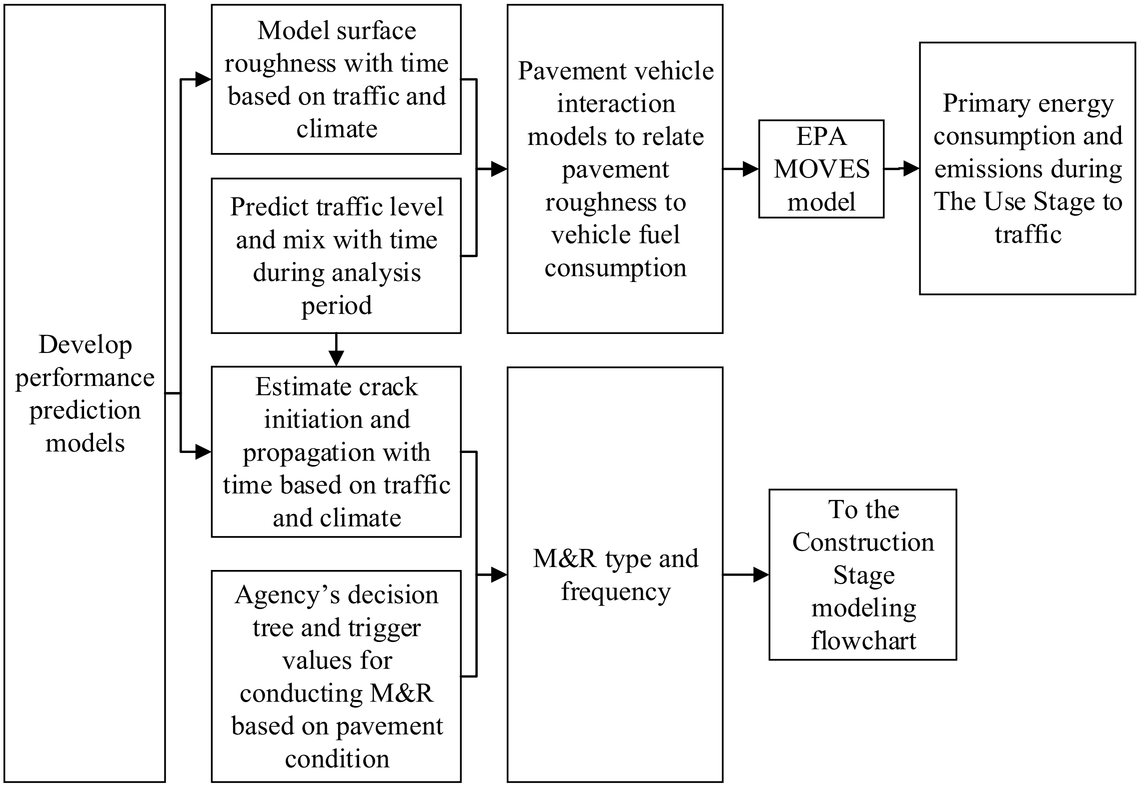


Figure 8.1: Application of performance models for a full life cycle comparative LCA between alternatives.

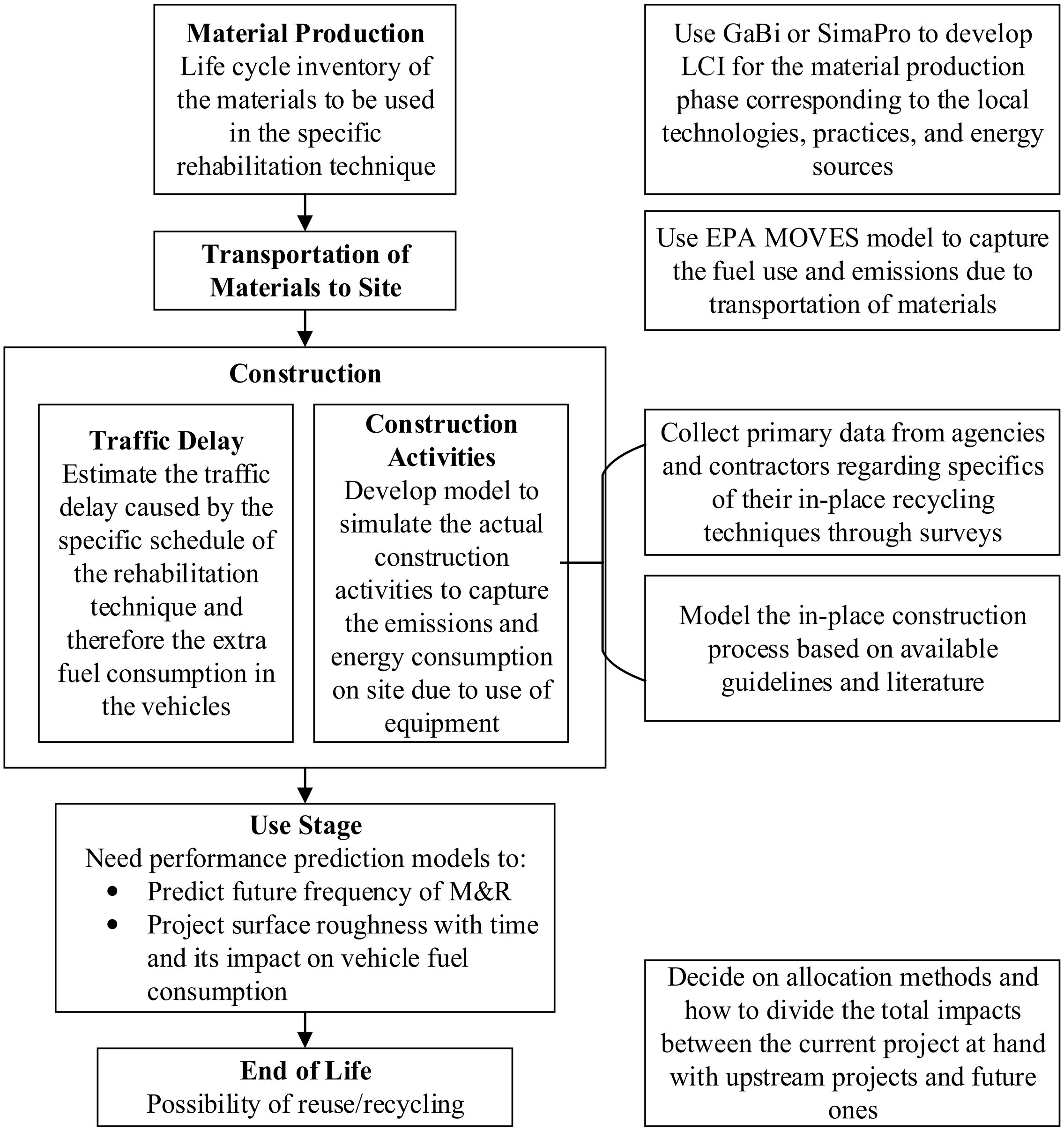


Figure 8.2: The framework to be used in the comparative LCA study between EOL treatments.

8.2. Data Collection

8.2.1. Initial Data Analysis and Characterization

The Caltrans' PMS condition survey database, consisting of data from the visual pavement condition survey (PCS) used from 1978 to 2014 and from the automated pavement condition survey (APCS) begun in 2011, provided the performance data for cracking and roughness for this study. The database was used to obtain data for sections that have had cold in-place (CIR) or full-depth reclamation (FDR) at any point during their service-life. FDR was initially introduced into California by the UCPRC in 2000, with the first section built in 2001. CIR has been used as early as the 1980s. The entire process of data collection, data filtering, and model development was performed twice.

In the first attempt, approximately 2.7 million observations were obtained for all CIR and FDR sections using the PCS and 2011 and 2012 APCS data. As the 2015 APCS data became available (there were no surveys in 2013 and 2014), a second attempt was carried out to examine any improvement of the models can be realized. The process of data extraction consisted of the following steps:

- Identification of the 32.6 ft (10 m) long data collection segments in the network, identified by "section IDs", that had CIR/FDR at any points in their history.
- Extraction of all the observations for those IDs from the database.

This method was used to capture the full-time history of the development of cracking and IRI on the sections that had CIR and FDR, immediately after the CIR/FDR applications and just before the next major treatment using the data collected from Caltrans pavement management system (PMS) database. Table 8.1 shows a general categorization of the collected data.

Table 8.1. General categorization of the data available in Caltrans' PMS database

General Section Information
Route
Direction
Beginning and ending odometer
Length
Lane
Climate
Unique ID for each sub-section
Traffic levels (ESALs* per year)
Project Contract Information (as-builts)
Expenditure authorization (EA) **
LOC of a project ***
Project award date
Project completion date
Project Construction Activities
Information about the previous layers that were in place
Number and thickness of the removed layers
Type of applied treatments
Number and type of the layers that were added /recycled in place
Condition Survey Data of the Sections
Date of condition survey
IRI in the left and right wheelpath
Fatigue cracking in the wheelpath (called alligator cracking) classified into three levels of severity: A (initial unconnected cracks), B (progression to intersecting cracks), and C (intersecting cracks extending between wheelpaths)
Other performance indices (such as bleeding, patching, rutting, …) ****

*: Equivalent Single Axle Load

**: EA is the funding source used for conducting the project. Multiple projects in various locations can have the same EA.

***: LOC is not an acronym, but the word that is used in PaveM to refer to a specific treatment (in terms of structural and mix design) and does not represent the project location. A single LOC could have been implemented in multiple locations.
***: These indexes were not directly used in this study but helped clarify the history of sections during data filtering.

Table 8.2 summarizes the database before data filtration. The information in the table is from the second round of data collection from Caltrans' PMS database in which separate data frames were extracted for CIR and FDR. There were two types of FDR in the collected data, FDR with no stabilization (FDR-NA) and FDR with foamed asphalt (FDR-FA) which means a few sections with foamed asphalt alone and the majority with both foamed asphalt and a small amount of cement. Table 8.3 presents the number of observations for each climate region.

Table 8.2. Summary of the databases extracted for CIR and FDR from Caltrans' PMS

Statistics	CIR	FDR
Number of Observations ([# of obs.] data segments times survey years with observations)	416,952	433,925
ID	12,367	15,918
LOC	509	1,025
EA	377	777
Climate Regions (out of 9 in state)	7	9

Table 8.3. Distribution of observations across climate regions

Climate (CIR)	# of observations	Climate (FDR)	# of observations
Inland Valley	143,181	Inland Valley	120,393
High Desert	91,712	Low Mountain	90,229
Desert	70,200	High Mountain	53,838
High Mountain	60,711	South Coast	46,761
Low Mountain	35,975	High Desert	45,367
South Coast	13,796	Central Coast	26,703
Central Coast	1,377	Desert	25,991
		North Coast	19,965
		South Mountain	4,678

8.2.2. Data Cleaning

Figure 8.3 was used as the framework for conducting data cleaning. The third stage of the flowchart resulted in:

- CIR: 120 unique LOCs were identified for IRI and 114 for WPC.
- FDR: 309 unique LOCs for IRI and 278 for WPC.

Figure 8.4 shows a sample of the scatter plots and box plots for the time histories of observations on sub-segments (section IDs) of roughness and wheelpath cracking developed for each LOC to evaluate the reasonableness of the data versus the as-built history.

The last step was to manually review the plot and its supporting data for each LOC and determine whether the observed trend was reasonable and if the data were useful for developing performance models. There were cases of unexpected reduction in IRI or cracking while there was no record of any maintenance or rehabilitation. This might be due to error in recording possible treatment. Additionally, there were cases where high values of IRI are recorded that are not consistent with the trend before or after those occurred and there was no record of a treatment. This indicates the possibility of measurement error in that particular survey. There were cases where the trends of progression of IRI and cracking are as would be expected but the reduction in IRI and/or cracking did not coincide with treatment construction date. Again, this could be related to errors in recording project completion dates. Errors in correctly recording the precise locations where the measurement was made are also a possible source of unexpected trends. The number of observations in the datasets after data filtration is presented in Table 8.4.

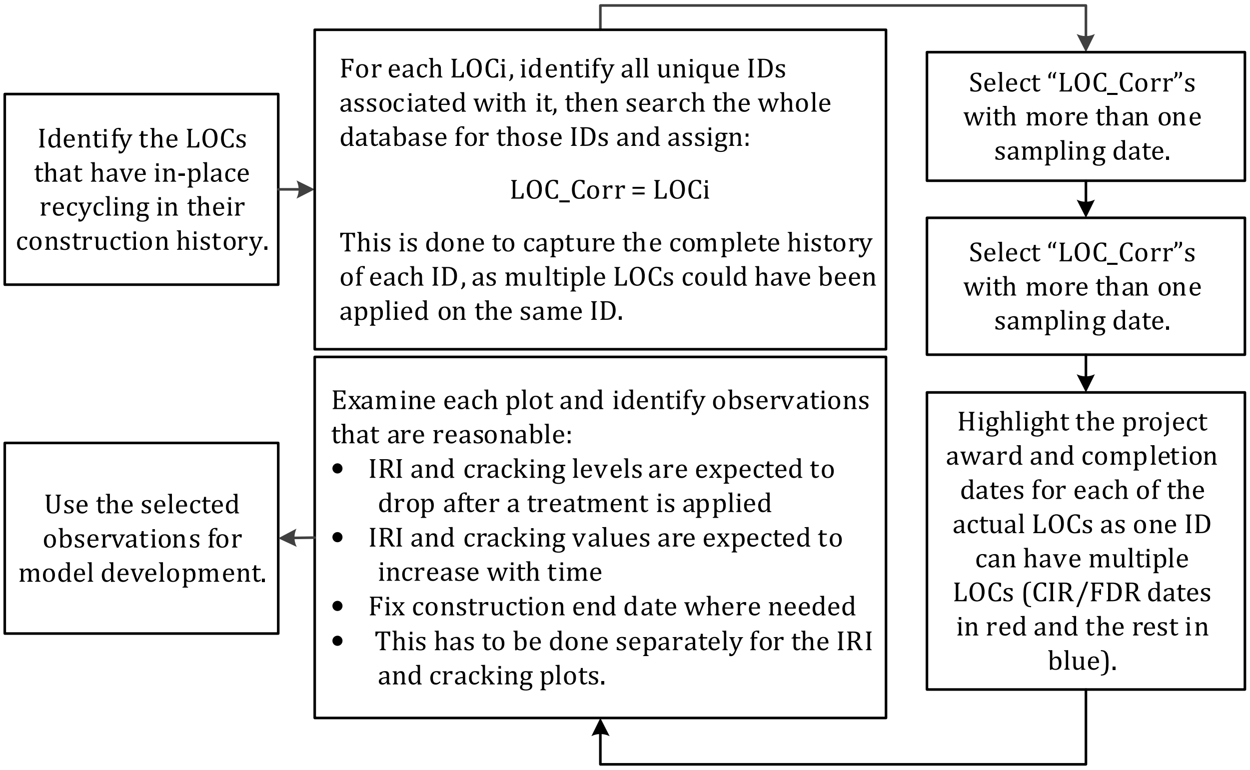
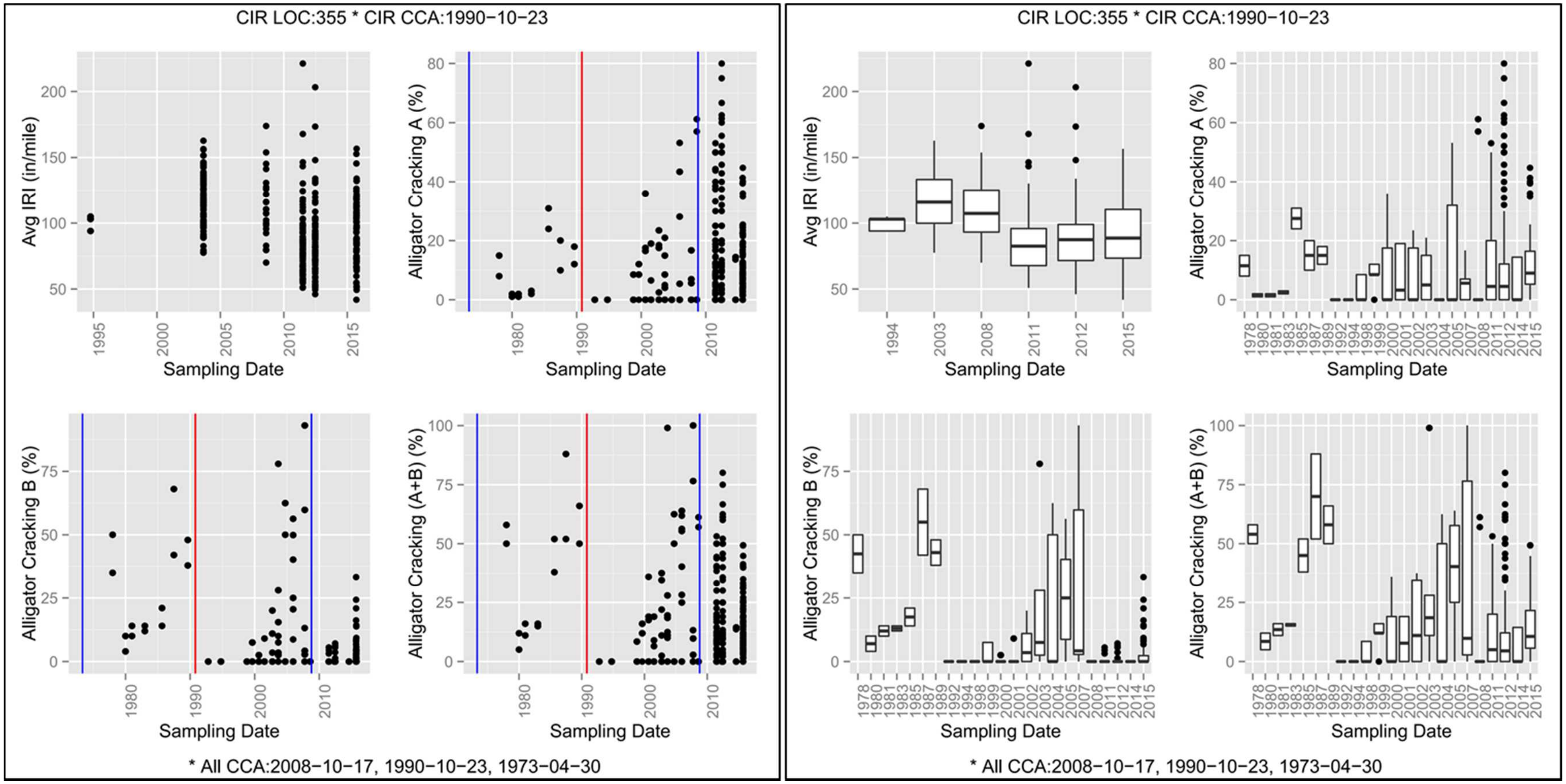


Figure 8.3: Flowchart for conducting the data cleaning.

Table 8.4. Summary of the data frames after data filtration

Statistics	IRI-CIR	IRI-FDR	WPC-CIR	WPC-FDR
Total Observations	29,229	35368	19,311	23,090
ID	8,645	6284	8,073	7,827
LOC	83	206	75	130
EA	126	100	63	143
Climate Region	6	9	7	9



CIR LOC:355 * CIR CCA:1990−10−23

* All CCA:2008−10−17, 1990−10−23, 1973−04−30

Figure 8.4: Sample of the scatterplots and boxplots for time versus distress developed for each LOC to evaluate reasonableness of roughness and cracking time histories (blue line indicating the application of a new treatment, red line indicating an FDR or CIR treatment.)

8.3. Performance Modeling

Two performance variables were selected for this project: IRI and WPC. The performance variable for IRI was defined as the IRI values measure for each of the section IDs. Each ID has a length of 0.1 mi and the average value of IRI reading on that section is reported as the IRI for that ID.

As defined by the Caltrans APCS manual (2011), there are two wheelpaths in each lane, defined as the left wheelpath (LWP) and the right wheelpath (RWP.) The width of each wheelpath is 3 ft (0.9 m) and the edge of the wheelpath is located at a distance of 1.5 ft (0.45 m) from the lane centerline. WPC is quantified by the "wheelpath crack length ratio" (R_{WPC}), which is the ratio of total length of all cracks in each wheelpath to the length of the data segment. There are three types of WPC defined by Caltrans: Alligator A, B, and C. Alligator A is defined as the initial longitudinal cracking that appears in the wheelpath. It was reported that these cracks connect in the wheelpath forming polygons defining the "alligator skin" pattern when at a threshold of $R_{WCR} = 1.6$, at which point the severity is defined as Alligator B (Caltrans, 2011.) Alligator C is the final form of fatigue cracking when the fatigue cracks between right and left wheelpaths connect. The performance variable for WPC was defined as percent of the wheelpath with alligator B cracking.

The modeling processes for IRI and WPC are empirical-mechanistic, meaning that the variables included in the model and the equation form of the model are predetermined based on the behavior expected from mechanistic analysis, but they are empirical because no mechanics calculations are performed. Other variables are treated as category variables and separate equations with time as the explanatory variable are developed for each permutation of the other explanatory variables. The other explanatory variables included in these models were regional climate, truck traffic expressed in equivalent single axle loads (ESAL) per year, and the type and thickness of any hot mix asphalt (HMA) overlay placed on top of the CIR or FDR. The result is a performance model tree in which each branch represents a unique combination of the main variables: traffic, overlay thickness, and climate. The performance models for conventional treatments, such as mill-and-fill and overlays, are shown in continuous form in Table 8.5.

To use climate as a categorical variable and have enough observations in each climate category, it was assumed that climate regions can be categorized either as severe or mild. Table 8.6 and Table 8.7 present the categories considered for the traffic level and the overlay thickness, respectively. The same HMA thickness overlay categories were used for the surfaces placed on CIR and FDR treatments and for HMA overlays without CIR and FDR. Figure 8.6 is a representation of one of the performance tree branches. Each branch has its own performance model coefficients (where data availability and data quality permit.) Models for HMA overlay without CIR or FDR used in this project were those developed previously for the Caltrans PMS (Tseng, 2012.)

Table 8.5. Performance equations used for HMA models without CIR or FDR (Tseng, 2012)

Performance Variable	Intended Purpose	Pavement Condition Index Used	Performance Equation Form
International Roughness Index	IRI is an indicator of surface roughness.	IRI	$y = a + bx^c$

Performance Variable	Intended Purpose	Pavement Condition Index Used	Performance Equation Form
Wheelpath Cracking	WPC is caused by aging and traffic load. Is used as an indicator of the structural capacity of pavement sections and therefore a metric for triggering rehabilitation.	Percent of wheelpath with crack length ratio greater than 1.6 (when cracks are specified as Alligator B by Caltrans)	$y = 100 * (1 - e^{-\left(\frac{x}{a}\right)^{b}}$

Table 8.6. Traffic categories considered for the performance tree

Traffic Levels	ESALs/Lane/Year
Low (A)	Less than 100,000
Medium (B)	100,000 to 500,000
High (C)	More than 500,000

Table 8.7. HMA Surface thickness categories considered for the performance tree

Overlay	Thickness
Thin	Less than 0.2 ft (6 m)
Medium	0.2 to 0.5 ft (6 to 15 cm)
Thick	More than 0.5 ft (15 cm)

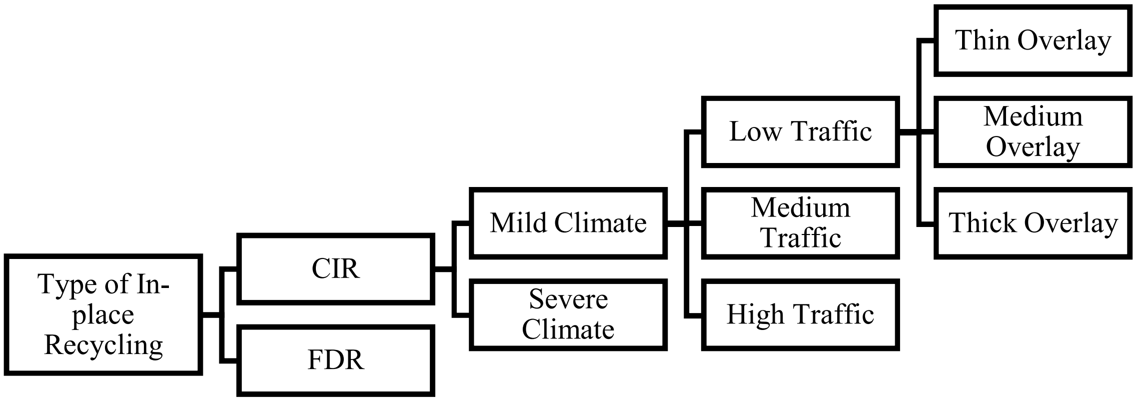


Figure 8.5: Representation of one of the performance model tree branches.

8.3.1. Cracking Models

The modeling of WPC is different from IRI as cracking is often a latent variable, which means that even though it is developing, it is not observed until it reaches the surface late in the crack development process. Structural deterioration of the pavement starts right after construction and is continuous under traffic load and climate impacts. As the pavement deteriorates, cracks start to form at the bottom of the HMA layer, however, these cracks will not appear on the pavement surface for a considerable amount of time. Even when cracking begins at the top of the HMA layer, it takes some time for the cracks to become wide enough to be measurable. On the other hand, surface roughness can be measured immediately after construction and a singular continuous model could be used for predicting future IRI values. Therefore, the WPC models developed under this study consist of two separate stages: models for determining the time to crack initiation (first cracks appearing on the surface) and models for predicting the propagation of additional cracks with time.

The method adopted for performance modeling was implemented in earlier efforts for developing WPC models for conventional treatments such as HMA overlays and seal coats (Madanat et al., 2005; Nakat et al., 2006; Farshidi and Harvey, 2008; and Tseng, 2012.) The collected data in this study for the sections built using in-place recycling represent time series observations of separate pavement sections, referred to as "panel data". These sections have different traffic levels, climate conditions, and overlay thicknesses. To develop models that takes into account the variability that exist in the parameters, mixed effect models were used in developing WPC models. Mixed effect models consider model parameters as random variables compared to fixed effects models in which parameters are fixed or non-random. Stata^{TM} software was used for running the analysis in this section (Stata webpage.)

WPC is measured separately for the right and left wheelpath by Caltrans and is quantified in terms of wheelpath crack length ratio, R_{WPC}, which is the ratio of total length of all wheelpath cracks to the length of data segment (Caltrans, 2011.) The dataset from Caltrans' PMS database report cracking in terms of percent of each section with Alligator A cracking and the percent of each section with Alligator B. Average values of Alligator B WPC for the right and left wheelpath were used for this study.

The WPC model consists of two parts, explained later: crack initiation and crack progression. Using a performance tree was deemed beneficial to facilitate combining these two models into one continuous form to be implemented in the final tool delivered by this project.

Crack initiation time was defined as the soonest of these two times after initial construction: 1) time when five percent or more of the section has alligator A cracking, or 2) time when alligator B cracking is greater than zero on the section. Survival analysis was used for estimating crack initiation time. It was assumed that crack initiation occurs at the time of median (50 percent of the sample have reached initiation) survival probability. The survival curves for CIR and FDR at different traffic levels are presented in Figure 8.6 and Figure 8.7 and the results of survival analysis are presented in Table 8.8 and Table 8.9. The survival curves in Figure 8.6 show that sections with higher traffic levels are expected to fail sooner than the other two categories of traffic, which was expected. This is due to lack of data for this section of analysis as CIR was not used for high traffic sections and this can be seen in the results presented in Table 8.8.

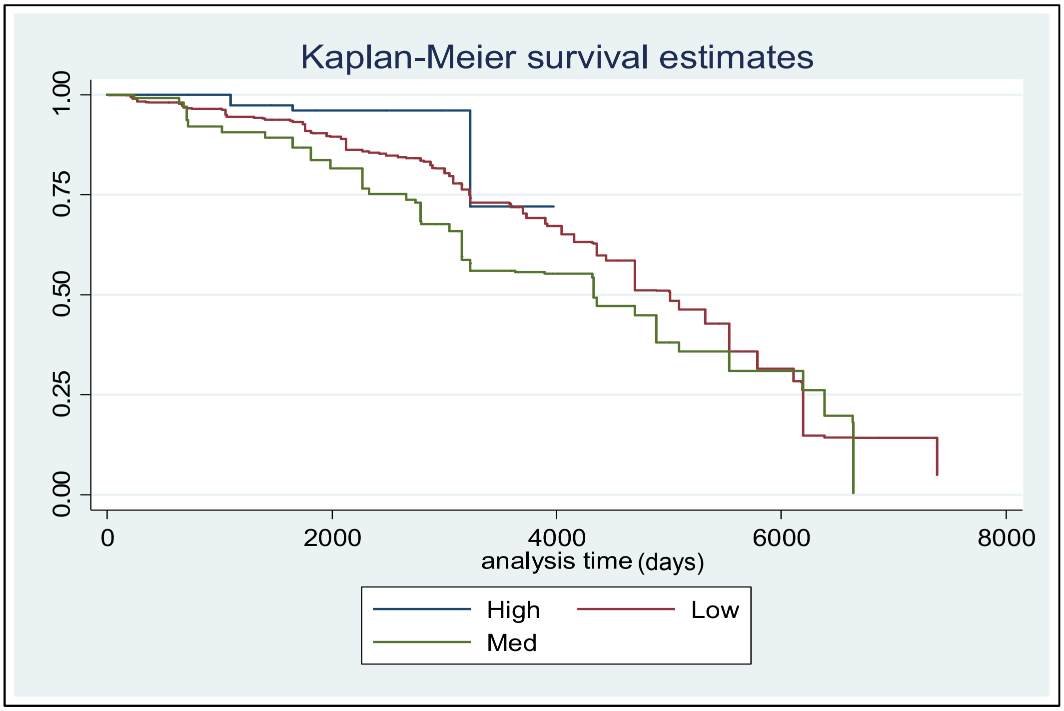


Figure 8.6: Survival curve for CIR sections (the legend refers to traffic levels) averaged across overlay thickness and climate regions.

Table 8.8. Survival analysis results for CIR sections (days to crack initiation)

ESALs	Time at risk	Incidence rate	no. of subjects	Survival time (days): 25%	Survival time (days): 50%	Survival time (days): 75%
High	78,926,208	0.0000148	57,441	-	-	-
Low	432,091,198	0.0001554	291,514	2,330	3,595	4,697
Med	49,575,317	0.0001791	36,738	2,658	2,791	4,359
Total	560,592,723	0.0001377	385,693	2,585	3,595	4,697

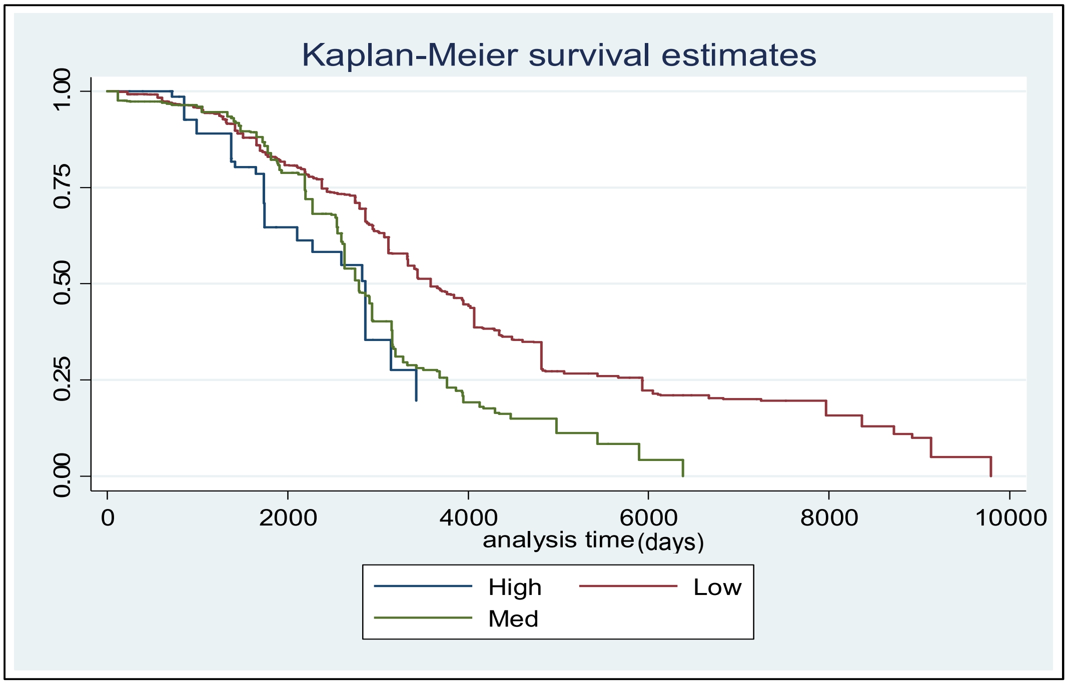


Figure 8.7: Survival curve for FDR sections (the legend refers to traffic level) , averaged across overlay thickness and climate regions.

Table 8.9. Survival analysis results for FDR sections (days to crack initiation)

ESALs	Time at risk	Incidence rate	no. of subjects	Survival time (days): 25%	Survival time (days): 50%	Survival time (days): 75%
High	26,189,705	0.0000240	16,185	1,734	2,860	3,421
Low	2,783,149,174	0.0001449	1,357,876	2,378	3,580	5,926
Med	500,862,801	0.0002010	281,799	2,185	2,791	3,766
Total	**3,310,201,680**	**0.0001541**	**1,655,860**	**2,378**	**3,400**	**4,862**

As stated earlier, WPC cracking is a latent variable. Therefore, possible data censorship, due to not knowing the value of WPC in places where it has not reached the surface yet need to be accounted for. To do this an incidental truncation term, lambda λ, was added to the crack progression stage. This correction term was added to address the possibility of the latent variable, WPC, being positive without being observed or measured. λ represents the possibility of crack initiation. To estimate λ, an ordered probit model was used assuming WPC to have three possible conditions: no cracking, alligator A, and alligator B. As explained earlier, details of statistical assumptions and theories for selection of modeling approaches are presented elsewhere (Madanat et al., 2005; Nakat et al., 2006; Farshidi and Harvey, 2008; and Tseng, 2012.)

Mixed effect logit models were used for crack progression. The Logit model was selected because the cracking index falls into three different categories as the section ages, and the mixed effects model was selected to accommodate the variability in the model parameters. The initial equation form and the transformations which were applied to change the equation into a linear form are presented in Equation 8.1. The transformation allowed use of linear regression on the data. Various combinations of possible explanatory variables were tested to determine the best possible model. The best possible model was a model that resulted in the highest accuracy (prediction of observed outcome based on input variables) and follow the expected trends (such as positive coefficient for the age variable.) Explanatory variables included λ, climate (a categorical variable represented by 1 for severe and 0 for mild), overlay thickness (in mm), traffic level (in ESALs), and previous alligator B extent before treatment.

$$Assuming\ y = 100 * \left(1 - e^{-\left(\frac{x}{a}\right)^{b}}\right), where\ y\ is\ WPC\ (\%)\ and\ x\ is\ time\ (days)$$

$$e^{-\left(\frac{x}{a}\right)^{b}} = 1 - \frac{y}{100}$$

$$-\left(\frac{x}{a}\right)^{b} = \ln\left(1 - \frac{y}{100}\right)$$

$$b * \ln\left(\frac{x}{a}\right) = \ln\left(-ln\left(1 - \frac{y}{100}\right)\right), therefore:$$

$$b * \ln x - b * lna = \ln(-\ln\left(1 - \frac{y}{100}\right)$$

Equation 8.1: Transformation applied to the original equation for WPCs.

The right-hand expression in the final equation (Equation 8.1) was considered as parameter z which is defined as linear combination of ln(age.) Mixed-effect linear regression models were tested on z versus ln(age.) To account for other explanatory variables, such as traffic and surface thickness, different combination of all the explanatory variables needed to be considered in each iteration. To develop a model with age as the only explanatory variable, other variables were included in combination with ln(age.)

Assuming a crack initiation time of t_0, crack initiation and progression can be combined as presented in Equation 8.2. Table 8.10 presents the final model that was selected for the CIR sections. As the results show, age, λ, traffic level, and total added overlay thickness are the significant factors affecting the performance of CIR sections. Previous alligator B level and climate region were not significant. Table 8.11 shows the best model for FDR sections. Traffic level, previous alligator B cracking, and climate condition were not significant factors in the final model, however, λ was a significant factor.

$$y = 100 * \left(1 - e^{-\left(\frac{(t-t_0)}{a}\right)^b}\right) * if(\frac{t}{t_0} \geq 1, 1, 0)$$

$where:$

$y = \; \%\, Alligator\ B\ cracking\ in\ the\ section$

$t = time\ in\ days$

$t_0 = crack\ initiation\ time\ in\ days\ where\ initiation,$

$\quad defined\ by\ 5\ percent\ Alligator\ A\ or\ any\ measurable\ Alligator\ B$

Equation 8.2: Combination of crack initiation and progression models.

To combine crack initiation and progression, the progression curves begin at the point on the horizontal axis (age) at which crack initiation is predicted. Figure 8.8 and Figure 8.9 show the performance curves for CIR and FDR. The model does not identify whether cracking is through the entire CIR or FDR layer as well as the overlay, or in the overlay alone. Regarding crack initiation, CIR performs quite similarly as FDR, however, CIR sections deteriorate quite rapidly after crack initiation while FDR sections show slower crack propagation. As would be expected, results show that sections with higher traffic levels have a higher rate of deterioration. Similarly, for the same level of traffic, thicker overlays result in lower rates of cracking with time. WPC performance curves for conventional options: thin, medium, and thick asphalt overlays are also provided here as Figure 8.10, Figure 8.11, and Figure 8.12, using models from Tseng (2012.)

The only cases that do not follow the expected trends for CIR are: 1) traffic level B with medium overlay which performs worse than traffic level B and thick overlay, and 2) thick overlay with traffic level B which performs worse than thick overlays with traffic level C. FDR curves also follow the expected trends except for two cases: 1) traffic level B with thin overlay performs better than traffic level B with medium overlay and 2) traffic level A for thin overlays shows worse performance compared to medium and thick overlays. Such cases are due to limitations in the number of observation records for such cases and in some situations were due to the low quality of collected data as there were unreasonable trends observed such as improvement of performance indexes with time without any surface treatments, likely due to unrecorded maintenance, or there was significant variability in the available data. As future APCS are conducted and more reliable data become available, these models can be improved.

Table 8.10. Descriptive statistics of final WPC model for CIR, with the confidence intervals (CI) and significance level of the parameters

z	Coef.	Std. Err.	z	P>|x|	95% CI lower limit	95% CI higher limit
“lnage”	1.797321	0.062065	28.96	0	1.67574	1.91896
“lambdalnage”	0.573032	0.024017	23.95	0	0.52823	0.62237
“lnesalslnage”	0.078876	0.005549	14.21	0	0.06799	0.08975
“total_added_thicknesslnage”	-0.002343	0.000289	-8.08	0	-0.0029	-0.0018
cons	-21.08975	0.400718	-52.63	0	-21.875	-20.304

z	Coef.	Std. Err.	z	P>|x|	95% CI lower limit	95% CI higher limit
Random-effects Parameters	**Estimate**	**Std. Err.**	**95% CI lower limit**	**95% CI higher limit**		
sd (cons)	1.42266	0.05548	1.31797	1.53566		
sd (Residuals)	0.78187	0.00203	0.77801	0.78851		

Table 8.11. Descriptive statistics of final WPC model for FDR, with the confidence intervals (CI) and significance level of the parameters

z	Coef.	Std. Err.	z	P>|x|	95% CI lower limit	95% CI higher limit
"lnage"	1.159264	0.0070786	163.77	0	1.14539	1.17314
"lambdalnage"	0.6306005	0.0034349	183.59	0	0.62387	0.63733
"total_added_thicknesslnage"	-0.0003864	0.0000434	-8.89	0	-0.0005	-0.0003
cons	-13.08842	0.052407	-249.75	0	-13.191	-12.986
Random-effects Parameters	**Estimate**	**Std. Err.**	**95% CI lower limit**	**95% CI higher limit**		
sd(cons)	1.51566	0.01775	1.48126	1.55087		
sd(Residuals)	0.702703	0.0007	0.70132	0.70408		

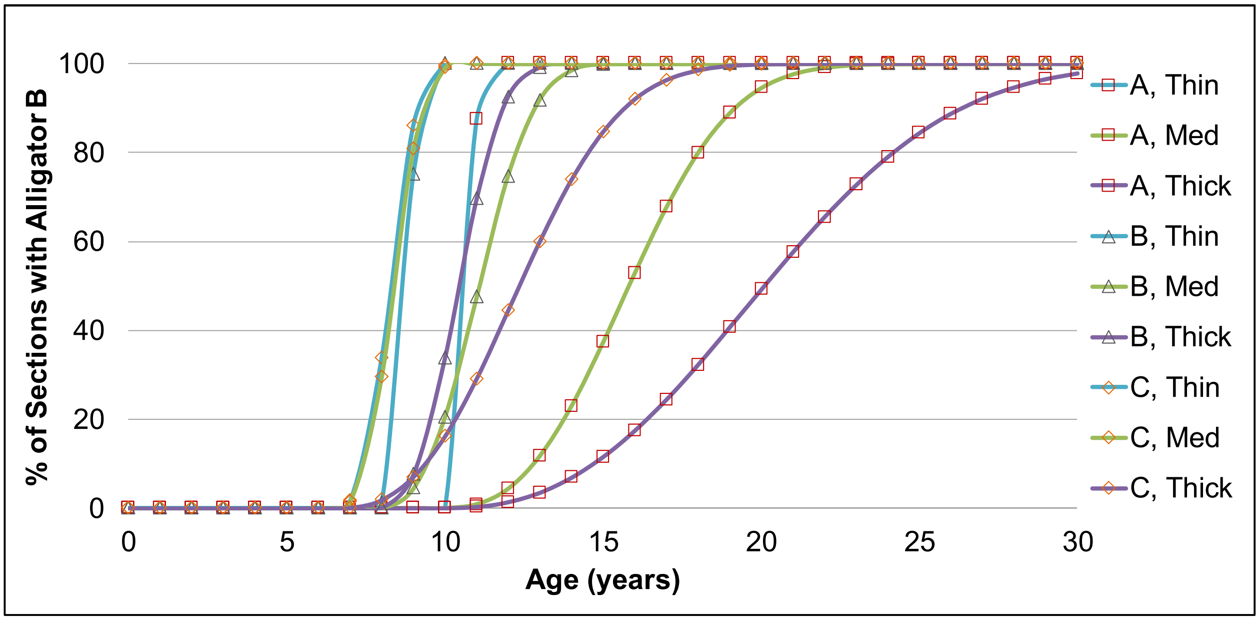


Figure 8.8: Crack initiation and progression models combined for CIR sections (A, B, C refer to low, medium, and high traffic levels; Thin, Med, and Thick refer to surface thickness category.)

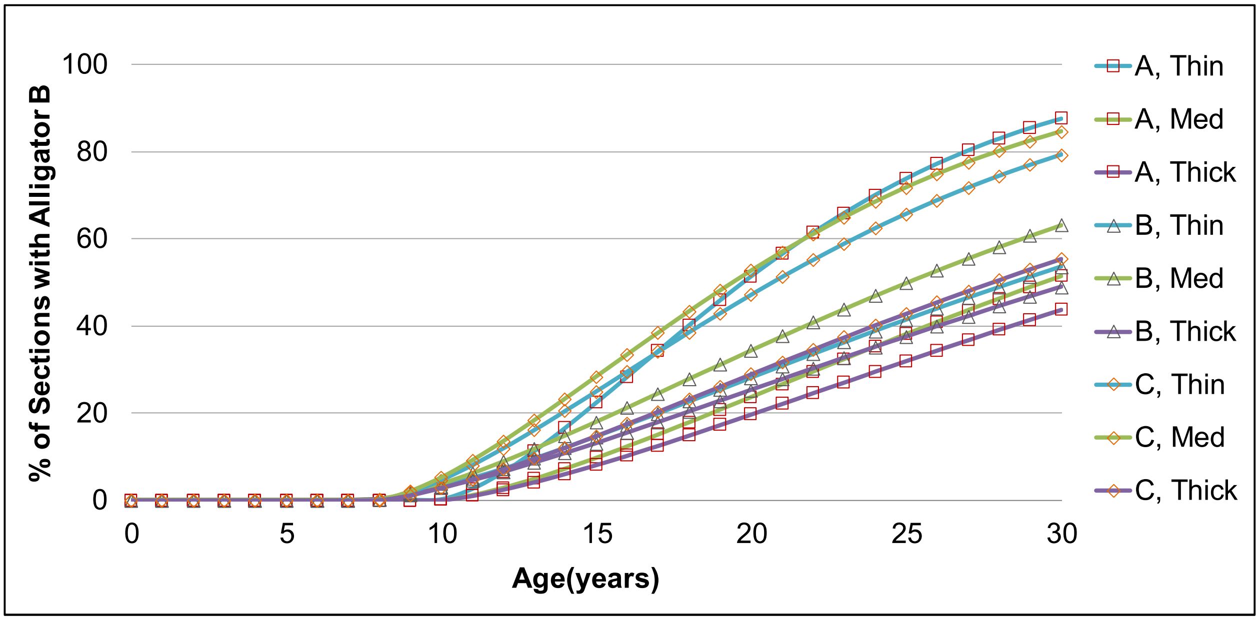


Figure 8.9: Crack initiation and progression models combined for FDR sections (A, B, C refer to low, medium, and high traffic levels.)

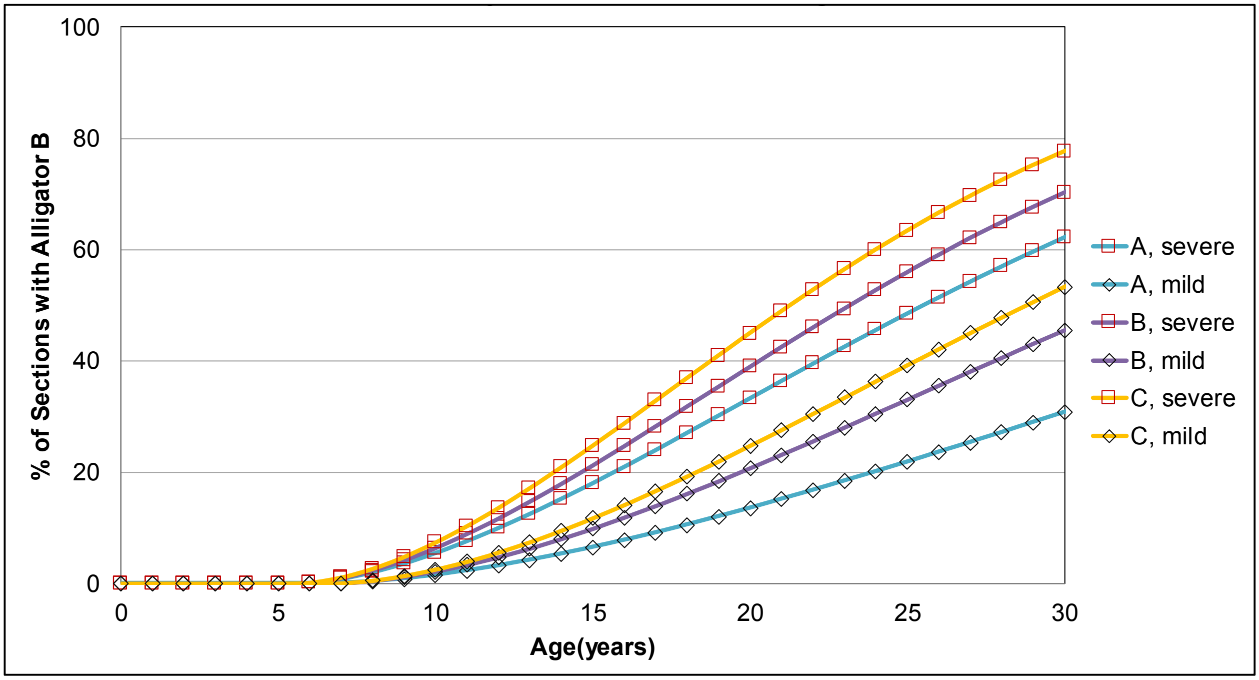


Figure 8.10: Crack initiation and progression models combined for conventional “Thin Overlay” sections (A, B, C refer to low, medium, and high traffic levels.)

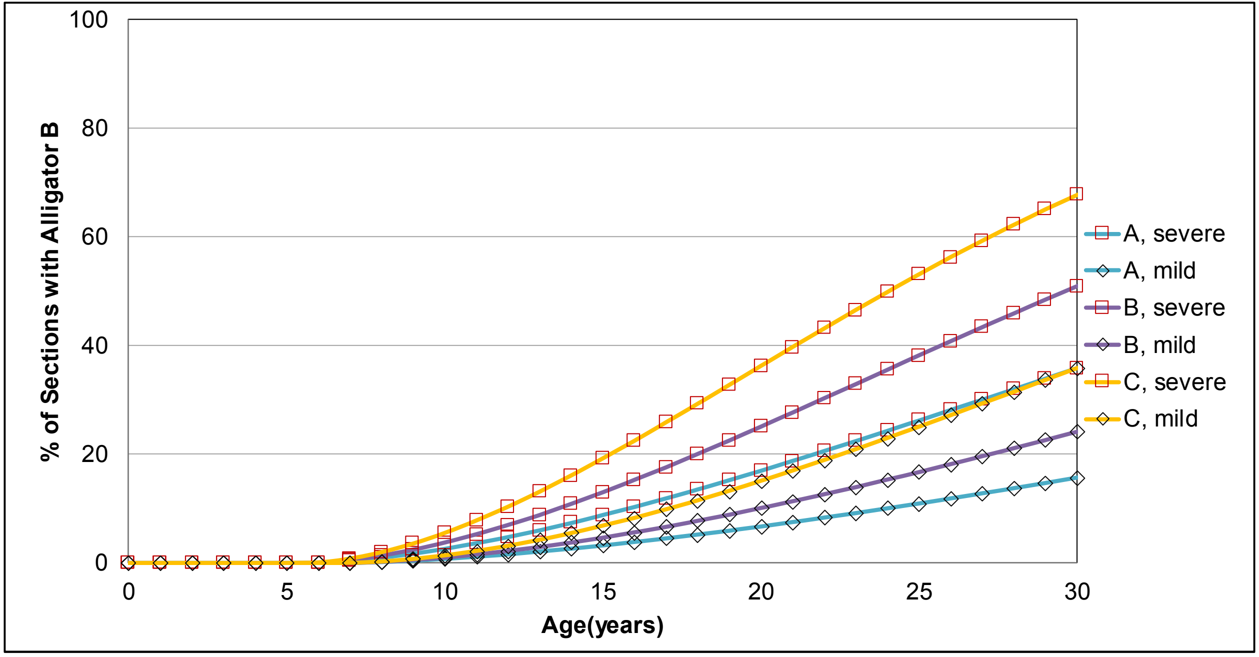


Figure 8.11: Crack initiation and progression models combined for conventional "Medium Overlay" sections (A, B, C refer to low, medium, and high traffic levels.)

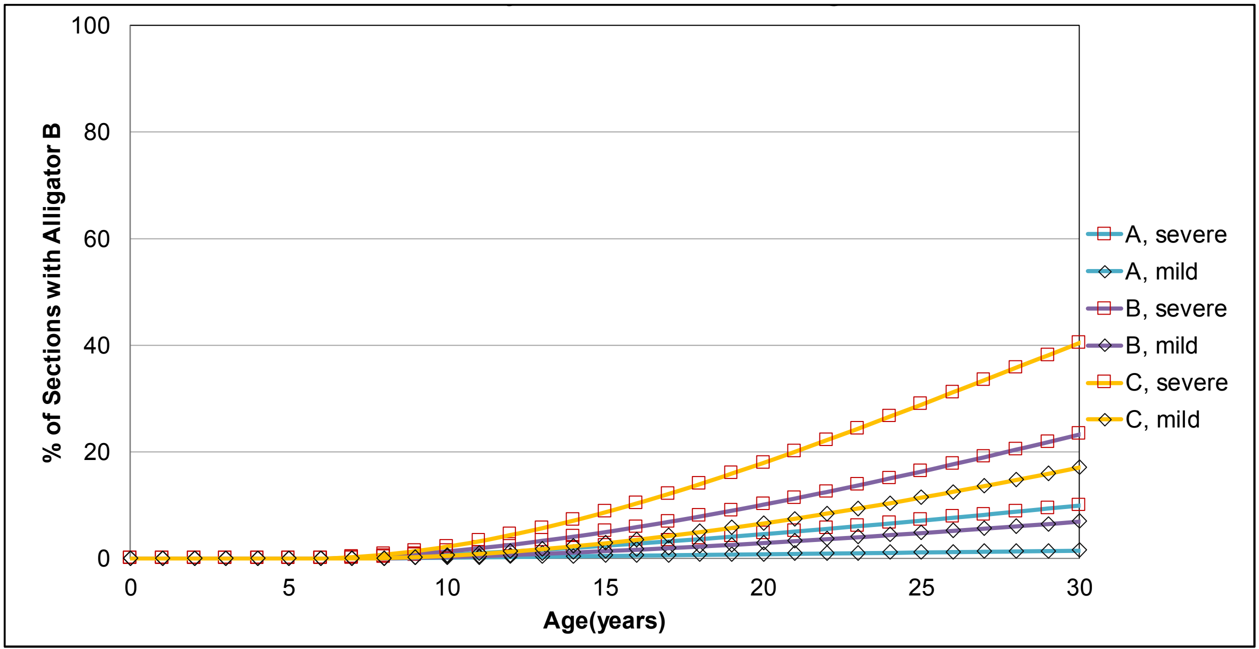


Figure 8.12: Crack initiation and progression models combined for conventional "Thick Overlay" sections (A, B, C refer to low, medium, and high traffic levels.)

8.3.2. Roughness Models

The filtered data frames were used for derivation of IRI models for CIR and FDR. As the analysis consists of cross-sectional data of pavement network across time (panel data), mixed effect linear regression was selected, and Stata software was used for model development.

The first step in the model development was to check if there is a significant difference in IRIs before and after treatment and if yes, how much is the reduction. This would allow determining the initial IRI after construction which combined with the IRI progression model would provide a complete picture of the use stage performance of the section. Student's unpaired t-test was conducted for this purpose which showed that CIR treatments significantly reduced IRI, with an average IRI reduction of 78 in/mi. The same procedure was adopted for FDR sections and the results showed that FDR result in an average reduction of 91 in/mi in average.

Determining the initial IRI after the end of construction requires two parameters: the average reduction in IRI due to surface treatment, and the IRI value prior to the construction. However, to accommodate cases where the IRI prior to construction is unknown, average values of initial IRI were calculated using the collected data. Average IRI after construction for CIR section was 90 in/mi, for FDR with no stabilization was 92 in/mi, and for FDR with foamed asphalt stabilization was 72.5 with standard deviations of 3.7, 3.3, and 5.7, respectively.

Various combinations of explanatory variables (age, thickness, traffic levels, climate; both in logarithmic and regular formats for numerical values) were tested in Stata to select the most appropriate model based on significance of explanatory variables in the model and the model accuracy in minimizing errors. For both CIR and FDR, average IRI (iri_avg) was regressed as the dependent variable versus multiple combinations of age, ESAL/lane/year, previous IRI, and climate as independent (explanatory) variables, and natural logarithm transforms of the explanatory variables were also tested to identify the best model. The analysis was weighted based on the length of subsections. Table 8.12 through Table 8.14 show the results for CIR, FDR with no stabilization and FDR with foamed asphalt. The models for each are shown in Equation 8.3, Equation 8.4, and Equation 8.5. The data are also summarized in Table 8.15.

Table 8.12. IRI performance model for CIR

Explanatory Variable	Coefficient	Standard Error	z	P>|x|	95% CI lower limit
age	-0.003304	0.000212	-15.6	0	-0.00372
agelnesals	0.008695	0.000018	49.91	0	0.00086
agesevere	0.004013	0.000091	44.08	0	0.00383
agethick	-3.52E-06	7.00E-07	-5.21	0	-4.85E-06
_cons	90.447512	3.707305	24.4	0	83.18133
Random-effects Parameters	**Estimate**	**Standard Error**	**95% CI lower limit**	**95% CI higher limit**	
sd(cons)	38.16008	2.63411	33.33132	43.6884	
sd(Residuals)	18.42575	0.02048	18.38564	18.46595	

Log Likelihood	-1,753,438
Number of observations	404,588
Number of groups	106
Obs. per group: min	12
Obs. per group: avg	3816.9
Obs. per group: max	23,926
Wald chi2(4)	39,329.58
prob>chi2 =	0

$$IRI = b_0 + b_1 * \ln(ESALs) * age + b_2 * severe * age + b_3 * thickness * age + \ b_4 * age$$

$$IRI\ \left(\frac{in}{mi}\right), ESALs\ (per\ lane\ per\ year),\ \ thickness\ (mm), age\ (days)$$

$$severe = 1\ if\ climate\ condition\ is\ severe$$

Equation 8.3: Performance model for IRI progression of CIR sections.

Table 8.13. IRI performance model for FDR with no stabilization

Explanatory Variable	Coefficient	Standard Error	z	P>|x|	95% CI lower limit	95% CI higher limit
age	0.001398	0.00065	2.13	0.033	0.00011	0.00268
agelnesals	0.00062	0.00006	10.53	0	0.0005	0.00074
_cons	92.49978	3.349089	27.62	0	85.93568	99.06387
Random-effects Parameters	**Estimate**	**Std. Err.**	**95% CI lower limit**	**95% CI higher limit**		
sd(cons)	32.19054	2.37182	27.86192	37.19166		
sd(Residuals)	24.46876	0.06486	24.34196	24.59622		

Log likelihood	-329,186.7
Number of observations	7,1246
Number of groups	93
Obs. per group: min	51
Obs. per group: avg	765.7
Obs. per group: max	7
Wald chi2(4)	3,201
prob>chi2 =	0

$$IRI = b_0 + b_1 * \ln(ESALs) * age + b_2 * age$$

Equation 8.4: Performance model for IRI progression of FDR-NS sections.

Table 8.14. IRI performance model for FDR with foamed asphalt stabilization

iri_avg	Coef.	Std. Err.	z	P>|x|	95% CI lower limit	95% CI higher limit
age	0.00804	0.00046	17.49	0	0.00714	0.00894
_cons	72.5212	5.75562	12.6	0	61.2404	83.802
Random-effects Parameters	**Estimate**	**Std. Err.**	**95% CI lower limit**	**95% CI higher limit**		
sd(cons)	20.5861	4.06797	13.9756	30.3234		
sd(Residuals)	21.328	0.27379	20.798	21.8714		

Log likelihood	-13679.9
Number of observation	3,047
Number of groups	13
Obs. per group: min	37
Obs. per group: avg	234.4
Obs. per group: max	546
Wald chi2(4)	305.98
prob>chi2 =	0

$$\boxed{IRI = b_0 + b_1 * age}$$

Equation 8.5: Performance model for IRI progression of FDR-FA sections.

Table 8.15. Summary of IRI models for CIR and FDR sections

Type	b_0	b_1	b_2	b_3	b_4
CIR	9.04E+01	8.97E-04	4.10E-03	-3.50E-06	-3.30E-03
FDR-NS	9.25E+01	6.20E-04	1.40E-03	--	--
FDR-FA	7.25E+01	8.04E-03	--	--	--

8.4. Conclusions

In this chapter, performance prediction models for IRI and WPC of in-place recycling were developed. These models are needed to quantify the environmental impacts of the use stage, which consists of two parts, vehicle fuel consumption, and frequency of future maintenance and rehabilitation of the pavement during its service life.

Roughness which is measured in IRI directly affects vehicle fuel economy and crack progression with time determines the frequency of future M&R. To develop these models, SQL queries were conducted on the California pavement management system, PaveM, and data related to sections that had in-place recycling were collected. After extensive data cleaning, empirical-mechanistic models were fit to the data. IRI progression equations were determined by multivariate regression analysis. The crack progression model consisted of two parts, crack initiation and crack progression. To determine the time to crack initiation, survival models were used, and for crack progression, random effect mixed models were utilized.

In terms of time until crack initiation, the results show that sections with CIR have a similar time to crack initiation as the sections with FDR. However, in crack progression, CIR sections deteriorate at a much faster rate compared to FDR sections after cracks appear on top. Therefore, all CIR savings in GHG emissions and energy consumption during the construction stage compared to FDR may be offset by more frequent M&R in the future. Similar crack progression models exist for conventional EOL alternatives.

Roughness models for FDR and CIR sections were also developed. FDR sections with no stabilization had the worst performance and highest rate of increase in roughness with time, while FDR sections stabilized with foamed asphalt performed better than the CIR sections and consistently maintained lower IRI values with time.

The development of crack progression and roughness models for CIR and FDR sections in this chapter, which did not exist up to this point, allows quantitative comparison of EOL alternatives for flexible pavements therefore the means necessary for quantifying the use stage impacts in LCA. As always, there is no solution that fits all cases, and the optimal decision is context sensitive. The selection of one treatment among all available alternatives depends on circumstances (traffic levels, climate, and structural design), agency goals (only considering costs or both costs and environmental impacts), scope and analysis period considered for the project (initial costs and impacts versus full life cycle), and potential limitations (in terms of budget, available technologies, and more.)

CHAPTER 9. Summary, Conclusions, and Recommended Future Work

9.1. Introduction

The main goal of this dissertation was to develop frameworks, quantitative models, and databases needed to support data-driven, informed, and integrated decision-making in managing the vast transportation infrastructure in California. Such a management system was envisioned to consider both costs and environmental impacts of management decisions, based on full life cycles of the infrastructure, and using reliable, high quality data that well represent local conditions in terms of materials and energy sources, production technologies, design methods, construction practices, and other critical parameters.

Various approaches were used in the studies included in this dissertation to be able to overcome uncertainty in assumptions, parameters, and challenges in data (availability, quality, variability.)

9.2. Knowledge Gaps and Research Objectives

The major gaps in the knowledge identified at the beginning of this effort were:

- Integration of environmental impacts into the infrastructure management system requires a reliable and representative life cycle inventories of different materials, surface treatments, and construction activities used in the state of California. The available datasets generally did not include a comprehensive list of all available options, were outdated, and were not representative of the local conditions in terms of processes, mix designs, and energy sources.
- Frameworks and models needed by state and local governments quantify the life cycle costs and environmental impacts of their decisions in transportation infrastructure management did not cover some important areas of their operations. Without such frameworks and data models, state and local governments could not properly evaluate all their strategies.
- There were limited and unreliable data for quantifying the environmental impacts of end-of-life strategies for flexible pavements. Such models were needed to select among conventional and novel approaches that are believed to more beneficial in terms of costs and environmental impacts.
- There were no reliable performance prediction models for pavements built from recycled materials. Therefore, it was unclear whether such sections perform better, equally, or worse compared to conventional strategies. If the performance of recycled sections is worse, compared to conventional methods, the potential savings in environmental impacts due to recycling may be offset by the need for more frequent maintenance and rehabilitation in the future compared to conventional strategies.
- A similar argument can be made regarding the surface roughness and how it would change with time because roughness directly affects vehicle fuel consumption during the use stage. Roughness performance models for sections built using in-place recycling were also not available.
- There was no consensus on how to allocate the environmental impacts and benefits of recycling between the upstream and the downstream projects.

Therefore, the main objectives of this research were defined according to the gaps identified above, to develop frameworks, models, and datasets needed to fill each gap.

9.3. UCPRC LCI Database

Through one of the research projects in this dissertation, the most comprehensive and up to date, as of 2019, life cycle inventory database, the UCPRC LCI Database, was developed for accurate quantification of transportation infrastructure management projects in the state of California. This database includes an extensive list of all the energy sources, materials, mixes, transportation modes, and construction processes used in the projects at state and local government levels.

The electricity grid mix and other energy sources used in various life cycle stages are modified to represent the state's local conditions. Mix designs are defined based on specifications enforced by Caltrans and also cover designs used by local governments. Construction practices are closely simulated based on data collected from local contractors and experts in addition to the collection of primary data collection from a few field projects. The LCI database developed and presented in this chapter has been verified by a third party according to ISO recommendations.

The UCPRC LCI Database needs to be continually reviewed and periodically updated because of the continuous improvements in material production technologies, construction practices, and energy sources used for generating electricity and running the material plants, as well as improvements in data collection. The revision and update process for the UCPRC LCI Database should be repeated every few years using the latest available information. However, the most critical measure that can be taken to improve the quality of the data is to collect primary data from local material production plants and contractors.

9.4. Complete Streets

This project demonstrated the use of LCA to consider the full life cycle environmental impacts of conversion of several types of conventional streets to complete streets. The full system impacts of complete streets on environmental impact indicators, considering materials, construction, and traffic changes, are driven by changes in reduction in VMT and changes in the operation of the vehicles with regard to speed and drive cycle changes caused by congestion, if it occurs. Therefore, the importance of objective and reliable models for changes in traffic volume and congestion from the implementation of complete streets and comparison with conventional streets cannot be overstated.

To avoid situations where well-intended efforts might result in greater environmental impacts, utilization of life cycle assessment should be used as a robust and objective methodology that consider the full life cycle of the alternatives. Each LCA study should use 1) high-quality data, 2) a correct definition of the system boundary, and 3) include a thorough investigation, identification, and quantification of possible significant unintended consequences.

The initial results indicate that application of the complete streets networks to streets where there is little negative impact on vehicle drive cycles from speed change will have the most likelihood of causing overall net reductions in environmental impacts.

The results also indicate that there is a range of potential VMT changes to which environmental impacts are more sensitive than they are to the effects of the materials and construction stages, and that changes in vehicle speed have different effects on environmental impacts depending on the context of their implementation, including the street type.

The effects on environmental impacts due to implementing a complete street should be analyzed on a project-by-project basis, and that the effects will not always be positive. This preliminary conclusion leads to recommendations that this type of analysis be performed on a project-by-project basis, that the analysis include the surrounding network, and that a sensitivity analysis should also be included.

The main limitation of this study was the lack of a reliable model for predicting changes in VMT and traffic speed. Another issue that was not within the scope of this study was the consequential changes in areas outsides the physical system boundary. Energy consumption for lighting and maintaining the landscapes during the use stage was also not included in the study. Future works should focus on the limitations identified above, specifically the lack of reliable models for changes in VMT and traffic speed.

9.5. Alternative Fuel Vehicles

This study was focused on comparing multiple pathways (scenarios) for Caltrans to transition their fleet from vehicles with internal combustion engines burning fossil fuels to alternative fleet vehicles (AFVs.) Four scenarios were considered based on AFV adoption rate including business as usual (BAU), all-at-once, based on the Department of General Services (DGS) recommendations, and a worst-case scenario (do nothing, keep the current mix.) The project compared the life cycle greenhouse gas (GHG) emissions, fuel consumption, and costs of vehicle purchase and maintenance between 2018 to 2050.

The results showed a total life cycle costs of 2.4 billion dollars for the BAU case with 7.4 and 3.3 percent increases versus BAU for the DGS and All-at-Once cases, and a 16.9 percent decrease for the Worst-Case Scenario. Purchase of new vehicles was the largest portion of total net costs for all four cases, ranging between 59 to 83 percent of final net total costs. Fuel costs were the second largest expense items for all cases, ranging between 30 to 35 percent of total net costs. Maintenance and repair on average made up about 24 percent of total net costs.

Total GHG emissions during the analysis period of 2018 to 2050 reached close to 1.46 million metric tonnes of CO_2e for the BAU case while the results for the DGS, All-at-Once show savings of 2 and 9 percent in total GHG emissions versus BAU for the DGS and All-at-Once scenarios. The Worst-Case Scenario results show that consequences of inaction in the adopting AFVs by Caltrans and maintaining the current mix of vehicle technology and fuel will result in 54 percent increase in the GHG footprint of their fleet between now and the year 2050.

The study did not include the cost and environmental impacts of building and maintaining fueling infrastructure for any of the fuel types considered in the analysis. Maintenance and upkeep of parking spaces for the fleet were also not included in the system boundary of the study.

California is aggressively moving towards decarbonization/minimization of GHG emissions in all its economic sectors, specifically the electricity sector with measures such the Renewable Portfolio Standard (CPUC webpage on RPS) which mandates 50 percent renewable electricity in California grid mix by 2030. Therefore, one fuel pathway which is expected to have major reductions in WTP impacts is electricity. However, these expected reductions in WTP were not implemented in this study, mainly due to the limited scope of this initial study. However, the fact that more than 80 percent of the state fleet consists of medium-duty pickups and trucks for which an EV option is not currently available reduces the significance of this issue, at least for the immediate future.

Due to current technological limitation for the range of EVs, conversion to EVs was not considered as an option for vehicles that had AVMT higher than typical current EV ranges. However, EV ranges are expected to increase in the future but due to uncertainty regarding the rate of range increase, it was not considered in this study.

Future work should consider more diverse portfolio of AFVs for different vehicle categories and also include cleaner electricity grid that will power the electric vehicles.

9.6. Increased Use of RAP in Construction Projects

This chapter focused on quantifying savings in greenhouse gases (GHG), energy, material consumption, and costs that might be possible through increased use of recycled asphalt pavements (RAP) in construction projects in California. The material production impacts of hot mix asphalt (HMA) in Caltrans construction projects throughout the state during the entire analysis period of 33 years (2018 to 2050) results in close to 11.5 Million Metric Tonnes (MMT) of CO_2e for the baseline scenario. RHMA production impacts within the same time period is about 15.2 MMT CO_2e. RHMA is responsible for about 44 percent of the combined GHG emissions of HMA and RHMA.

The use of RAP is currently not permitted in RHMA mixes, use of RAP in RHMA is a significant untapped area for cutting emissions if it becomes technically possible to obtain same performance.

Increasing the RAP content in HMA from the baseline of the 11.5 percent can result in up to a 6 percent of GHG savings with 30.5 percent RAP content during the 33-year analysis period, when using aromatic BTX rejuvenating agents (RAs.) These reductions are equivalent to 0.7, 5.2, 6.2 percent reductions in GHG emissions compared to the baseline. The potential saving can be as high as 9 percent when bio-based RA is used.

Increasing RAP content in HMA can also result in cost savings of up to 9 percent reduction compared to the baseline.

There are existing concerns, however, regarding the performance of HMA with higher RAP content. This study was conducted assuming similar performance during the use stage across all the scenarios. Decreases in performance can result in more frequent maintenance and rehabilitation needs in the future. Higher surface roughness due to poor performance can cause in an increase in vehicle fuel consumption. These issues can result in not only offsetting the original savings due to use of higher RAP content, but also causing higher environmental impacts compared to the base scenario.

Therefore, further research is needed for investigating the performance of HMA with higher than 15 percent RAP content, and also RHMA with RAP. The research findings would allow design guidelines to be developed and unintended consequences, that can arise from good intentions, to be avoided.

Allocating the environmental impacts of recycled materials between the upstream (which used the virgin material and is the source of current recycled materials) and the downstream project (which uses the recycled materials) is a pending challenge. There is currently no consensus on how to handle the issue of allocation and tow common methodology currently in use are the 50-50 and the cut-off methods. In the cut-off method, the impacts of virgin material production are assigned to the upstream project and the downstream project is responsible for the recycling process impacts. In the 50-50 method, the total impacts (virgin material production, the recycling process at the end of service life and possible hauling to the treatment plant) are divided equally between the upstream and downstream project. To understand the impact of the allocation methodology on the impacts of material production assigned to HMA with RAP, the LCA of material production for the cases defined in the first part of this chapter was calculated using both the 50-50 and the cut-off methods and the results were compared. The sensitivity of the results to the hauling distances considered for the RAP materials was also investigated.

The results show that GWP of HMA with RAP using the cut-off method is consistently lower compared to GWP HMA with RAP using the 50-50 method. Increased RAP hauling distances results in increased GWP of HMA under both allocation methods compared to HMA with virgin materials, with a more dramatic increase when the cut-off method is used. For hauling distances above 50 miles, there are cases where GWP of 1 kg of HMA with RAP will be higher than HMA with virgin materials (depending on the values of other input parameters.) The cases where the use of virgin materials results in less GWP compared to the use of RAP for the cut-off method all have hauling distance of 100 miles with RAP binder recovery of 50 or 60 percent. Binder recovery is the portion of the binder in the RAP that blends with the virgin binder in the mix to create the final binder content. Binder recovery is increased for longer and hotter mixing and silo storage times, and for RAP binders that are less aged. For the 50-50 method, binder recovery ratios of 60 percent and above, with hauling distances of over 100 miles, resulted in lower GWP for HMA with virgin materials compared to HMA with RAP. The binder recovery ratio threshold that results in lower GWP for HMA with virgin materials compared to HMA with RAP decreases with shorter hauling distances.

This section of the study was limited to comparison of allocation methodologies for EOL treatments. Due to these limitations, no recommendation is made in terms of what allocation methodology should be implemented in similar studies. Future studies should cover a more comprehensive system boundary and consider more allocation methodologies.

9.7. LCA Benchmarking of EOL Alternatives

This study was conducted to benchmark the environmental impacts of several EOL treatments used in California for flexible pavements at their end of service life. The system boundary consisted of material production, transportation to the site and construction activities that together make up the EOL treatment. The system boundary did not include other life cycle stages such as use stage, future maintenance and rehabilitation, and traffic delays during construction activities. Ten treatments were studied, consisting of eight in-place recycling alternatives (CIR and FDR with different stabilization methods and wearing courses on top) and two conventional treatments (HMA overlay and HMA mill-and-fill.)

The results show that the material production stage is dominant in all impact categories for all treatments. The results also show that the total amount of stabilizer added (which depends on percent stabilizer and the layer thickness) has a significant impact on the total impacts. HMA overlay and HMA mill-and-fill, have lower impacts compared to all the FDR options with stabilizers across all impact categories. Binder and stabilizer production caused more than 90 percent of the total impacts of the material production across all cases.

The study also examined the sensitivity of the results to the transportation distance of the virgin materials. The results showed that changing the transportation distance has an important effect on total impacts of conventional treatments. This was already expected, as conventional treatments require the largest amount of materials transported.

Comparing the CIR with stabilizers and HMA overlay with the conventional treatment of an HMA overlay shows that total GWP of the two options are close with the conventional treatment performing slightly better. This remains true up to transport distance of 80 miles (two-way) for the virgin materials, at which point the impacts of the two options become equal. For longer hauling distances the CIR outperforms the conventional treatment.

Similar comparison of FDRs with conventional mill-and-fill resulted in very long transport distances for virgin materials at which the impacts of the two treatments become equal. The transport distances were all above 150 miles. At shorter hauling distances, conventional treatments had lower impacts.

There are large differences between the initial impacts of the treatments in each impact category but due to limited scope of this stage and the fact that the system boundary does not include all life cycle stages, comparison of the results shall not be used as basis for decision making and selecting between alternatives. Such decision making requires a study that include the full life cycle of all the alternatives considering the results of this chapter combined with the use stage impacts of each alternative when calculated through models discussed in the next chapter. There are unsolved questions regarding the use stage that need to be addressed:

- How does pavement surface roughness, which directly affects vehicle fuel consumption, change with time under each treatment?

- What is the extension of life in terms of cracking, that determines future maintenance and rehabilitation frequency and the section service life, differ between alternatives?

9.8. Performance Prediction Models

In this chapter, performance prediction models for IRI and WPC of in-place recycling were developed. These models are needed to quantify the environmental impacts of the use stage, which consists of two parts, vehicle fuel consumption, and frequency of future maintenance and rehabilitation of the pavement during its service life.

Roughness which is measured in IRI directly affect vehicle mpg and crack progression with time determines the frequency of future M&R. To develop these models, SQL queries were conducted on the California pavement management system, PaveM, and data related to sections that had in-place recycling were collected. After extensive data cleaning, mechanistic-empirical models were fit to the data. IRI progression equations were determined by multivariate regression analysis. The crack progression model consisted of two parts, crack initiation and crack progression. To determine the time to crack initiation, survival models were used, and for crack progression, random effect mixed models were utilized.

In terms of time until crack initiation, the results show that sections with CIR have a similar time to crack initiation as the sections with FDR. However, in crack progression, CIR sections deteriorate at a much higher rate compared to FDR sections after cracks appear on top. Therefore, all CIR savings in GHG emissions and energy consumption during the construction stage compared to FDR may be offset by more frequent M&R in the future. Similar crack progression models exist for conventional EOL alternatives.

Roughness models for FDR and CIR sections were also developed. FDR sections with no stabilization had the worst performance and highest rate of increase in roughness with time, while FDR sections stabilized with foamed asphalt performed better than the CIR sections and consistently maintained lower IRI values with time.

The development of crack progression and roughness models for CIR and FDR sections in this chapter, which did not exist up to this point, allows a fair comparison of EOL alternatives for flexible pavements by providing the means necessary for quantifying the use stage impacts and including them in the analysis. As always, there is no solution that fits all cases, and the optimal decision is context sensitive. The selection of one treatment among all available alternatives depends on circumstances (traffic levels, climate, and structural design), agency goals (only considering costs or both costs and environmental impacts), scope and analysis period considered for the project (initial costs and impacts versus full life cycle), and potential limitations (in terms of budget, available technologies, and more.)

Some other thoughts, that are currently not included in the scope of this project but can be investigated through lab/field tests and scenarios analysis, are:

- What is the damage level of the recycled layer when the surface layer fails?
- How many times can the surface be replaced before the underlying recycled layer needs to be treated?

- Is there a difference in recyclability of a new pavement at its EOL versus a section that is built using any of the conventional rehabilitation techniques?
- How many times can a recycling strategy be repeated on the same section? and do the construction activities change with subsequent recycling?
- If the material quality changes with each subsequent recycling, how should the impacts be allocated between the current and future recycling processes?
- Does consequent recycling have a detrimental impact on the pavement performance? Is the same performance model applicable to a section recycled once and a section that that has been recycled multiple times?
- Should the LCA consider repeated use of the same treatment or are there paths in the analysis period in which different alternative should be considered?

REFERENCES

AFDC webpage on AFVs. https://afdc.energy.gov/vehicles/search/. Last accessed on 16 Apr 2020.

AFDC webpage on EPAct. https://afdc.energy.gov/files/pdfs/2527.pdf. Last accessed on 16 Apr 2020.

AFDC webpage on EPAct History. https://afdc.energy.gov/files/u/data/data_source/10355/10355_epact_state_fp_vehicle_history.xlsx. Last accessed in May 2019.

AFDC webpage on Fuel Prices. https://afdc.energy.gov/fuels/prices.html. Last accessed on 16 Apr 2020.

Alkins, A. E., Lane, B., and Kazmierowski, T. 2009. Sustainable Pavements: Environmental, Economic, and Social Benefits of In-Situ Pavement Recycling. **Transportation Research Record: Journal of the Transportation Research Board, No. 2084(1).** Washington, DC: Transportation Research Board of the National Academies. pp 100-103.

ANL webpage on AFLEET. https://greet.es.anl.gov/afleet_tool. Last accessed on 16 Apr 2020.

ANL webpage on GREET. https://greet.es.anl.gov/. Last accessed on 16 Apr 2020.

ARRA. 2014. **Recommended Construction Guidelines for Cold In-place Recycling (CIR) Using Bituminous Recycling Agents.** Annapolis, MD: Asphalt Recycling and Reclaiming Association.

ASTM 2007. **Standard Specification for Epoxy-Coated Steel Reinforcing Bars**. West Conshohocken, PA: American Society for Testing and Materials International. (Standard A775/A775M).

ASTM 2012. **Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement.** West Conshohocken, PA: American Society for Testing and Materials International. (Standard A615/A615M).

Athena Institute. 2006. **A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential.** Ontario, Canada: Athena Institute.

Aurangzeb, Q., Al-Qadi, I. L. Ozer, H., and Yang, R. 2014. Hybrid Life Cycle Assessment for Asphalt Mixtures with High RAP Content. **Resources, Conservation and Recycling, Vol. 83**. pp 77-86.

Autonomie webpage. https://www.autonomie.net/docs/Annex%202%20-%20Vehicle%20Energy%20Consumption.xlsx. Last accessed on 16 Apr 2020.

Bare, J. 2012. **Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). TRACI Version 2.1 User's Guide.** Cincinnati, OH: Environmental Protection Agency. (EPA/600/R-12/554 2012). Last accessed on 16 Apr 2020 at: https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

Bemanian, S., Polish, P., and Maurer G. 2006. Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice. **Transportation Research Record: Journal of the Transportation Research Board, No. 1949(1).** Washington, DC: Transportation Research Board of the National Academies. pp 54-71.

Birgisdóttir, H. 2005. **Life Cycle Assessment Model for Road Construction and Use of Residues from Waste Incineration.** Ph.D. Dissertation. Copenhagen, Denmark: Technical University of Denmark.

BLS webpage on Producer Price Index. http://www.bls.gov/regions/mid-atlantic/data/producerpriceindexconcrete_us_table.htm. Last accessed on 16 Apr 2020.

Brown, E. R., Parker, F., and Smith, M. R. 1992. Study of the Effectiveness of Styrene-Butadiene Rubber Latex in Hot Mix Asphalt Mixes. **Transportation Research Record: Journal of the Transportation Research Board, No. 1342.** Washington, DC: Transportation Research Board of the National Academies. pp 85.

CA DGS webpage on Fuel Efficiency Requirements. https://www.dgsapps.dgs.ca.gov/documents/sam/SamPrint/new/sam_master/sam_master_File/chap3600/3620.1.pdf. Last accessed on 16 Apr 2020.

CA DGS webpage on Fuel Purchasing Policy. https://www.documents.dgs.ca.gov/sam/SamPrint/new/sam_master/sam_master_file/chap3600/3627.pdf. Last accessed on 16 Apr 2020.

CA DGS webpage on State Fleet. https://data.ca.gov/dataset/california-state-fleet. Last accessed in May 2020.

CA DGS webpage on Vehicle Replacement Policy. https://www.documents.dgs.ca.gov/osp/sam/mmemos/MM17_05.pdf. Last accessed in May 2020.

CA DGS webpage on ZEV Purchasing Policy. http://sam.dgs.ca.gov/TOC/4100.aspx. Last accessed in May 2020.

CA Legislature webpage on AB32. http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201920200AB32. Last accessed on 16 Apr 2020.

CA Legislature webpage on AB338. http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200520060AB338. Last accessed on 16 Apr 2020.

CA Legislature webpage on SB1275. http://www.leginfo.ca.gov/pub/13-14/bill/sen/sb_1251-1300/sb_1275_bill_20140921_chaptered.pdf,. Last accessed on 16 Apr 2020.

CA Legislature webpage on SB32. http://leginfo.legislature.ca.gov/faces/billPdf.xhtml?bill_id=201520160SB32&version=20150SB3288CHP. Last accessed on 16 Apr 2020.

CA Legislature webpage on SB522. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200320040SB552. Last accessed on 16 Apr 2020.

CA Legislature webpage on AB236. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200720080AB236. Last accessed on 16 Apr 2020.

CA State webpage on Climate Change. https://www.climatechange.ca.gov/state/executive_orders.html. Last accessed in May 2019.

CA State webpage on EO-B1612. https://www.gov.ca.gov/news.php?id=17472. Last accessed in May 2019.

CA State webpage on ZEV Action Plan. https://www.gov.ca.gov/wp-content/uploads/2017/09/2016_ZEV_Action_Plan.pdf. Last accessed in May 2019.

Cai, H., Burnham, A., Wang, M., Hang, W., and Vyas A. 2015. **The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles.** Argonne, IL: Argonne National Lab. (No. ANL/ESD-15/9). Last accessed on 17 Apr 2020 at: https://greet.es.anl.gov/publication-heavy-duty

Cai, H., Dunn, J., Pegallapati, A., Li, Q., Canter, C., Tan, E., and Biddy M. 2017. **Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Fast Pyrolysis, and Hydrothermal Liquefaction: Update of the 2016 State-of-Technology Cases and Design Cases**. Argonne, IL: Argonne National Lab. (No. ANL-17/04)

Caltrans. 2011. **Caltrans Automated Pavement Survey (APCS).** Sacramento, CA: California Department of Transportation.

Caltrans. 2014. **Pervious Pavement Design Guide.** Sacramento, CA: California Department of Transportation.

Caltrans. 2015a. **Highway Design Manual.** Sacramento, CA: California Department of Transportation.

Caltrans. 2017. **Complete Streets Implementation Action Plan 2.0.** Sacramento, CA: California Department of Transportation. Last accessed on 27 Nov 2017 at: http://www.dot.ca.gov/hq/tpp/offices/ocp/docs/CSIAP2_rpt.pdf

Caltrans. 2018a. **California Public Road Data 2017.** Sacramento, CA: California Department of Transportation.

Caltrans. 2018b. **Caltrans Fact Booklet 2018.** Sacramento, CA: California Department of Transportation. Last accessed in March 2019 at: http://www.dot.ca.gov/drisi/library/cfb/2018-CFB.pdf

Caltrans. 2018c. **Standard Specifications, Section 39-2.02B.** Sacramento, CA: California Department of Transportation. Last accessed in March 2019 at: http://ppmoe.dot.ca.gov/hq/esc/oe/construction_contract_standards/std_specs/2018_StdSpecs/2018_StdSpecs.pdf

Caltrans MTAG. 2008. **Maintenance Technical Advisory Guide (MTAG).** Sacramento, CA: California Department of Transportation.

Caltrans webpage on Asphalt Price Index. http://www.dot.ca.gov/hq/esc/oe/ac_index.html. Last accessed in Jan 2016.

Caltrans webpage on CCDB 2018. http://ppmoe.dot.ca.gov/hq/esc/oe/awards/2018CCDB/2018ccdb.pdf. Last accessed on 17 Apr 2020.

Cao, X., Tang, B., Zhu, H., Zhang, A., and Chen S. 2011. Cooling Principle Analyses and Performance Evaluation of Heat-Reflective Coating for Asphalt Pavement. **Journal of Materials in Civil Engineering 23 (7).** pp 1067-1075.

Cao, X., Tang, B., Zhu, H., and Yuan Y. 2014. Preparation of Fluorinated Acrylate Heat Reflective Coating for Pavement and Evaluation on Its Cooling Effect. **TRB 93rd Annual Meeting Compendium of Papers.** Washington, DC: Transportation Research Board of the National Academies.

CARB webpage on AB32. https://www.arb.ca.gov/cc/ab32/ab32.htm. Last accessed on 16 Apr 2020.

CARB webpage on CA GHG Emissions. https://www.arb.ca.gov/cc/inventory/data/data.htm,. Last accessed on 16 Apr 2020.

CARB webpage on CA Scoping Plan. https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm. Last accessed on 16 Apr 2020.

CARB webpage on LCSF. https://www.arb.ca.gov/fuels/lcfs/lcfs.htm. Last accessed on 16 Apr 2020.

CARB webpage on SB375. https://ww2.arb.ca.gov/our-work/topics/sustainable-communities. Last accessed on 16 Apr 2020.

CEC webpage on Electricity Generation in CA. California Energy Commission, Sacramento, CA. https://ww2.energy.ca.gov/almanac/electricity_data/total_system_power.html. Last accessed on 17 Apr 2020.

Chatti, K. and Zaabar I. 2012. **Estimating the Effects of Pavement Condition on Vehicle Operating Costs.** Washington, DC: Transportation Research Board of the National Academies. **(**NCHRP Report 720).

City of LA. 2014. **Complete Streets Manual.** Los Angeles, CA: Department of City Planning. (CPC-2013.910.GPA.SP.CA.MSC). Last accessed on 16 Apr 2020 at: https://planning.lacity.org/odocument/c9596f05-0f3a-4ada-93aa-e70bbde68b0b/Complete_Street_Design_Guide.pdf.

Corti, A. and Lombardi, L. 2004. End Life Tyres: Alternative Final Disposal Processes Compared By LCA. **Energy 29 (12)**. pp 2089-2108.

CPUC webpage on RPS. Renewable Portfolio Standard on CA Public Utility Commission webpage. http://www.cpuc.ca.gov/rps_homepage/, 17Apr 2020

Cross, S. A., Chesner, W. H., Justus, H. G., and Kearney E. R. 2011. Life-Cycle Environmental Analysis for Evaluation of Pavement Rehabilitation Options. **Transportation Research Record: Journal of the Transportation Research Board 2227(1)**. Washington, DC: Transportation Research Board of the National Academies. pp: 43-52,

Davis, S. C., Diegel, S. W., and Boundy, R. G. 2015. **Transportation Energy Data Book Edition 34** Oak Ridge, TN: Oak Ridge National Laboratory. (ORNL 6991).

DOE webpage on EPAct. https://epact.energy.gov/key-federal-statutes. Last accessed on 16 Apr 2020.

Eckmann, B., Delfosse, F., and Chevalier, E. 2012. Reducing Emissions and Consumption of Virgin Aggregates Through Cold In-Place Recycling. **Eurasphalt and Eurobitume Congress, 5th, 2012**. Istanbul, Turkey.

ecoinvent webpage. https://www.ecoinvent.org/database/database.html. Last accessed on 16 Apr 2020.

EIA webpage on AEO2018. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2018&cases=ref2018&sourcekey=0. Last accessed on 16 Apr 2020.

EIA webpage on AER2018. https://www.eia.gov/totalenergy/data/browser/?tbl=T01.08. Last accessed on 16 Apr 2020.

EIA webpage on Natural Gas. https://www.eia.gov/dnav/ng/ng_pri_sum_a_epg0_pdv_dmcf_a.htm. Last accessed on 16 Apr 2020.

EIA webpage on New Vehicle Attributes in AEO 2018. https://www.eia.gov/outlooks/aeo/data/browser/?id=52-AEO2018&cases=ref2018&sourcekey=0#/?id=52-AEO2018&cases=ref2019&sourcekey=0. Last accessed on 16 Apr 2020.

EIA webpage on Price of Petroleum and Other Liquids. http://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_m.htm. Last accessed on 16 Apr 2020.

EIA webpage on the Electricity Sector. https://www.eia.gov/electricity/data/browser/#/topic/7?agg=0,1&geo=vvvvvvvvvvvvo&endsec=vg&freq=M&start=200101&end=201412&ctype=linechart&ltype=pin&rtype=s&pin=&rse=0&maptype=0. Last accessed on 16 Apr 2020.

EIA webpage on Vehicle Cost Projections. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=114-AEO2018andcases=ref2018andsourcekey=0. Last accessed on 16 Apr 2020.

Elgowainy, A., Han, J., Ward, J., Joseck, F., Gohlke, D., Lindauer, A., Ramsden T. 2016. **Cradle-to-Grave Life cycle Analysis of US Light Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies.** Argonne, IL: Argonne National Lab. (No. ANL/ESD-16/7). Last accessed on 17 Apr 2020 at: https://publications.anl.gov/anlpubs/2016/05/127895.pdf

Elgowainy, A., Han, J., Poch, L., Wang, M., Vyas, A., Mahalik, M., and Rousseau A. 2010. **Well-To-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles.** Argonne, IL: Argonne National Lab. (No. ANL/ESD/10-1). Last accessed on 17 Apr 2020 at: https://afdc.energy.gov/files/pdfs/argonne_phev_evaluation_report.pdf

EMFAC2017 Web Database. Last accessed on 16 Apr 2020 at: https://www.arb.ca.gov/emfac/2017/

EPA webpage on Compliance and Fuel Economy. https://www.epa.gov/compliance-and-fuel-economy-data. Last accessed on 16 Apr 2020.

EPA webpage on Fuel Economy Trends. https://www.epa.gov/fuel-economy-trends/highlights-co2-and-fuel-economy-trends. Last accessed on 16 Apr 2020.

EPA webpage on LCA Glossary. https://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=Lifecycle%20Assessment%20Glossary. Last accessed on 16 Apr 2020.

EPA webpage on the U.S. GHG Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions. Last accessed on 16 Apr 2020.

Eurobitume 2012. **Life Cycle Inventory: Bitumen.** Brussels, Belgium: Eurobitume. Last accessed on 16 Apr 2020 at: https://www.eurobitume.eu/fileadmin/pdf-downloads/LCI%20Report-Website-2ndEdition-20120726.pdf

Farshidi, F. and Harvey, J. 2008. **Evaluation of the Washington State Performance Model for Use by Caltrans.** Davis, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2008-13).

FHWA 2014. **Development of a Pavement Life Cycle Assessment (LCA) Framework: Synthesis and Literature Review.** Unpublished. Washington, DC: Federal Highway Administration.

Finnveden, G. and Moberg, Å. 2005. Environmental systems analysis tools–an overview. **Journal of cleaner production, 13(12)**. pp 1165-1173.

GaBi. 2014. **Life Cycle Assessment Software, version 6.3. LCIs for Reflective Coating Materials.** Unpublished. San Francisco, CA: PE International. (PE Order Number PEA-11128).

GaBi webpage. http://www.GaBi-software.com/america/index/. Last accessed on 16 Apr 2020.

Gilbert, H. E., Rosado, P. J., Ban-Weiss, G., Harvey, J. T., Li, H., H. Mandel, B., Millstein, D., Mohegh, A., Saboori, A., and Levinson, R. M. 2017. Energy and Environmental Consequences of a Cool Pavement Campaign. **Energy and Buildings 157**. pp 53-77. Last accessed on 16 Apr 2020 at: https://www.sciencedirect.com/science/article/pii/S0378778817309908?via%3Dihub

Green CA webpage. https://green.ca.gov/. Last accessed on 16 Apr 2020.

Harvey, J. T., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., and, Kendall, A. 2016. **Pavement Life Cycle Assessment Framework.** Washington, DC: U.S. Department of Transportation Federal Highway Administration (FHWA-HIF-16-014).

Harvey, J., Kendall, A., Lee, I. S., Santero, N., Van Dam, T., and Wang T. 2010. **Pavement Life Cycle Assessment Workshop: Discussion Summary and Guidelines.** Davis, CA: University of California. (UCPRC-TM-2010-03). The conference webpage last accessed on 16 Apr 2020 at: http://www.ucprc.ucdavis.edu/p-lca/

Harvey, J., Kendall, A., and Saboori, A. 2015a. **The Role of Life Cycle Assessment in Reducing Greenhouse Gas Emissions from Road Construction and Maintenance.** Davis, CA: The National Center for Sustainable Transportation, Institute of Transportation Studies, University of California.

Harvey, J., Julliѐn, A., Steyn, W., Kendall, A., Jones, D., and Saboori, A. 2015b. Recommendations for Application of the Results of the Pavement LCA 2014 Symposium to Southern Africa. **Asphalt Pavements for Southern Africa (CAPSA15), 11th, 2015**. Sun City, South Africa. Last accessed in Apr 2020 at https://trid.trb.org/view.aspx?id=1404841.

Harvey, J. T., Kendall, A., Saboori, A., Ostovar, M., Butt, A. A., Hernandez, J., and Haynes, B. 2018. **Framework for Life Cycle Assessment of Complete Streets Projects.** Davis, CA: National Center for Sustainable Transportation, Institute of Transportation Studies, University of California.

Horvath, A. 2003. **Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements.** University of California Transportation Center, Berkeley, CA.

Horvath, A. and Hendrickson, C. 1998. Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements. **Transportation Research Record: Journal of the Transportation Research Board 1626 (1)**. Washington, DC: Transportation Research Board of the National Academies. pp: 105-113.

Huang, Y., Spray, A., and Parry, A. 2013. Sensitivity Analysis of Methodological Choices in Road Pavement LCA. **The International Journal of Life Cycle Assessment. Volume 18, Issue 1.** Springer.

IPCC. 2006. **IPCC Guidelines for National Greenhouse Gas Inventories**. Kanagawa, Japan: Institute for Global Environmental Strategies. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds).

ISO. 2006. **Environmental Management – Life Cycle Assessment – Principles and Framework.** Geneva, Switzerland: International Organization for Standardization. (ISO 14040).

Jones, D., Fu, P., and Harvey, J. T. 2009a. **Full-Depth Pavement Reclamation with Foamed Asphalt in California: Guidelines for Project Selection, Design, and Construction.** Davis, CA: University of California Pavement Research Center. (No. UCPRC-GL-2008-01).

Jones, D., Louw, S., and Wu, R. 2016. **Full-Depth Recycling Study: Test Track Construction and First-Level Analysis of Phase 1 and Phase 2 HVS Testing, Forensic Investigation, and Phase 1 Laboratory Testing.** Davis, CA: University of California Pavement Research Center. (No. UCPRC-RR-2015-02).

Jones, D., Wu, R., and Louw, S. 2014. **Full-Depth Recycling Study: Test Track Construction and First Level Analysis Of Phase 1 HVS And Laboratory Testing.** Davis, CA: University of California Pavement Research Center. (No. UCPRC-RR-2014-03).

Jones, S. B., Meyer, P. A., Snowden-Swan, L. J., Padmaperuma, A. B., Tan, E., Dutta, A., Jacobson, J., and Cafferty, K. 2013. **Process Design and Economics for the Conversion of Lignocellulosic Biomass To Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway.** Richland, WA: Pacific Northwest National Lab. (No. PNNL-23053; NREL/TP-5100-61178.) https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf. Last accessed on 17 Apr 2020.

Jullien, A., Dauvergne, M., and Proust, C. 2015. Road LCA: The Dedicated ECORCE Tool and Database. **The International Journal of Life Cycle Assessment, 20(5).** pp 655-670.

Kandhal, P. S. and Mallick, R. B. (1997). **Pavement Recycling Guidelines for State and Local Governments Participant's Reference Book.** Washington, DC: Federal Highway Administration.

Kang, S., Yang, R., Ozer, H., and Al-Qadi, I. 2014. Life-Cycle Greenhouse Gases and Energy Consumption for Material and Construction Phases of Pavement with Traffic Delay. **Transportation Research Record: Journal of the Transportation Research Board 2428 (1).** Washington, D.C.: Transportation Research Board of the National Academies. pp 27-34.

Kendall, A. 2007. **Concrete Infrastructure Sustainability: Life Cycle Metrics, Materials Design, and Optimized Distribution of Cement Production**. PhD Dissertation, University of Michigan at Ann Arbor.

Kendall, A. 2012. **Life Cycle Assessment for Pavement: Introduction. Presentation in Minutes**. Davis CA: FHWA Sustainable Pavement Technical Working Group Meeting, April 25-26, 2012.

Keoleian, G., Kendall, A., Lepech, M., and Li, V. 2005. Guiding the Design and Application of New Materials for Enhancing Sustainability Performance: Framework and Infrastructure Application. **MRS Proceedings, 895, 0895-G06-01.** doi:10.1557/PROC-0895-G06-01

Lepert, P. and Brillet, F. 2009. The Overall Effects of Road Works on Global Warming Gas Emissions. **Transportation Research Part D; Vol (14).** pp 576–84.

Levinson, R., Gilbert, H. E., Jin, L., Mandel, B., Millstein, D., Rosado, P. J., Harvey, J. T., Kendall, A. M., Li, H., Saboori, A., Lea, J. Ban-Weiss, G., Mohegh, A., and Santero, N. 2017. **Life-Cycle Assessment and Co-Benefits of Cool Pavements.** Sacramento, CA: California Air Resources Board. Last accessed on 16 Apr 2020 at: https://www.arb.ca.gov/research/single-project.php?row_id=65149.

Levis, J. W., Barlaz, M. A., Tayebali, A., and Ranjithan S. R. 2012. Quantifying the Greenhouse Gas Emission Reductions Associated with Recycling Hot Mix Asphalt. **Road Materials and Pavement Design 12(1)**. pp 57-77.

Li, H., Saboori, A., and Cao, X. 2016. Information synthesis and Preliminary Case Study for Life Cycle Assessment of Reflective Coatings for Cool Pavements. **International Journal of Transportation Science and Technology, 5(1).** pp 38-46.

Li, H. 2012. **Evaluation of Cool PStrategies for Heat Island Mitigation.** PhD Dissertation, Davis, CA: University of California, Davis.

Liu, X., Cui Q., and Schwartz C. 2014. Performance Benchmark of Greenhouse Gas Emissions from Asphalt Pavement in the United States. **ICSI 2014@ Creating Infrastructure for a Sustainable World.** American Society of Civil Engineers.

Madanat, S., Nakat, Z., and Sathaye N. 2005. **Development of Empirical-Mechanistic Pavement Performance Models Using Data from the Washington State PMS Database.** Davis, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2005-05)

Marceau, M., Nisbet, M. A., Van Geem, M. G. 2007. **Life Cycle Inventory of Portland Cement Concrete.** Skokie, IL: Portland Cement Association.

MOVES webpage. https://www.epa.gov/moves. Last accessed on 16 Apr 2020.

NACTO. 2013. **Urban Street Design Guide**. Island Press. Last accessed on 16 Apr 2020 at: https://nacto.org/publication/urban-street-design-guide/

Nakat, Z., Madanat, S., Farshidi, F., and Harvey, J. 2006. **Development of an Empirical-Mechanistic Model of Overlay Crack Progression Using Data from the Washington State PMS Database.** Davis, CA: University of California Pavement Research Center. (Research Report UCPRC-RR-2006-15).

Nantes 2012 LCA Conference webpage. http://lca-construction2012.ifsttar.fr/. Last accessed on 16 Apr 2020.

Nixon, H., Agrawal, A. W., and Simons, C. 2017. **Designing Road Diet Evaluations: Lessons Learned from San Jose's Lincoln Avenue Road Diet.** San Jose, CA: Mineta Transportation Institute. (MTI Report WP 12-14).

NREL webpage on USLCI. https://www.nrel.gov/lci/. Last accessed on 16 Apr 2020.

PaLATE webpage. http://faculty.ce.berkeley.edu/horvath/palate.html. Last accessed on 16 Apr 2020.

Pavement LCA 2014 Conference webpage. http://www.ucprc.ucdavis.edu/p-lca2014/Default.aspx. Last accessed on 16 Apr 2020.

Pavement LCA 2017 Conference webpage. https://lcasymposium.ict.illinois.edu/. Last accessed on 16 Apr 2020.

Pereira, P. A. and Santos, L. P. 2006. Technical-Economical Evaluation of Pavement Recycling Alternatives. **Third Gulf Conference on Roads (TGCR06).** Muscat, Oman.

Quillin, K. 2007. **Calcium Sulfoaluminate Cements : Reduced CO2, Concrete Properties and Applications.** Bracknell, United Kingdom: IHS BRE Press.

Reinhart, T. E. 2016. ***Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study – Report #2.*** Washington, DC: National Highway Traffic Safety Administration. (Report No. DOT HS 812 194).

Robinette, C. and Epps, J. 2010. Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement. **Transportation Research Record: Journal of the Transportation Research Board, No. 2179.** Washington, DC: Transportation Research Board of the National Academies. pp. 10–22.

Saboori, A., Harvey, J., Butt, A. A., and Jones, D. 2017. Life Cycle Assessment and benchmarking of end of life treatments of flexible pavements in California. **Pavement Life-Cycle Assessment: Proceedings of the Symposium on Life-Cycle Assessment of Pavements (Pavement LCA 2017).** CRC Press. pp. 241-250.

Saboori, A., Harvey, J., Li, H., Lea, J., Kendall, A., and Wang, T. 2020. **Documentation of UCPRC Life Cycle Inventory used in CARB/Caltrans LBNL Heat Island Project and other LCA Studies Davis.** CA: University of California Pavement Research Center.

Sacramento County. 2009. **Improvement Standards, Section 4: Streets. Office of County Engineering.** Sacramento, CA: Sacramento County. Last accessed on 16 Apr 2020 at: http://www.engineering.saccounty.net/Documents/Sect4StreetStds_Saccounty_%20Ver11_01_09.pdf

Santamouris, M., Synnefa, A., and Karlessi, T. 2011. Using Advanced Cool Materials in the Urban Built Environment to Mitigate Heat Islands and Improve Thermal Comfort Conditions. **Solar Energy 85 (12)**. pp. 3085-3102.

Santero, N. J. 2009. **Pavements and the Environment: A Life-Cycle Assessment Approach.** PhD Dissertation. Berkeley, CA: University of California, Berkeley.

Santero, N. J. 2011. Life-Cycle Assessment of Pavements. Part I: Critical Review. **Resources, Conservation and Recycling. Volume 55, Issues 9-10.** Philadelphia, PA: Elsevier.

Santero, N. J., and Horvath, A. 2009. Global Warming Potential of Pavements. **Environmental Research Letters, 4(3), 034011.**

Santos, J., Bryce, J., Flintsch, G., Ferreira, A., and Diefenderfer, B. 2014. A Life Cycle Assessment of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices. **Structure and Infrastructure Engineering 11(9)**. pp 1199-1217.

Sayagh, S., Ventura, A., Hoang, T., François, D., and Jullien, A. 2010. Sensitivity of the LCA Allocation Procedure for BFS Recycled into Pavement Structures. **Resources, Conservation and Recycling, 54(6)**. pp 348-358.

SB1 Overview webpage. http://rebuildingca.ca.gov/overview.html. Last accessed on 16 Apr 2020.

Smart Growth America 2015 Conference in Baltimore webpage. https://www.newpartners.org/2015/. Last accessed on 16 Apr 2020.

Smart Growth America webpage on Implementing Complete Streets. https://www.smartgrowthamerica.org/app/legacy/documents/cs/factsheets/cs-networks.pdf. Last accessed on 16 Apr 2020.

Stata webpage. https://www.stata.com/. Last accessed on 16 Apr 2020.

Stripple, H. 2001. Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis. **Rapport IVL** Swedish Environmental Research Institute. pp.1-96.

Stroup-Gardiner, M. 2011. **Recycling and Reclamation of Asphalt Pavements Using In-Place Methods.** Washington DC: Transportation Research Board of the National Academies. (No. Project 20-05 (Topic 40-13).

Synnefa, A., Santamouris, M., and Livada, I. 2006. A Study of the Thermal Performance of Reflective Coatings for the Urban Environment. **Solar Energy 80 (8)**. pp. 968-981.

Tseng, E. 2012. **The Construction of Pavement Performance Models for Flexible Pavement Wheelpath Cracking and IRI for the California Department of Transportation New Pavement Management System.** Master of Science Thesis. Davis, CA: University of California.

UCPRC LCI DB Shared Folder on Box. Last accessed on 16 Apr 2020 at: https://ucdavis.box.com/s/va9w2mx6momdxq3dn3z4ym2lj5ucujdu

Van Dam, T.J., Harvey, J., Muench, S.T., Smith, K.D., Snyder, M.B., Al-Qadi, I.L., Ozer, H., Meijer, J., Ram, P., Roesler, J.R., and Kendall, A. 2015. **Towards Sustainable Pavement Systems: A Reference Document** Washington, DC: Federal Highway Administration. (No. FHWA-HIF-15-002).

van Leest, A. J., van Hartskamp, S. B., and Meijer, J. P. 2008. Decision Support Model for Road Pavements Based on Whole Life Costing, Life Cycle Assessment and Multi-Criteria Analysis. **9th International Conference on Concrete Pavements.**

Wang, H., Zhong, J., Feng, D., Meng, J., and Xie, N. 2012. Nanoparticles-modified Polymer-based Solar-reflective Coating as a Cooling Overlay for Asphalt Pavement. **International Journal of Smart and Nano Materials 4 (2)**. pp. 102-111.

Wang, T., Lee, I. S., Kendall, A., Harvey, J., Lee, E. B., and Kim, C. 2012. Life Cycle Energy Consumption and GHG Emission from Pavement Rehabilitation with Different Rolling Resistance. ***Journal of Cleaner Production*, *33***. pp 86-96.

Wang, T. 2013. **Reducing Greenhouse Gas Emissions and Energy Consumption Using Pavement Maintenance and Rehabilitation: Refinement and Application of a Lifecycle Assessment Approach.** PhD Dissertation. Davis, CA: University of California, Davis.

Wirtgen. 2012. **Wirtgen Cold Recycling Technology.** Wirtgen Company, Windhagen, Germany. Last accessed on 17 Apr 2020 on http://media.wirtgen-group.com/media/02_wirtgen/infomaterial_1/kaltrecycler/kaltrecycling_technologie/kaltrecycling_handbuch/Cold_recycling_Manual_EN.pdf

Xu, X., Wildnauer, M., Gregory, J., and Kirchain, R. 2016. “Accounting for Variation in Life Cycle Inventories: The Case of Portland Cement Production in the U.S.,” in Rewas 2016: Towards Materials Resource Sustainability, eds. R.E. Kirchain, B. Blanpain, C. Meskers, E. Olivetti, D. Apelian, J. Howarter, A. Kvithyld, B. Mishra, N. R. Neelameggham, J. Spangenberger (Hoboken, New Jersey: John Wiley and Sons, 2016), 145-149. dx.doi.org/10.1002/9781119275039.ch21

Yang, R., Ozer, H., and Al-Qadi, I. L. 2016. Regional Upstream Life-Cycle Impacts of Petroleum Products in the United States. ***Journal of Cleaner Production*, *139*. pp** 1138-1149.

Yang, R. 2014. **Development of A Pavement Life Cycle Assessment Tool Utilizing Regional Data and Introducing an Asphalt Binder Model**. Master of Science Thesis. Urbana/Champaign, IL: University of Illinois at Urbana Champaign.

Yu, B. and Lu, Q. 2012. Life Cycle Assessment of Pavement: Methodology and Case Study. **Transportation Research Part D: Transport and Environment, 17(5)**. pp 380-388.

Zhang, H. 2009. ***Sustainable Pavement Asset Management Based on Life Cycle Models and Optimization Methods*.** PhD Dissertation. Ann Arbor, MI: University of Michigan at Ann Arbor.

Zhang, H., Keoleian, G. A., Lepech M. D., and Kendall, A. 2010. Life-Cycle Optimization of Pavement Overlay Systems. **Journal of Infrastructure Systems, Vol. 16, No. 4**. pp 310- 322.

APPENDIX I. Review of Pavement LCA Models, Databases, and EOL Studies

App-Table 1. Summary of inventory data sources (FHWA, 2014)

Inventory Data Source	Number of Studies Using Data Source	Date of Last Update of Data Source
Literature/new models	31	Varying
econinvent	15	Varying (updated periodically)
Stripple	11	2001
Athena	10	2006
Field Investigation/Surveys	9	Varying
PCA (Portland Cement Association)	7	Multiple LCIs (latest 2007)
GaBi	7	Varying (updated periodically)
USLCI (US Life Cycle Inventory)	4	Varying (updated periodically)
GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation)	3	2013
ELCD (European Life Cycle Database)	3	2012
UPC (Union of Lime Producers – French)	3	2010
Eurobitume	2	2012
eCalc (emission Calculator)	2	2009
EPA AP-42 (Pollutants emission factors)	2	1995
TRI (Toxic Release Inventory)	1	2013

According to Caltrans highway design manual (Caltrans, 2015), there are five major types of pavement projects in California:

- New construction
- Widening: addition of a new lane to an existing pavement
- Pavement preservation:
    - Preventive maintenance: to preserve the pavement in good condition such as removal and replacement of a non-structural wearing course, or adding a thin non-structural overlay, seal costs, slurry seals, and more.
    - Capital preventive maintenance (CAPM): the key element of this program is to improve ride quality and preservation of serviceability. The main purpose is to repair sections with minor surface distress and/or IRI values greater than 170 inches/mile. Some of the examples of CAPM projects are surface overlays less than or equal to 0.2 ft. or surface in-place recycling (overlay not to exceed 0.2 ft..) Caltrans considers surface overlays greater than 0.25 ft. as rehabilitation.

- Rehabilitation: major, non-routine work intended to return the roadway that exhibits major structural distress to a good condition. Examples of roadway rehabilitation projects include:
    - Overlay
    - Removal and replacement of the surface course
    - Crack, seat, and overlay of rigid pavements regardless of overlay thickness
    - Lane/shoulder replacements.
- Reconstruction: the replacement of the entire pavement section with a new structure.

App-Table 2. Pavement LCA models used frequently in pavement LCA studies, adapted from Wang (2013)

Model	Developed and Year	Life Cycle Stages Included	Main LCI Sources	Outputs	Main Function of the Model	Limitations
PaLATE (PaLATE webpage)	University of Berkeley, 2003	Material production, Construction, Maintenance, End-of-life	(1) Economic Input Output table; (2) U.S. EPA's emission factors from AP-42; (3) OFFROAD model from CARB	Fuel consumption, water consumption, GHG, NOx, PM10, SO2, CO, Hg, Pb, and hazardous waste generation, global warming potential (in CO2-e), and human toxicity potential.	Estimate the environmental and economic burdens associated with different pavement designs (material and thickness)	Outdated dataset; EIO-LCA is not as accurate as process-based LCA; incomplete set of surface treatment and construction materials
ROAD-RES (Birgisdóttir, 2005)	Technical University of Denmark, 2005	Material production, Construction; Maintenance; Use (leachate); End-of-life	(1) Stripple's LCI study for conventional material; (2) Laboratory experiments for municipal solid waste incineration (MSWI); (3) A Finnish model (MELI) for roads with residue material other than MSWI residues.	Global warming potential (in CO2-e), photochemical ozone formation (in C2H4-e), nutrient enrichment (in NO3-e), acidification (in SO2-e), stratospheric ozone depletion (in CFC-11-e), human toxicity in air/water/soil, ecotoxicity in water/soil, and stored ecotoxicity in water/soil (for long-term leaching.)	(1) Evaluate the environmental impacts of two alternatives: using virgin materials and residues from MSWI; (2) Compare two disposal methods for waste incineration residues: landfilling and use in road construction. (1) Infiltration, (2) Distribution of heavy metals in the environment after leaching from the material (3) Transport distance.	Outdated dataset; not representative of processes and designs in California, limited options for pavement treatment and construction materials
Pavement LCA model from University of Michigan (Kendall et al., 2008)	University of Michigan, 2008	Material production; Construction; Use (rolling resistance); Maintenance and Rehabilitation; End-of-life	(1) LCI database from software such as SimaPro or equivalent LCI studies, for raw material LCIs; (2) U.S. EPA's on-road vehicle emission model MOBILE6.2, for on-road vehicle emissions; (3) U.S. EPA's off-road equipment emission model, NONROAD, for construction equipment emissions.	Energy consumption, GHG emissions, global warming potential (in CO2-e), resource depletion potential, air pollutant emissions, and water pollutant emissions.	Perform life cycle assessment and life cycle cost analysis of pavement overlay or bridge deck designed with conventional material (HMA and concrete) and an alternative material, engineered cementitious composites (ECC.)	Limited set of pavement treatments and construction materials; dataset not representative of the local conditions
PE-2 (Project Emission Estimator)	Michigan Technological	Material production; Construction;	(1) Stripple's LCI study; (2) Athena Institute's LCI study (3)	Global warming potential (in CO2-e)	Evaluate the carbon footprints of typical HMA and PCC pavements for	Only global warming potential; outdated data;

Model	Developed and Year	Life Cycle Stages Included	Main LCI Sources	Outputs	Main Function of the Model	Limitations
(PE-2 webpage)	University, 2011	Maintenance and Rehabilitation	National Renewable Energy Laboratory (NREL) LCIs		both reconstruction and rehabilitation projects.	unrepresentative of the local practice

App-Table 3. Summary of the recent LCA studies on EOL alternatives of pavements as of 2016

Author	Year	Goal of the Study	Location	Functional Unit	Life Cycle Stages Considered	Main Dataset Used	Results	Study Limitations
Alkins et al.,	2009	Comparison of CIR (100 mm of milling, in-place recycling with foamed asphalt with 40 mm of HMA on top) with conventional rehabilitation technique of mill-and-fill (100 mm of milling with 130 mm of HMA on top) in terms of: •Aggregate consumption, •Energy use, •GHG emissions, •NOx and SO2 emissions, •Future ride quality	Ontario, Canada	1 ln-km (width of 7.5 m)	Material production and construction	PaLATE	62% reduction in aggregate consumption, 52% reduction in CO2 emissions, 54% reduction in NOx emissions, and 61% reduction in sulfur dioxide emissions. Better IRI and PCI (pavement condition index) progression with time for the CIR sections compared to mill and fill	• PaLATE dataset is out of date and also EIO-LCA is not as accurate as process-based LCA. • Does not consider the use stage impacts and future maintenance and rehabilitation frequencies. • The progression models for IRI are not discussed and it is not explained based on what data and methodology the models were developed.
Cross et al.,	2011	Comparative LCA between CIR, mill-and-fill, and overlay in terms of the 12 impact categories of the PaLATE software • CIPR with 4 in. mill and 1.5 in HMA overlay (CIR-4) • Mill and fill with 3 in. mill and 3 in. HMA overlay (MF-3) • Two-course overlay (TCO, 2 equal thickness of 3-in HMA overlays)	New York, USA	1 centerline-mile of a 2-lane 24-ft-wide roadway	Material production, transportation, and construction	PaLATE	• Material production has the highest share of energy consumption and GHG emissions for all treatments. • CIR has 12% and 9% lower energy consumption and 14% and 3% lower GHG emissions compared to MF-3 and TCO • Trans. reduction is the highest for CIR	• PaLATE dataset is out of date and also EIO-LCA is not as accurate as process-based LCA for quantification of the impacts. • Does not consider the use stage impacts and future maintenance and rehabilitation frequencies. • No consideration of use stage and future M&R. • No discussion of allocation of impacts between upstream and downstream projects.

Author	Year	Goal of the Study	Location	Functional Unit	Life Cycle Stages Considered	Main Dataset Used	Results	Study Limitations
Eckman et al.,	2012	Comparison of CIR versus two conventional methods of rehabilitation in terms of GHG emissions, energy consumption, and virgin aggregates consumption 70mm milling with 50mm of semi-coarse HMA layer topped by a 25mm of surface mix compared vs 70mm milling and CIR with foamed asphalt and cement topped with 40 mm of HMA overlay 60 mm milling with 60mm of semi-coarse HMA layer topped by 40 mm of surface mix compared vs 70 mm CIR with foamed asphalt and lime covered with 50 mm HMA layer	France	N/A	Material production, transportation, and construction	GAÏA$_{BE}$ software developed by EUROVIA	• The software developed well presents the local practice and mix designs for the construction activities and, therefore, increases the reliability of the results. • CIR has ~30% lower energy consumption, ~30% lower GHG emissions, and ~50% lower virgin aggregate consumption compared to the two conventional methods.	• Even though performance of the CIR is compared with the conventional methods through lab testing and recommendations have been made for proper project selection and construction checkpoints, the use stage is not considered in the comparison leaving out the impacts that each of the rehabilitation methods have on the vehicle fuel consumption during use stage due to the surface roughness and the also the frequency of future maintenance and rehabilitation activities needed for each case. • Allocation of the reduction in environmental impacts, due to the use of recycled materials and substituting virgin aggregate, between the upstream project and downstream project is not discussed.
Levis et al.,	2012	Comparison of the GHG emissions of the following three alternatives for waste management at the end-of-life of pavements: • Recycling as new aggregate • Recycling as new HMA • Disposal in a land fill	USA	1 ton of recycled HMA	Material production and transportation	NREL database (USLCI)	A reduction of 16 and 9 kg of CO$_2$e per ton of HMA recycled as new HMA and as new aggregate respectively when compared to the CO$_2$e emissions of landfilling.	• Very limited scope and system boundary; does not consider the recycling processes to acquire the recycled materials from the old pavement, and no consideration of use stage. • No discussion of allocation of the benefits between the upstream and downstream projects.

Author	Year	Goal of the Study	Location	Functional Unit	Life Cycle Stages Considered	Main Dataset Used	Results	Study Limitations
Liu et al.,	2014	Comparison of the GHG emissions mill-and-fill with CIR and cold central plant recycling (CCPR.)	USA	1 ton of HMA compared with 1 ton of foam treated base (CIR and CPPR)	Material production, transportation, and construction	EIO-LCA and EPA NONROAD	• Adjusted for different structural capacity of the HMA vs foamed treated base by assigning 0.8 to FTB vs 1 for HMA • Mill-and-fill of conventional HMA) causes 115 kgCO$_2$e/MT of HMA placed on site while CIR and CCPR result in 13.2 and 77.2 kgCO$_2$e/MT reductions in GHG emissions respectively.	• EIO-LCA is not as accurate as process-based LCA, and the 1997 dataset used in this study is very outdated. • No discussion of allocation of the reductions in environmental impacts due to recycling between upstream and downstream projects. • No consideration of the use stage.
Santos et al.	2014	Comparison of GHG and energy consumption of three rehab alternatives for an interstate section (AADT of 25,000, traffic growth rate of 3%, and an analysis period of 50 years): • Recycling based: CIR to 7 in. on the left lane and FDR to 22 in. on the right lane followed by HMA on both lanes. • Traditional reconstruction: mill and fill to 7 in. with HMA on the left lane and total removal of right lane with cement treating the base followed by HMA overlay on top of both lanes.	Virginia	3.66 mi. long, 2 lane asphalt section	All life cycle stages	LCI datasets from literature, EPA NONROAD	• Use stage is the dominant in total GHG emissions and energy consumption for all three alternatives (at least two order of magnitude larger than the other life cycle stages) • Putting the use stage impacts aside, for GHG emissions, recycling-based practices result in 75% reduction in material production, 62% reduction in construction and M&R, and 81% reduction in transportation compared to	• LCI databases collected from the literature are outdated in some cases and generally are not representative of local practices. • Assumed the sections are going to remain in place and adopted a “cut-off” allocation method in which environmental impacts were assigned to the EOL stage of all M&R scenarios in comparison in the current pavement system. • No consideration of low-volume roads where the use stage impacts may not be as large as it is in this study (two orders of magnitude larger than other life cycle stages)

Author	Year	Goal of the Study	Location	Functional Unit	Life Cycle Stages Considered	Main Dataset Used	Results	Study Limitations
		• Corrective maintenance: both lanes receive 5% full depth patching followed by 4 in. mill and overlay.					traditional reconstruction.	

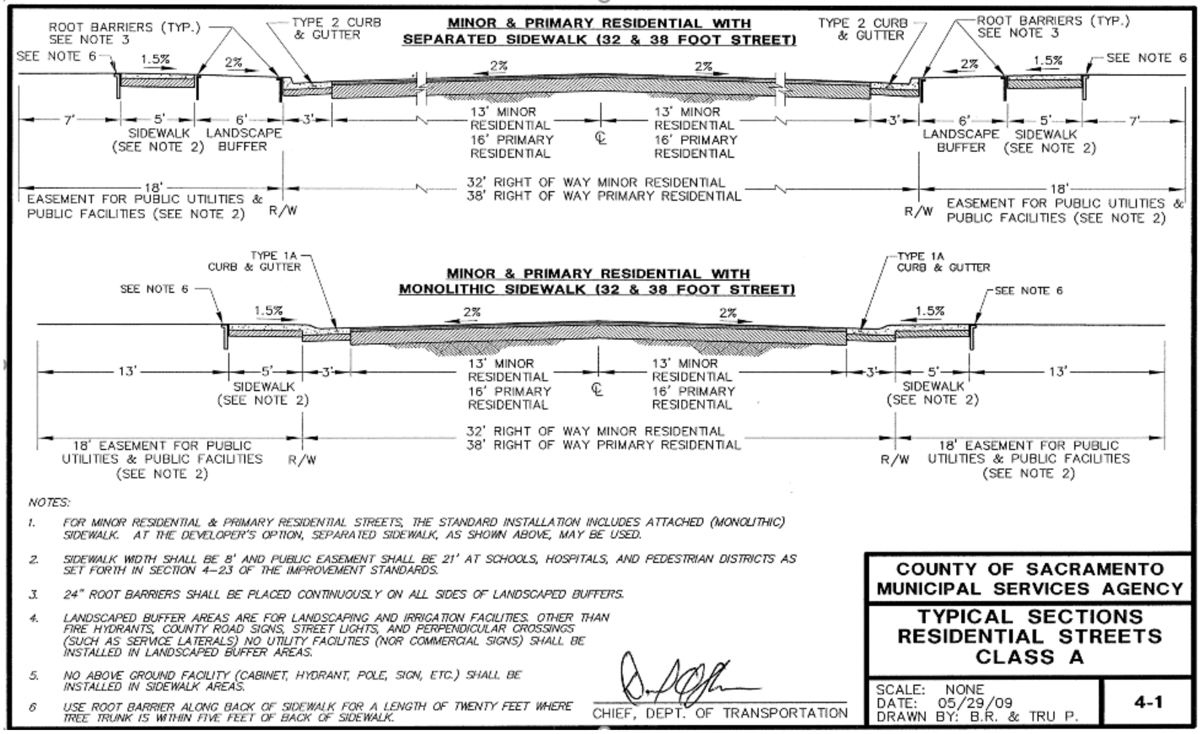
App-Table 4. Cost comparison of conventional rehabilitation methods for flexible pavements with in-place recycling

Author	Year	Location	Methods Compared in the Study	Assumptions	Main Findings	Study Limitations
Kandhal et al.	1997	Survey of contractors and agencies in the USA	CIR and FDR versus conventional rehabilitation methods such as reconstruction or mill-and-fill	Just the construction stage, considering the traffic changes	• Up to 55% savings in construction costs for CIR and up to 67% for FDR compared to conventional rehabilitation methods • Substantial savings in user cost due to reduced interruptions in traffic flow when in-place recycling is conducted • In-place recycling provides the opportunity to maintain the highway geometry • Cost savings in the hauling of the new materials and avoided landfill tipping fees.	• Outdated data • Not a full life cycle cost study
Pereira and Santos	2006	Comparison of the costs of the construction stage for conventional HMA overlay with CIR	Conventional method consists of an interlayer with 10 cm of base and 5 cm of overlay while the CIR consist of 15 cm of recycling and 5 cm of overlay	Conventional overlay consists of stress absorbing membrane interlayer with	• CIR will perform better as it does not require the interlayer and recycling the cracked surface will prevent reflection cracking. • CIR initial construction costs are 40% lower than the conventional overlay with the interlayer.	• Study includes only the initial construction and no consideration of the other life cycle costs of the two alternatives
Bemanian et al.,	2006	Nevada	Comparison of the conventional method of 2-in. plant-mixed bituminous surface overlay and chip seal with a matrix of in-place recycling with different milling and overlay thicknesses	20-year analysis period with a 4% discount rate. Service lives of the treatments were based on empirical data of the agency's previous experiences	CIR with a double chip seal surface treatment can cut the life cycle cost of NDOT’s conventional treatment by half and save an average of $100,000 per centerline mile in life cycle costs.	• Outdated costs • Performance of the suggested treatment is dependent on the local climate and traffic and may not be the

Author	Year	Location	Methods Compared in the Study	Assumptions	Main Findings	Study Limitations
						best option everywhere
Alkins et al.,	2009	Ontario, Canada	Conventional: milling the surface to 100 mm and paving 130 mm of HMA on top compared to 100 mm of CIR with foamed asphalt and 50 mm of HMA on top.	Analysis period of 50 years 5% discount rate 15 year service life for CIR and 18 years for conventional method	42% reduction in initial construction costs and 35% reduction in life cycle costs for CIR compared to the conventional method	• Service life of CIR is estimated, and not enough empirical data exist for the location of the study, might be too optimistic • No consideration of the user cost
Robinette and Epps	2010	Survey of selected states in the USA	• Comparison of initial construction costs and life cycle cost of mill-and-fill and CIR • For sections with high and low traffics and different initial conditions (good, fair, poor) • Thicknesses of fill and overlay dependent on the initial condition of the section)	40-year analysis period with 2.7% discount rate, estimates for service life for each alternative was taken based on empirical data collected through literature survey	Savings between 11% to 52% in initial construction costs and between 6% to 46% for the life cycle cost (in both cases the highest savings occurred when comparison was for a section in poor condition)	• Service lives for treatments and costs were collected based on average of data collected from multiple regions

APPENDIX II. Complete Streets LCA

App III-Section I. Design Guidelines



NOTES:

1. FOR MINOR RESIDENTIAL & PRIMARY RESIDENTIAL STREETS, THE STANDARD INSTALLATION INCLUDES ATTACHED (MONOLITHIC) SIDEWALK. AT THE DEVELOPER'S OPTION, SEPARATED SIDEWALK, AS SHOWN ABOVE, MAY BE USED.
2. SIDEWALK WIDTH SHALL BE 8' AND PUBLIC EASEMENT SHALL BE 21' AT SCHOOLS, HOSPITALS, AND PEDESTRIAN DISTRICTS AS SET FORTH IN SECTION 4–23 OF THE IMPROVEMENT STANDARDS.
3. 24" ROOT BARRIERS SHALL BE PLACED CONTINUOUSLY ON ALL SIDES OF LANDSCAPED BUFFERS.
4. LANDSCAPED BUFFER AREAS ARE FOR LANDSCAPING AND IRRIGATION FACILITIES. OTHER THAN FIRE HYDRANTS, COUNTY ROAD SIGNS, STREET LIGHTS, AND PERPENDICULAR CROSSINGS (SUCH AS SERVICE LATERALS) NO UTILITY FACILITIES (NOR COMMERCIAL SIGNS) SHALL BE INSTALLED IN LANDSCAPED BUFFER AREAS.
5. NO ABOVE GROUND FACILITY (CABINET, HYDRANT, POLE, SIGN, ETC.) SHALL BE INSTALLED IN SIDEWALK AREAS.
6. USE ROOT BARRIER ALONG BACK OF SIDEWALK FOR A LENGTH OF TWENTY FEET WHERE TREE TRUNK IS WITHIN FIVE FEET OF BACK OF SIDEWALK.

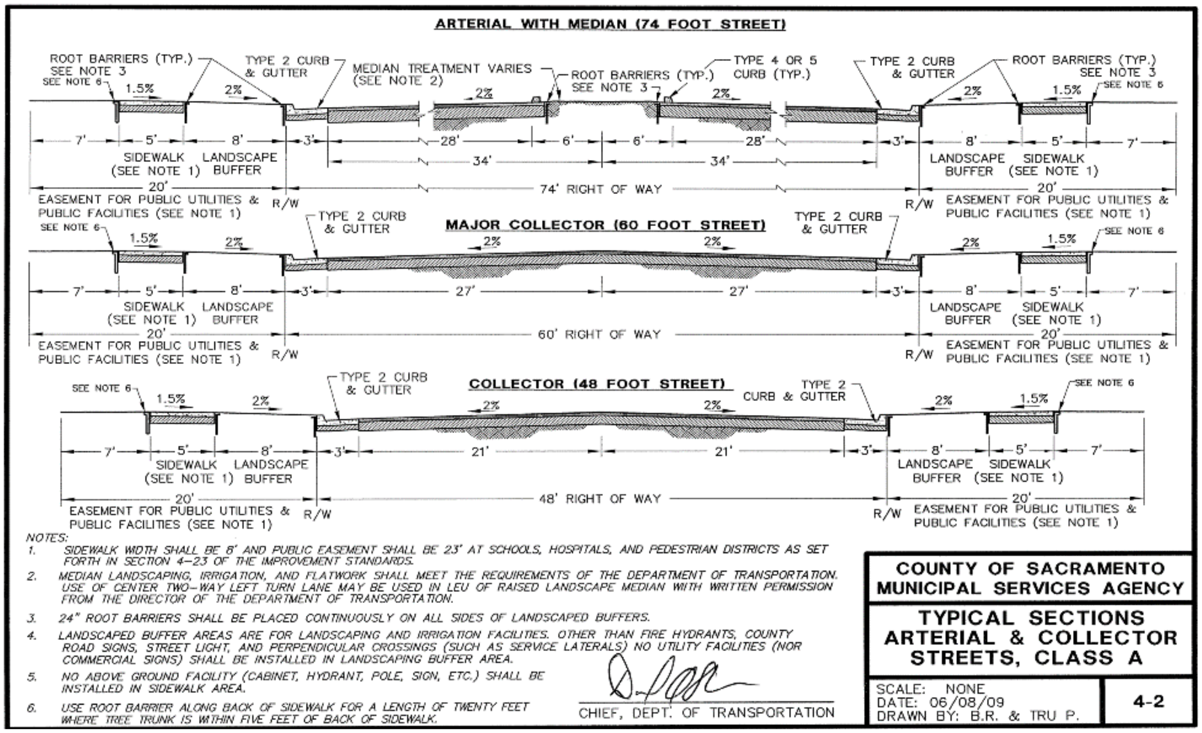
COUNTY OF SACRAMENTO
MUNICIPAL SERVICES AGENCY

TYPICAL SECTIONS
RESIDENTIAL STREETS
CLASS A

SCALE: NONE
DATE: 05/29/09
DRAWN BY: B.R. & TRU P.

4-1

App-Figure 1: Cross section of Minor and Primary Residential (Sacramento County, 2009.)



NOTES:

1. SIDEWALK WIDTH SHALL BE 8' AND PUBLIC EASEMENT SHALL BE 23' AT SCHOOLS, HOSPITALS, AND PEDESTRIAN DISTRICTS AS SET FORTH IN SECTION 4-23 OF THE IMPROVEMENT STANDARDS.
2. MEDIAN LANDSCAPING, IRRIGATION, AND FLATWORK SHALL MEET THE REQUIREMENTS OF THE DEPARTMENT OF TRANSPORTATION. USE OF CENTER TWO-WAY LEFT TURN LANE MAY BE USED IN LEU OF RAISED LANDSCAPE MEDIAN WITH WRITTEN PERMISSION FROM THE DIRECTOR OF THE DEPARTMENT OF TRANSPORTATION.
3. 24" ROOT BARRIERS SHALL BE PLACED CONTINUOUSLY ON ALL SIDES OF LANDSCAPED BUFFERS.
4. LANDSCAPED BUFFER AREAS ARE FOR LANDSCAPING AND IRRIGATION FACILITIES. OTHER THAN FIRE HYDRANTS, COUNTY ROAD SIGNS, STREET LIGHT, AND PERPENDICULAR CROSSINGS (SUCH AS SERVICE LATERALS) NO UTILITY FACILITIES (NOR COMMERCIAL SIGNS) SHALL BE INSTALLED IN LANDSCAPING BUFFER AREA.
5. NO ABOVE GROUND FACILITY (CABINET, HYDRANT, POLE, SIGN, ETC.) SHALL BE INSTALLED IN SIDEWALK AREA.
6. USE ROOT BARRIER ALONG BACK OF SIDEWALK FOR A LENGTH OF TWENTY FEET WHERE TREE TRUNK IS WITHIN FIVE FEET OF BACK OF SIDEWALK.

CHIEF, DEPT. OF TRANSPORTATION

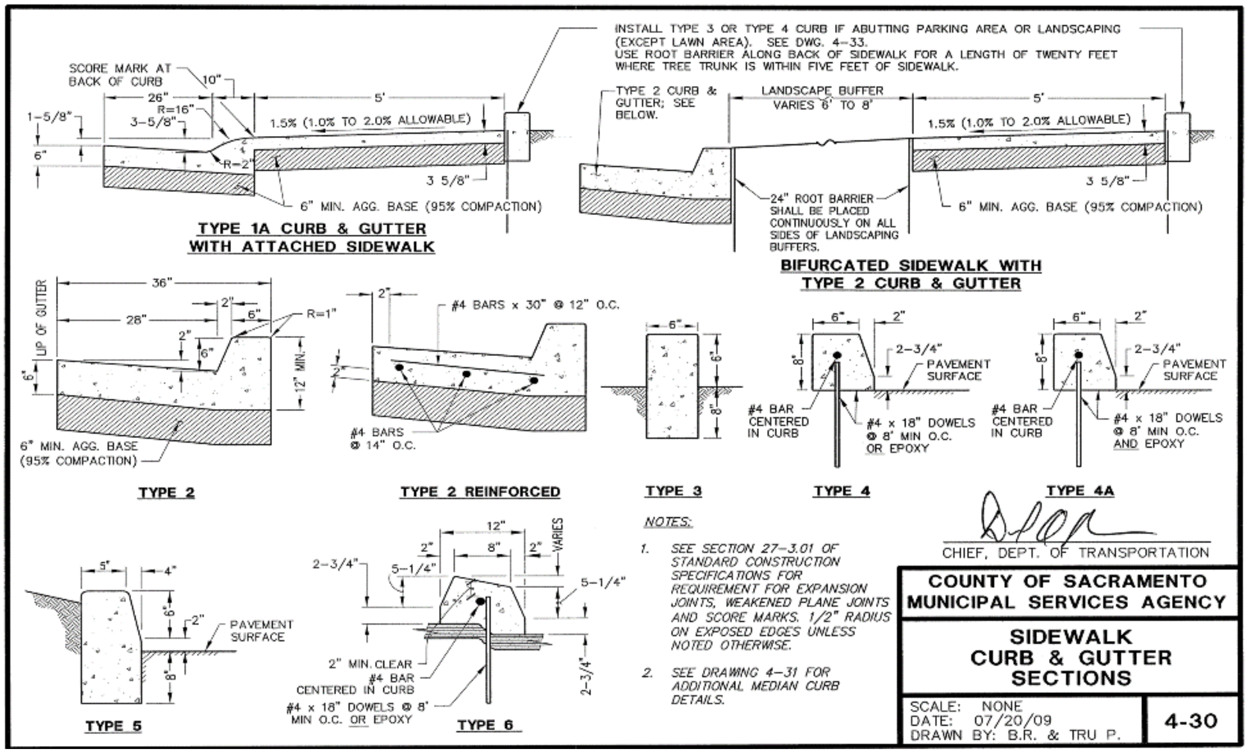
COUNTY OF SACRAMENTO
MUNICIPAL SERVICES AGENCY

TYPICAL SECTIONS
ARTERIAL & COLLECTOR
STREETS, CLASS A

SCALE: NONE
DATE: 06/08/09
DRAWN BY: B.R. & TRU P.

4-2

App-Figure 2: Cross Section of Collector, Major Collector, and Arterial Streets (Sacramento County 2009



NOTES:

1. SEE SECTION 27-3.01 OF STANDARD CONSTRUCTION SPECIFICATIONS FOR REQUIREMENT FOR EXPANSION JOINTS, WEAKENED PLANE JOINTS AND SCORE MARKS. 1/2" RADIUS ON EXPOSED EDGES UNLESS NOTED OTHERWISE.
2. SEE DRAWING 4-31 FOR ADDITIONAL MEDIAN CURB DETAILS.

CHIEF, DEPT. OF TRANSPORTATION

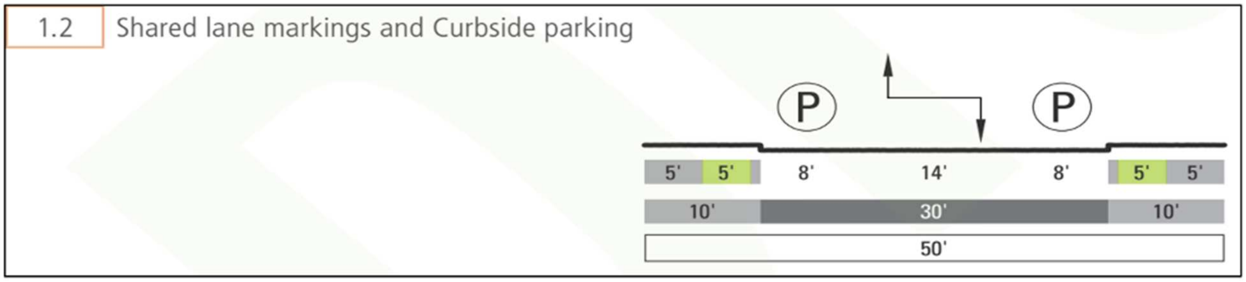
COUNTY OF SACRAMENTO
MUNICIPAL SERVICES AGENCY

SIDEWALK
CURB & GUTTER
SECTIONS

SCALE: NONE
DATE: 07/20/09
DRAWN BY: B.R. & TRU P.

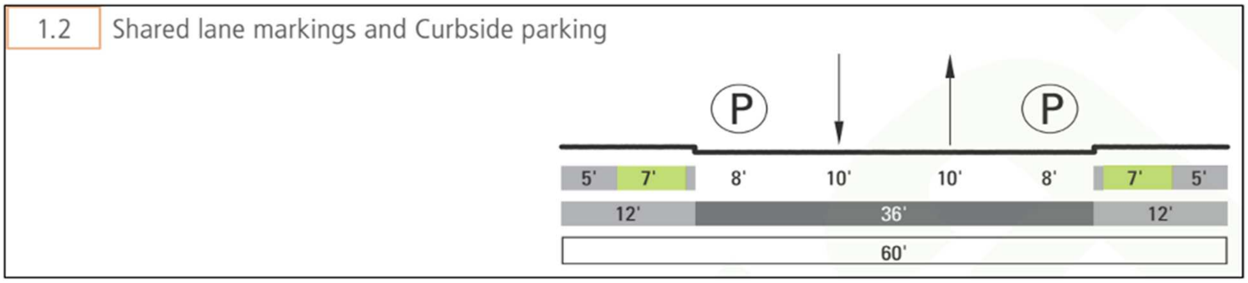
4-30

App-Figure 3: Cross section of Sidewalk, Curb, and Gutter (Sacramento County 2009)

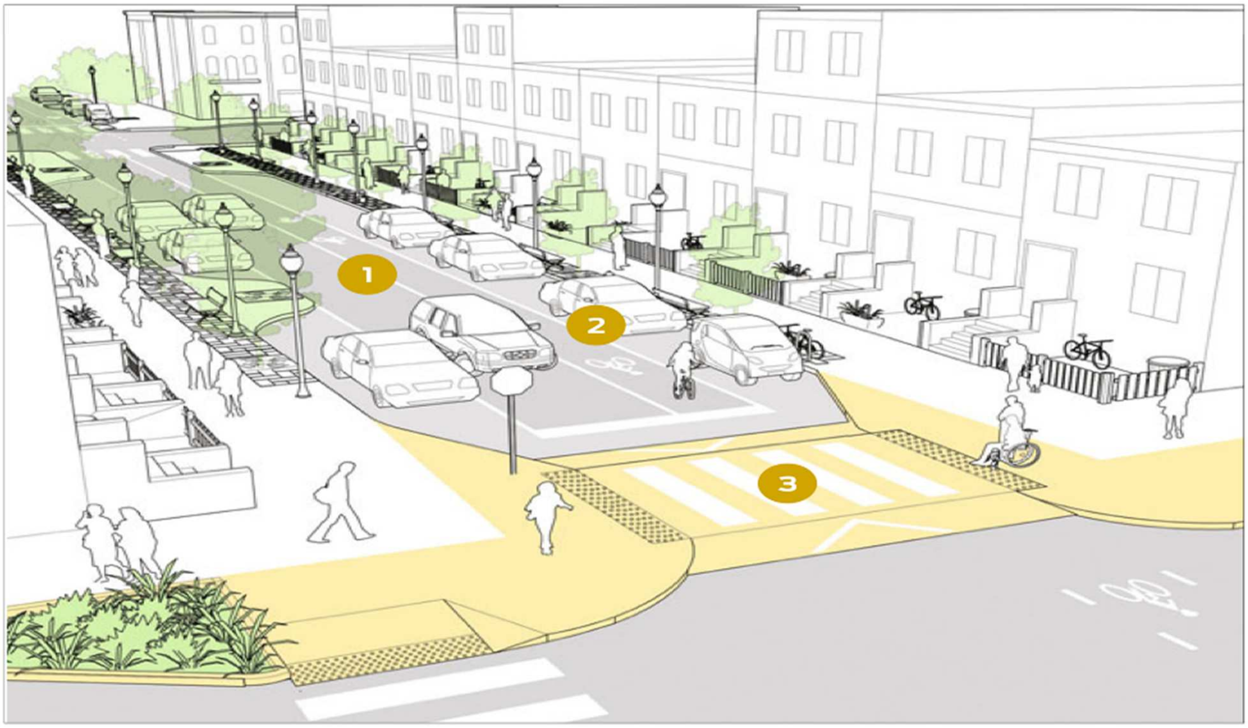


App-Figure 4: LA-DG Recommendation for Minor Residential Street (City of LA 2014)

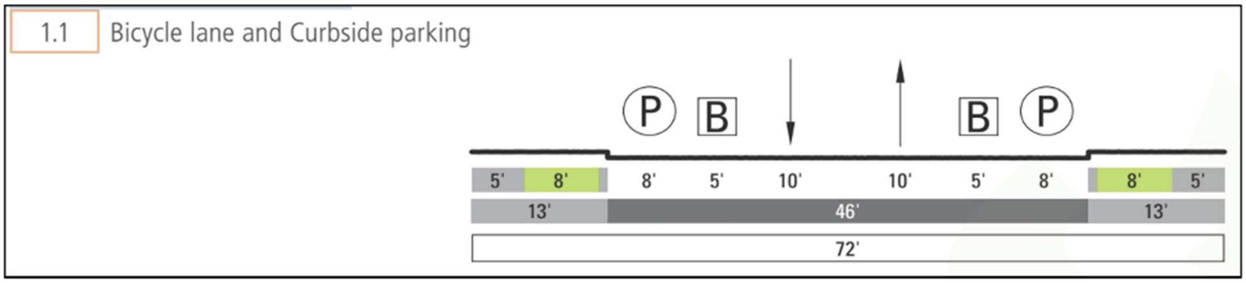
App-Figure 5: NACTO Recommendation for Minor Residential Street (From *Urban Street Design Guide*, by NACTO, pp. 17)



App-Figure 6: LA-DG Recommendation for Primary Residential Street (City of LA 2014)

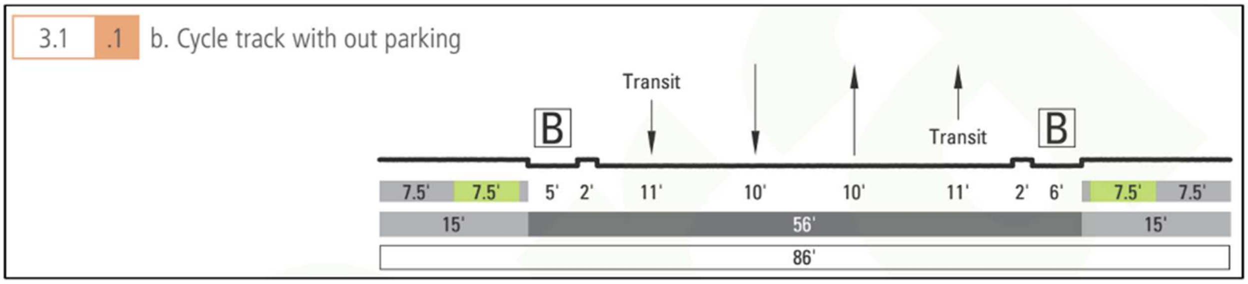


App-Figure 7: NACTO Recommendation for Primary Residential Streets (From(From *Urban Street Design Guide*, by NACTO, pp. 16.)



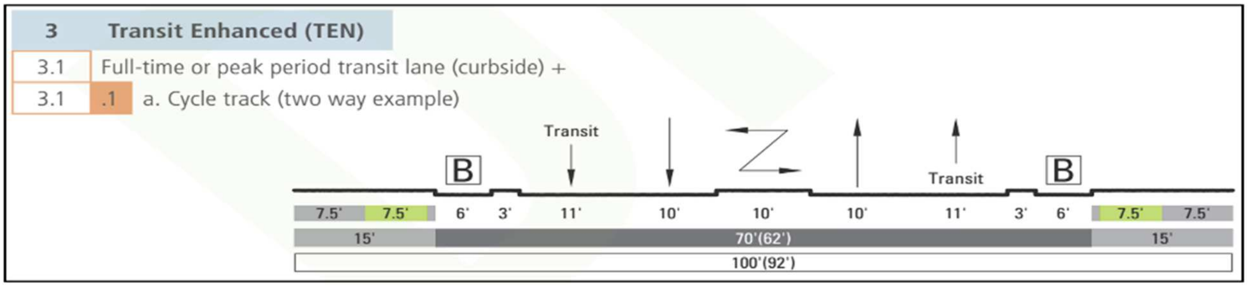
App-Figure 8: LA-DG Recommendation for Collector Street (City of LA 2014)

App-Figure 9: NACTO Recommendation for Collector Street (From *Urban Street Design Guide*, by NACTO, pp. 11.)



App-Figure 10: LA-DG Recommendation for Major Collector Street (City of LA 2014)

App-Figure 11. NACTO recommendation for Major Collector Street (From *Urban Street Design Guide*, by NACTO, pp. 15.)



App-Figure 12: LA-DG Recommendation for Arterial Street (City of LA 2014)

App-Figure 13: NACTO Recommendation for Major Arterial Street (From *Urban Street Design Guide*, by NACTO, pp. 13.)

App III-Section II. LCA Results for Materials, Surface Treatments, and Complete Street Elements

App-Table 6. LCI and PED Values Used for the Materials Used in this Study

Item	Functional Unit	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Aggregate, Crushed	1 kg	3.43E-03	6.53E-04	1.59E-06	6.05E-02	0.00E+00
Aggregate, Natural	1 kg	2.36E-03	4.04E-04	9.54E-07	4.31E-02	0.00E+00
Bitumen	1 kg	4.75E-01	8.09E-02	4.10E-04	4.97E+01	4.02E+01
Bitumen Emulsion (Residual Bitumen)	1 kg	5.07E-01	8.23E-02	4.17E-04	5.09E+01	4.02E+01
Blast Furnace Slag (Ground)	1 kg	1.03E-01	1.13E-02	1.16E-04	1.97E+00	0.00E+00
Crumb Rubber Modifier (CRM)	1 kg	2.13E-01	6.90E-03	1.05E-04	3.47E+01	3.02E+01
Diesel Burned in Equipment	1 gal.	1.19E+01	5.27E+00	9.37E-03	1.65E+02	0.00E+00
Dowel & Tie Bar	each	3.69E+00	1.30E-01	1.39E-03	4.87E+01	0.00E+00
Electricity	1 MJ	1.32E-01	4.28E-03	2.54E-05	2.92E+00	0.00E+00
Limestone	1 kg	4.44E-03	2.11E-04	8.24E-08	7.84E-02	0.00E+00
Natural Gas Combusted	1 m3	2.41E+00	5.30E-02	1.31E-03	3.84E+01	0.00E+00
Paint (GaBi)	1 kg	1.04E-02	1.28E-01	9.51E-07	1.68E-02	0.00E+00
Paraffin (Wax)	1 kg	1.37E+00	7.57E-02	4.70E-04	5.46E+01	0.00E+00
Polypropylene Fibers	1 kg	2.33E+00	8.65E-02	5.53E-04	8.39E+01	0.00E+00
PCA*, Accelerator	1 kg	1.26E+00	5.71E-02	1.88E-04	2.28E+01	0.00E+00
PCA*, Air Enterainer	1 kg	2.66E+00	8.68E+00	2.55E-03	2.10E+00	0.00E+00
PCA*, Plasticizer	1 kg	2.30E-01	1.34E-02	5.57E-05	4.60E+00	0.00E+00
PCA*, Retarder	1 kg	2.31E-01	4.23E-02	9.81E-05	1.57E+01	0.00E+00
PCA*, Superplasticizer	1 kg	7.70E-01	4.55E-02	2.33E-04	1.83E+01	0.00E+00
PCA*, Waterproofing	1 kg	1.32E-01	4.00E-02	6.74E-05	5.60E+00	0.00E+00
Portland Cement, Regular	1 kg	8.72E-01	7.28E-02	4.99E-04	5.94E+00	0.00E+00
Portland Cement, with 19% Slag	1 kg	7.04E-01	2.60E-02	1.78E-04	3.40E+00	0.00E+00
Portland Cement, with 50% Slag	1 kg	4.45E-01	1.76E-02	1.23E-04	2.75E+00	0.00E+00
Quicklime	1 kg	1.40E+00	3.52E-02	7.11E-04	7.88E+00	0.00E+00
Reclaimed Asphalt Pavement (RAP)	1 kg	7.16E-03	1.39E-03	2.70E-06	1.02E-01	0.00E+00
RC*, BPA	1 kg	3.73E+00	1.61E-01	9.92E-04	9.08E+01	0.00E+00
RC*, Polyester Styrene	1 kg	4.40E+00	2.08E-01	5.10E-03	9.17E+01	0.00E+00
RC*, Polyurethane	1 kg	2.34E+00	1.02E-01	9.24E-04	5.15E+01	0.00E+00
RC*, Styrene Acrylate	1 kg	1.56E+00	6.34E-02	4.92E-04	3.66E+01	0.00E+00
Styrene Butadiene Rubber (SBR)	1 kg	4.13E+00	1.29E-01	4.48E-04	1.03E+02	0.00E+00

* PCA: Portland Cement Admixture, RC: Reflective Coating

App-Table 7. LCIA and PED Values for 1 ln-km of Various Surface Treatments Applied in Construction of Urban Streets, with Typical Service Lives and Thicknesses

Item	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	Item	Funct-ional Unit
Aggregate, Crushed	1.44E+04	2.55E+03	5.49E+00	2.22E+05	0.00E+00	15	15
BCOA*	2.04E+05	2.11E+04	1.13E+02	1.60E+06	0.00E+00	15	10
BCOA (High SCM*)	8.40E+04	1.16E+04	4.78E+01	7.88E+05	0.00E+00	15	10
BCOA (Low SCM)	1.31E+05	1.32E+04	7.09E+01	1.10E+06	0.00E+00	15	10
Cape Seal	7.17E+03	1.58E+03	5.40E+00	1.35E+05	3.75E+05	6	NA
Chip Seal	4.93E+03	1.03E+03	3.70E+00	9.41E+04	2.69E+05	6	NA
Curb Type 5	2.54E+04	2.35E+03	1.39E+01	1.96E+05	0.00E+00	15	NA
Fog Seal	1.29E+03	2.69E+02	1.05E+00	2.56E+04	8.42E+04	3	NA
HMA (mill and fill)	3.81E+04	5.34E+03	2.35E+01	4.48E+05	1.22E+06	10	7.5
HMA (overlay)	3.35E+04	4.23E+03	2.14E+01	3.82E+05	1.22E+06	10	7.5
Paint (area)	6.36E-03	7.82E-02	5.81E-07	1.03E-02	0.00E+00	3	NA
Paint (linear)	4.84E-04	5.96E-03	4.43E-08	7.82E-04	0.00E+00	3	NA
Pavers	9.74E+04	1.17E+04	1.17E+02	9.77E+05	0.00E+00	15	NA
PCC	2.65E+05	2.46E+04	1.45E+02	2.05E+06	0.00E+00	20	17.5
PCC (High SCM)	1.16E+05	1.59E+04	6.57E+01	1.08E+06	0.00E+00	20	17.5
PCC (Low SCM)	1.88E+05	1.94E+04	1.02E+02	1.49E+06	0.00E+00	20	17.5
Permeable HMA	8.42E+04	1.16E+04	4.93E+01	1.40E+06	2.25E+06	10	27
Permeable PCC	2.51E+05	2.46E+04	1.36E+02	2.01E+06	0.00E+00	15	30
Permeable RHMA	8.96E+04	1.25E+04	5.40E+01	1.51E+06	2.70E+06	10	27
Planting (GaBi)	1.08E+02	2.24E+01	1.37E-01	1.61E+03	0.00E+00	5	NA
RC*, Bisphenol A (BPA)	1.06E+04	5.38E+02	2.91E+00	2.55E+05	0.00E+00	2	NA
RC, Polyester Styrene	1.24E+04	6.68E+02	1.43E+01	2.58E+05	0.00E+00	2	NA
RC, Polyurethane	8.88E+03	4.71E+02	3.58E+00	1.94E+05	0.00E+00	2	NA
RC, Styrene Acrylate	5.98E+03	3.27E+02	1.99E+00	1.39E+05	0.00E+00	2	NA
RHMA (mill and fill)	3.65E+04	5.08E+03	2.28E+01	3.78E+05	1.31E+06	10	5
RHMA Concrete (overlay)	3.25E+04	4.06E+03	2.09E+01	3.21E+05	1.31E+06	10	5
Sand Seal	2.67E+03	6.57E+02	1.98E+00	4.84E+04	1.18E+05	6	NA
Slurry Seal	2.24E+03	5.52E+02	1.71E+00	4.11E+04	1.06E+05	6	NA

* BCOA: Bonded Concrete Overlay on Asphalt, SCM: Supplementary Cementitious Materials, RC: reflective coating

App-Table 8. LCI and PED of MAC of Each of the CS Elements Used in This Study

CS Element	Serv. Life (yrs.)	Material Used	L* (m)	W* (m)	Area (m2)	Thick. (cm)	Vol. (m3)	Quantity (kg/m3) (kg/m2) (kg/m)	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Buffered Cycle Track	3	Paint (area)	1.00	1.00	1.00	NA	NA	0.61	1.72E-06	2.11E-05	1.57E-10	2.78E-06	0.00E+00
Coloring Lanes	3	Paint (area)	1.00	1.00	1.00	NA	NA	0.61	1.72E-06	2.11E-05	1.57E-10	2.78E-06	0.00E+00
Curb Extension	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00
Curb Type 5	15	PCC	1.00	NA	NA	NA	NA	149	2.54E+01	2.35E+00	1.39E-02	1.96E+02	0.00E+00
Island	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00
Planted Furniture Zone	5	Planting	1.00	1.00	1.00	NA	NA	1300	1.08E-02	2.24E-03	1.37E-05	1.61E-01	0.00E+00
Raised Bicycle Buffer	10	HMA (overlay)	1.00	NA	NA	NA	NA	9	4.67E-01	5.90E-02	2.99E-04	5.33E+00	1.70E+01
Raised Cycle Track	10	HMA (overlay)	1.00	1.00	1.00	NA	NA	122	6.13E+00	7.75E-01	3.93E-03	7.00E+01	2.23E+02
Raised Middle Lane	10	HMA (overlay)	1.00	1.00	1.00	NA	NA	122	6.13E+00	7.75E-01	3.93E-03	7.00E+01	2.23E+02
Raising the Intersection*	10	HMA (overlay)	1.00	1.00	1.00	NA	NA	244	1.23E+01	1.55E+00	7.85E-03	1.40E+02	4.45E+02
Shelter/Transit station	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00
Striping	3	Paint (linear)	1.00	NA	NA	NA	NA	0.05	4.84E-07	5.96E-06	4.43E-11	7.82E-07	0.00E+00
Pervious Pavement	10	Permeable HMA	1.00	1.00	1.00	100.0	1.00	2400	8.43E+01	1.16E+01	4.94E-02	1.40E+03	2.25E+03
Widening Sidewalk	15	PCC on AB	1.00	1.00	1.00	NA	NA	602	4.17E+01	4.19E+00	2.22E-02	3.53E+02	0.00E+00

* L: Length, W: Width, Raising the Intersection to Sidewalk Grade

App III-Section III. LCA Results for Conventional Streets

In all the tables below:

# of App:	Number of treatment application during the analysis period
SL:	Service Life
SV:	Salvage value at the end of analysis period (expressed as percent of service life)
T:	Thickness
W:	Width

App-Table 9. Itemized Impacts of The Conv. Option During the Analysis Period for a Minor Residential 1 Block)

Total	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	9.18E+03	1.16E+03	5.88E+00	1.05E+05	3.34E+05	10.0	7.6	3	0%	3.70	1	Street Top Layer	19.1%
Aggregate, Crushed	4.39E+03	7.77E+02	1.67E+00	6.77E+04	0.00E+00	15.0	25.4	2	0%	3.70	1	Street AB	9.1%
PCC	1.54E+04	1.43E+03	8.44E+00	1.19E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	32.1%
Aggregate, Crushed	1.30E+03	2.30E+02	4.96E-01	2.01E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	2.7%
Planting	2.13E+01	1.20E+01	7.31E-02	8.59E+02	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	1.55E+04	1.44E+03	8.50E+00	1.20E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	32.3%
Aggregate, Crushed	2.17E+03	3.84E+02	8.27E-01	3.34E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	4.5%

App-Table 10. Itemized Impacts of the Conv. Option During the Analysis Period for A Primary Residential 1 Block)

Total	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	3.76E+04	4.76E+03	2.41E+01	4.30E+05	1.37E+06	10.0	7.6	3	0%	3.70	3	Street Top Layer	34.5%
Aggregate, Crushed	1.80E+04	3.19E+03	6.86E+00	2.77E+05	0.00E+00	15.0	25.4	2	0%	3.70	3	Street AB	16.5%
PCC	2.40E+04	2.22E+03	1.31E+01	1.85E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	22.0%
Aggregate, Crushed	2.02E+03	3.59E+02	7.72E-01	3.12E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.9%
Planting	3.31E+01	1.86E+01	1.14E-01	1.34E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	2.42E+04	2.24E+03	1.32E+01	1.87E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	22.1%
Aggregate, Crushed	3.37E+03	5.98E+02	1.29E+00	5.20E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	3.1%

App-Table 11. Itemized Impacts of the Conv. Option During the Analysis Period for a Collector (1 Block)

Total	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	6.79E+04	8.59E+03	4.35E+01	7.76E+05	2.47E+06	10.0	8.9	3	0%	3.70	3	Street Top Layer	40.6%
Aggregate, Crushed	3.62E+04	6.41E+03	1.38E+01	5.58E+05	0.00E+00	15.0	33.0	2	0%	3.70	3	Street AB	21.6%
PCC	2.83E+04	2.62E+03	1.55E+01	2.18E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	16.9%

Total	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
Aggregate, Crushed	2.39E+03	4.23E+02	9.10E-01	3.68E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.4%
Planting	3.91E+01	2.19E+01	1.34E-01	1.58E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	2.85E+04	2.63E+03	1.56E+01	2.20E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	17.0%
Aggregate, Crushed	3.98E+03	7.04E+02	1.52E+00	6.13E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	2.4%

App-Table 12. Itemized Impacts of the Conv. Option During the Analysis Period for a Major Collector (1 Block)

Total	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	1.24E+05	1.57E+04	7.95E+01	1.42E+06	4.51E+06	10.0	10.2	3	0%	3.70	4	Street Top Layer	46.8%
Aggregate, Crushed	6.23E+04	1.10E+04	2.37E+01	9.60E+05	0.00E+00	15.0	35.6	2	0%	3.70	4	Street AB	23.5%
PCC	3.51E+04	3.25E+03	1.92E+01	2.71E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	13.3%
Aggregate, Crushed	2.96E+03	5.25E+02	1.13E+00	4.57E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	1.1%
Planting	4.85E+01	2.73E+01	1.66E-01	1.96E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	3.54E+04	3.27E+03	1.94E+01	2.73E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	13.4%
Aggregate, Crushed	4.94E+03	8.75E+02	1.88E+00	7.62E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	1.9%

App-Table 13. Itemized Impacts of the Conv. Option During the Analysis Period for an Arterial (1 Block)

Total	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	2.20E+05	2.78E+04	1.41E+02	2.51E+06	7.99E+06	10.0	14.0	3	0%	3.70	5	Street Top Layer	47.7%
Aggregate, Crushed	1.18E+05	2.08E+04	4.48E+01	1.81E+06	0.00E+00	15.0	52.1	2	0%	3.70	5	Street AB	25.5%
Planting	1.21E+02	6.78E+01	4.14E-01	4.87E+03	0.00E+00	5.0	NA	6	0%	3.66	2	Landscape	0.0%
Curb Type 5	2.63E+04	2.43E+03	1.44E+01	2.03E+05	0.00E+00	15.0	NA	2	0%	3.66	1	Curb around Median	5.7%
PCC	4.37E+04	4.04E+03	2.39E+01	3.38E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	9.5%
Aggregate, Crushed	3.69E+03	6.53E+02	1.41E+00	5.69E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	0.8%
Planting	6.04E+01	3.39E+01	2.07E-01	2.44E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	4.40E+04	4.07E+03	2.41E+01	3.40E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	9.5%
Aggregate, Crushed	6.15E+03	1.09E+03	2.34E+00	9.48E+04	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	1.3%

App-Table 14. Itemized Impacts of the Conv. Option During the Analysis Period for a Thoroughfare (1 Block)

Total	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
HMA (overlay)	4.47E+05	5.65E+04	2.86E+02	5.11E+06	1.62E+07	10.0	16.8	3	0%	3.70	6	Street Top Layer	61.1%
Aggregate, Crushed	2.23E+05	3.96E+04	8.52E+01	3.44E+06	0.00E+00	15.0	58.4	2	0%	3.70	6	Street AB	30.6%
Planting	1.47E+02	8.24E+01	5.03E-01	5.92E+03	0.00E+00	5.0	100.0	6	0%	3.66	2	Landscape	0.0%
Curb Type 5	3.18E+04	2.95E+03	1.74E+01	2.46E+05	0.00E+00	15.0	NA	2	0%	3.66	1	Curb around Median	4.4%
PCC	5.31E+04	4.91E+03	2.91E+01	4.10E+05	0.00E+00	20.0	15.2	2	50%	0.91	2	Curb & Gutter Surface	7.3%
Aggregate, Crushed	4.48E+03	7.94E+02	1.71E+00	6.91E+04	0.00E+00	15.0	15.2	2	0%	0.91	2	Curb & Gutter AB	0.6%

Total	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]	SL* (yrs.)	T* (cm)	# of App*	SV*	W* (m)	# per Block	Note	% of Total GWP
Planting	7.34E+01	4.12E+01	2.52E-01	2.96E+03	0.00E+00	5.0	NA	6	0%	1.83	2	Landscape	0.0%
PCC	5.35E+04	4.95E+03	2.93E+01	4.13E+05	0.00E+00	20.0	9.2	2	50%	1.52	2	Sidewalk Surface	7.3%
Aggregate, Crushed	7.47E+03	1.32E+03	2.85E+00	1.15E+05	0.00E+00	15.0	15.2	2	0%	1.52	2	Sidewalk AB	1.0%

* SL: Service Life

T: Thickness

# of App.: Number of treatment application during the analysis period

W: Width

SV: Salvage value at the end of analysis period (expressed as % of service life)

App III-Section IV. LCA Results for Complete Streets

In all the table below:

- # of App: Number of treatment application during the analysis period
- percentConv rep. by CS* Percent of surface area normally covered by Conv. options that is now covered by CS elements
- L: Length
- Mat: Material
- SL: Service Life
- SV: Salvage value at the end of analysis period (expressed as percent of service life)
- T: Thickness
- W: Width

App-Table 15. Itemized Impacts of the CS Element During the Analysis Period for a Minor Residential (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block*	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App*	SV*	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Coloring Lanes	3	Paint (area)	1	90	2.13	192	0%	NA	NA	192	10	0%	3.30E-03	4.06E-02	3.02E-07	5.33E-03	0.00E+00
Curb Extension	15	PCC on AB	2	8	2.44	20	100%	NA	NA	39	2	0%	3.25E+03	3.27E+02	1.73E+00	2.75E+04	0.00E+00

App-Table 16. Itemized Impacts of the CS Element During the Analysis Period for a Primary Residential (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block*	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App*	SV*	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Coloring Lanes	3	Paint (area)	1	140	2.13	299	0%	NA	NA	299	10	0%	5.13E-03	6.32E-02	4.69E-07	8.29E-03	0.00E+00
Curb Extension	15	PCC on AB	3	8	2.44	20	100%	NA	NA	59	2	0%	4.88E+03	4.91E+02	2.59E+00	4.13E+04	0.00E+00

App-Table 17. Itemized Impacts of the CS Element During the Analysis Period for a Collector (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block*	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App*	SV*	GWP [kg CO_2e]	POCP [kg O_3e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Coloring Lanes	3	Paint (area)	2	165	2.13	352	0%	NA	NA	704	10	0%	1.21E-02	1.49E-01	1.11E-06	1.95E-02	0.00E+00
Shelter/Transit station	15	PCC on AB	1	15	3.00	45	100%	NA	NA	45	2	0%	3.75E+03	3.77E+02	1.99E+00	3.17E+04	0.00E+00

App-Table 18. Itemized Impacts of the CS Element During the Analysis Period for a Major Collector (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block*	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App*	SV*	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Coloring Lanes	3	Paint (area)	2	205	1.68	344	0%	NA	NA	687	10	0%	1.18E-02	1.45E-01	1.08E-06	1.91E-02	0.00E+00
Curb Extension	15	PCC on AB	4	8	2.44	20	100%	NA	NA	78	2	0%	6.51E+03	6.54E+02	3.46E+00	5.50E+04	0.00E+00
Planted Furniture Zone	5	Planting	1	185	0.91	169	100%	NA	NA	169	6	0%	1.09E+01	2.28E+00	1.39E-02	1.63E+02	0.00E+00
Curb Type 5	15	PCC	1	372	NA	NA	0%	NA	NA	372	2	0%	1.89E+04	1.75E+03	1.03E+01	1.46E+05	0.00E+00
Coloring Lanes	3	Paint (area)	2	205	3.35	687	0%	NA	NA	1375	10	0%	2.36E-02	2.91E-01	2.16E-06	3.81E-02	0.00E+00
Raised Bicycle Buffer	10	HMA (overlay)	2	205	NA	NA	0%	NA	NA	410	3	0%	5.74E+02	7.26E+01	3.68E-01	6.56E+03	2.09E+04

App-Table 19. Itemized Impacts of the CS Element During the Analysis Period for an Arterial (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block*	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App*	SV*	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Coloring Lanes	3	Paint (area)	2	255	1.68	427	0%	NA	NA	855	10	0%	1.47E-02	1.81E-01	1.34E-06	2.37E-02	0.00E+00
Raised Bicycle Buffer	10	HMA (overlay)	2	255	NA	NA	0%	NA	NA	510	3	0%	7.14E+02	9.03E+01	4.58E-01	8.16E+03	2.59E+04
Coloring Lanes	3	Paint (area)	2	255	3.35	855	0%	NA	NA	1710	10	0%	2.94E-02	3.62E-01	2.69E-06	4.75E-02	0.00E+00
Shelter/Transit station	15	PCC on AB	1	8	3.00	24	100%	NA	NA	24	2	0%	2.00E+03	2.01E+02	1.06E+00	1.69E+04	0.00E+00
Island	15	PCC on AB	1	4	1.00	4	100%	NA	NA	4	2	0%	3.34E+02	3.35E+01	1.77E-01	2.82E+03	0.00E+00

App-Table 20. Itemized Impacts of the CS Element During the Analysis Period for a Thoroughfare (1 Block)

CS Element	SL* (yrs.)	Mat*	# per Block*	L* (m)	W* (m)	Area (m2)	%Conv rep. by CS*	T* (cm)	V* (m3)	Total	# of App*	SV*	GWP [kg CO$_2$e]	POCP [kg O$_3$e]	PM2.5 [kg]	PED (Total) [MJ]	PED (Non-Fuel) [MJ]
Coloring Lanes	3	Paint (area)	2	310	1.68	520	0%	NA	NA	1039	10	0%	1.79E-02	2.20E-01	1.63E-06	2.88E-02	0.00E+00
Raised Bicycle Buffer	10	HMA (overlay)	5	310	NA	NA	0%	NA	NA	1550	3	0%	2.17E+03	2.75E+02	1.39E+00	2.48E+04	7.89E+04
Coloring Lanes	3	Paint (area)	2	310	3.96	1228	0%	NA	NA	2457	10	0%	4.22E-02	5.19E-01	3.86E-06	6.82E-02	0.00E+00
Shelter/Transit station	15	PCC on AB	1	310	3.05	945	100%	NA	NA	945	2	0%	7.88E+04	7.92E+03	4.19E+01	6.66E+05	0.00E+00
Island	15	PCC on AB	2	3	1.00	3	100%	NA	NA	6	2	0%	5.00E+02	5.03E+01	2.66E-01	4.23E+03	0.00E+00

APPENDIX III. Increased Use of RAP

App-Table 25. Amount of HMA and RHMA in MMT (Million Metric Tonnes) predicted to be used in Caltrans's statewide pavement projects between 2017 and 2050

Year	HMA	RHMA	RHMA / HMA	Total
2017	3.28	1.72	0.52	5.00
2018	0.31	0.16	0.52	0.48
2019	0.32	0.17	0.52	0.49
2020	0.33	0.17	0.52	0.51
2021	0.76	0.40	0.52	1.16
2022	1.29	0.67	0.52	1.96
2023	1.77	0.92	0.52	2.69
2024	1.70	0.89	0.52	2.58
2025	1.42	0.75	0.52	2.17
2026	1.35	0.71	0.52	2.06
2027	1.08	0.56	0.52	1.64
2028	1.83	0.96	0.52	2.78
2029	1.65	0.86	0.52	2.52
2030	1.21	0.63	0.52	1.84
2031	1.32	0.69	0.52	2.02
2032	1.30	0.68	0.52	1.98
2033	1.54	0.81	0.52	2.34
2034	1.79	0.94	0.52	2.73
2035	1.46	0.77	0.52	2.23
2036	1.20	0.63	0.52	1.83
2037	1.12	0.59	0.52	1.71
2038	1.30	0.68	0.52	1.98
2039	1.88	0.98	0.52	2.86
2040	1.28	0.67	0.52	1.96
2041	1.70	0.89	0.52	2.59
2042	0.89	0.46	0.52	1.35
2043	0.90	0.47	0.52	1.37
2044	1.56	0.81	0.52	2.37
2045	1.36	0.71	0.52	2.08
2046	1.22	0.64	0.52	1.86
2047	1.40	0.74	0.52	2.14
2048	1.40	0.74	0.52	2.14
2049	1.40	0.74	0.52	2.14
2050	1.40	0.74	0.52	2.14

App-Table 26. Baseline mix designs (mass-based) for HMA and RHMA to be used in Caltrans' pavement projects

Item	HMA	RHMA
Aggregate	81.0%	92.5%
Bitumen	4.0%	5.8%
Crumb Rubber Modifier	0.0%	1.5%
Extender Oil	0.0%	0.2%
RAP	15.0%	0.0%

App-Table 27. GHG emissions (Tonnes CO_2e per year) due to HMA and RHMA material production stage in all Caltrans' statewide pavement projects during the analysis period of 2018-2050

Year	HMA (Max 15% RAP)	HMA (Max 25% RAP, no Rejuv)	HMA (Max 25% RAP, Bio-based)	HMA (Max 25% RAP, Aromatic)	HMA (Max 40% RAP, Bio-based)	HMA (Max 40% RAP, Aromatic)	HMA (Max 50% RAP, Bio-based)	HMA (Max 50% RAP, Aromatic)	RHMA-G
2018	104,409	100,936	101,998	103,702	96,635	99,020	94,571	97,979	114,701
2019	108,165	104,567	105,667	107,432	100,111	102,582	97,973	101,503	118,827
2020	110,755	107,072	108,198	110,005	102,509	105,039	100,320	103,934	121,673
2021	254,304	245,846	248,432	252,581	235,370	241,179	230,343	238,642	279,373
2022	429,757	415,464	419,834	426,846	397,760	407,577	389,265	403,290	472,122
2023	588,943	569,356	575,344	584,954	545,094	558,548	533,453	552,672	647,000
2024	565,516	546,708	552,458	561,686	523,412	536,330	512,233	530,688	621,264
2025	474,580	458,797	463,622	471,366	439,246	450,087	429,865	445,353	521,364
2026	450,378	435,399	439,979	447,327	416,846	427,134	407,943	422,641	494,775
2027	359,021	347,080	350,731	356,589	332,291	340,492	325,194	336,910	394,413
2028	609,494	589,223	595,421	605,366	564,115	578,038	552,067	571,957	669,577
2029	550,561	532,250	537,848	546,832	509,570	522,146	498,687	516,654	604,834
2030	402,144	388,769	392,859	399,420	372,203	381,390	364,254	377,378	441,787
2031	441,822	427,128	431,620	438,830	408,927	419,020	400,194	414,612	485,376
2032	433,480	419,063	423,471	430,544	401,206	411,108	392,638	406,784	476,212
2033	512,934	495,875	501,091	509,460	474,745	486,462	464,606	481,345	563,499
2034	597,174	577,313	583,385	593,129	552,712	566,354	540,908	560,396	656,042
2035	488,037	471,806	476,768	484,731	451,701	462,849	442,054	457,981	536,147
2036	401,039	387,701	391,779	398,323	371,180	380,341	363,253	376,340	440,573
2037	374,194	361,749	365,554	371,659	346,334	354,882	338,937	351,149	411,081
2038	433,536	419,117	423,525	430,599	401,257	411,161	392,688	406,836	476,273
2039	625,507	604,704	611,064	621,270	578,936	593,225	566,572	586,984	687,169
2040	428,491	414,240	418,597	425,589	396,588	406,377	388,119	402,102	470,731
2041	567,653	548,774	554,546	563,808	525,389	538,357	514,169	532,693	623,611
2042	296,170	286,320	289,332	294,164	274,119	280,885	268,265	277,930	325,366
2043	300,215	290,230	293,283	298,182	277,863	284,721	271,929	281,726	329,810
2044	519,113	501,848	507,127	515,597	480,464	492,322	470,202	487,143	570,287
2045	454,448	439,334	443,955	451,370	420,613	430,994	411,630	426,461	499,247
2046	407,142	393,601	397,741	404,385	376,829	386,130	368,781	382,068	447,278
2047	460,109	444,806	449,485	456,992	425,852	436,363	416,757	431,772	505,466
2048	465,163	449,693	454,423	462,013	430,530	441,156	421,335	436,515	511,018
2049	457,947	442,716	447,373	454,845	423,851	434,312	414,799	429,743	503,090
2050	453,316	438,239	442,849	450,246	419,565	429,920	410,605	425,398	498,003

Year	HMA (Max 15% RAP)	HMA (Max 25% RAP, no Rejuv)	HMA (Max 25% RAP, Bio-based)	HMA (Max 25% RAP, Aromatic)	HMA (Max 40% RAP, Bio-based)	HMA (Max 40% RAP, Aromatic)	HMA (Max 50% RAP, Bio-based)	HMA (Max 50% RAP, Aromatic)	RHMA-G
Total	**14,125,517**	**13,655,723**	**13,799,359**	**14,029,843**	**13,073,824**	**13,396,501**	**12,794,611**	**13,255,578**	**15,517,988**

App-Table 28. Cost savings per year across the whole network for each HMA scenario

Year	Total Treated (ln-mi)	HMA (Tonne)	Cost Savings vs Baseline (Million $)		
			HMA (Max 25% RAP)	HMA (Max 40% RAP)	HMA (Max 50% RAP)
2018	704	3.1E+5	0.48	2.03	2.51
2019	729	3.2E+5	0.49	2.10	2.60
2020	747	3.3E+5	0.51	2.15	2.66
2021	1,714	7.6E+5	1.16	4.94	6.11
2022	2,897	1.3E+6	1.97	8.36	10.32
2023	3,970	1.8E+6	2.69	11.45	14.15
2024	3,812	1.7E+6	2.59	11.00	13.58
2025	3,199	1.4E+6	2.17	9.23	11.40
2026	3,036	1.4E+6	2.06	8.76	10.82
2027	2,420	1.1E+6	1.64	6.98	8.62
2028	4,108	1.8E+6	2.79	11.85	14.64
2029	3,711	1.7E+6	2.52	10.70	13.22
2030	2,711	1.2E+6	1.84	7.82	9.66
2031	2,978	1.3E+6	2.02	8.59	10.61
2032	2,922	1.3E+6	1.98	8.43	10.41
2033	3,457	1.5E+6	2.35	9.97	12.32
2034	4,025	1.8E+6	2.73	11.61	14.34
2035	3,290	1.5E+6	2.23	9.49	11.72
2036	2,703	1.2E+6	1.83	7.80	9.63
2037	2,522	1.1E+6	1.71	7.28	8.99
2038	2,922	1.3E+6	1.98	8.43	10.41
2039	4,216	1.9E+6	2.86	12.16	15.02
2040	2,888	1.3E+6	1.96	8.33	10.29
2041	3,826	1.7E+6	2.60	11.04	13.63
2042	1,996	8.9E+5	1.35	5.76	7.11
2043	2,024	9.0E+5	1.37	5.84	7.21
2044	3,499	1.6E+6	2.37	10.09	12.47
2045	3,063	1.4E+6	2.08	8.84	10.92
2046	2,744	1.2E+6	1.86	7.92	9.78
2047	3,158	1.4E+6	2.14	9.11	11.25
2048	3,158	1.4E+6	2.14	9.11	11.25
2049	3,158	1.4E+6	2.14	9.11	11.25
2050	3,158	1.4E+6	2.14	9.11	11.25
Total	**95,463**	**4.2E+7**	**64.8**	**275.4**	**340.2**