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16. ABSTRACT

The California Department of Transportation (Caltrans) has a growing need to be able to quantify its greenhouse gas (GHG) emissions and the other environmental impacts of pavement operations, and to consider GHG and those other impacts in pavement management, conceptual design, design, materials selection, and construction project delivery decisions. Caltrans also needs to be able to evaluate the life cycle environmental impacts as part of policy and standards development. All these tasks can be performed using life cycle assessment (LCA), although there are different constraints and requirements with respect to the scope of the LCA and the data available for each of these different applications. The web-based software environmental Life Cycle Assessment for Pavements (eLCAP) is a project-level LCA tool that uses California- and Caltrans-specific life cycle inventories (LCIs) and processes. The LCI database has been critically reviewed by outside experts following ISO standards. eLCAP models the life cycle history of a pavement project by allowing a user to specify any number of construction-type events, occurring at a user-specified date, followed by an automatically generated Use Stage event that begins immediately afterward and lasts until the next construction-type event or the end-of-life date. The Use Stage models currently consider the effects of roughness in terms of International Roughness Index and use the same performance models that are used in the Caltrans pavement asset management system software, PaveM. eLCAP performs a formal mass-balancing procedure on a pavement LCA project model and then computes 18 different impact category values including Global Warming Potential, Human Health Particulate Air, Acidification, and different forms of Primary Energy and generates a detailed Excel report file to display graphs and tables of results. The results can be presented in terms of life cycle stage, material types, and other details.

17. KEY WORDS

life cycle assessment, environmental life cycle assessment, life cycle inventory, greenhouse gas, use stage, web application, cradle-to-gate

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# eLCAP: A Web Application for Environmental Life Cycle Assessment for Pavements

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Funded by Partnered Pavement Research Center (PPRC) Project Numbers 3.46 (DRISI Task 3207, “Environmental Life-Cycle Analysis Tool for Project Level Use”), 4.54 (DRISI Task 2718, “Environmental Life Cycle Assessment Updates and Applications”), and 4.66 (DRISI Task 3191, “Environmental Life Cycle Assessment Updates and Applications”), and with funds from the University of California Pavement Research Center

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## LIST OF ABBREVIATIONS

---

AB	Aggregate base
AADT	Annual average daily traffic
AADTT	Annual average daily truck traffic
ASP	Active Server Pages
BLL	Business logic layer
CCPR	Cold central plant recycling
CLR	Common language runtime
CSS	Cascading Style Sheets
CSV	Comma separated values
DAL	Data access layer
DLL	Dynamic link library
DB	Database
EPA	Environmental Protection Agency
EPD	Environmental product declarations
ESAL	Equivalent single axel loads
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GWP	Global warming potential
HMA	Hot mix asphalt
ICE	Infrastructure Carbon Estimator
IPR	In-place recycled
IRI	International Roughness Index
LCA	Life cycle assessment
LCI	Life cycle inventories
LCIA	Life cycle impact assessment
MOVES	MOtor Vehicle Emission Simulator
MPD	Mean profile depth
NREL	National Renewable Energy Lab
PCC	Portland cement concrete
PCE	Passenger car equivalent
PM	Post mile
PPRC	Partnered Pavement Research Center
PS	Paved shoulder
RAP	Reclaimed asphalt pavement

RCA	Recycled concrete aggregate
RPC	Remote procedure call
TW	Traveled way
UCPRC	University of California Pavement Research Center
UI	User interface
UPS	Unpaved shoulder
WIM	Weigh-in-motion

## SI\* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

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

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

## PROJECT OBJECTIVES

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This project is part of Partnered Pavement Research Center Strategic Plan Elements (PPRC SPEs) 3.46, “Environmental Life Cycle Assessment Tool for Project-Level Use,” and 3.55, “Implementation of Environmental Life Cycle Assessment (LCA) Data and Models for Project-Level Use in the eLCAP Software.” The coding and software development were partially funded using internal University of California Pavement Research Center (UCPRC) funds.

The objective of Project 3.55 is to continue the development of a web-based online pavement LCA tool that uses California-specific datasets for energy and material and that follows Caltrans construction practices. The tool will be updated using information developed by the UCPRC for Caltrans in previous projects (4.66: Environmental Life Cycle Assessment Updates and Applications and 4.73: Fast Model Energy Consumption Structural Response) and the companion project in the current contract (4.80: Environmental LCA Updates and Applications). The tool will be consistent with the Federal Highway Administration (FHWA) Pavement Life Cycle Assessment Framework and the work of federal agencies (including FHWA) in the Federal Commons initiative.

The data and procedures in *eLCAP* will be updated for use at the conceptual-level design and project-level design stages. User interfaces and documentation for the tool will also be updated based on user feedback. *eLCAP* will also be further updated so it is compatible with how *PaveM* calculates roughness performance and greenhouse gas (GHG) emissions and other LCA updates that may be made in *PaveM*. The work will include an outside critical review of the tool itself (the inventories and models will be subject to a formal outside critical review as part of Project 4.80).

The objective of Project 3.55 will be achieved by completing its following tasks:

- Task 1: Update *eLCAP* with improved and new models at every pavement life cycle stage.
- Task 2: Implement a conceptual design-level module for roadway analysis.
- Task 3: Update the user interface and system requirements.
- Task 4: Implement *eLCAP* after review and testing by UCPRC and Caltrans.
- Task 5: Submit the tool for outside critical review and respond to comments.
- Task 6: Update the software, software documentation, and help system.

This technical memorandum is one deliverable satisfying Task 6. It should be noted that the *eLCAP* software discussed and depicted in this technical memorandum represented the most recent version of the software available at the time of the writing. However, as the development of *eLCAP* is continual, the software’s functions, user steps, and/or interface may be different at a later date.

# 1 OVERVIEW

---

## 1.1 Need for eLCAP

The California Department of Transportation (Caltrans) has a growing need to be able to quantify its greenhouse gas (GHG) emissions and the other environmental impacts of pavement operations, and to consider GHG and those other impacts in pavement management, conceptual design, design, materials selection, and construction project delivery decisions. Caltrans also needs to be able to evaluate the life cycle environmental impacts as part of policy and standards development. All these tasks can be performed using life cycle assessment (LCA), though there are different constraints and requirements with respect to the scope of the LCA and the data available for each of these different applications.

Caltrans currently uses the *PaveM* asset management software for pavement management. This software includes models for roughness, in terms of the International Roughness Index (IRI), that are used with previously developed life cycle inventories (LCIs) to calculate GHG emissions at the network level for planned scenarios of treatments versus “do nothing.”

Caltrans is also currently using a spreadsheet-based LCA tool from the Federal Highway Administration (FHWA) called the *Infrastructure Carbon Estimator (ICE) (1)* to obtain an estimate for GHG production at an earlier stage in project development<sup>1</sup> than what *environmental Life Cycle Assessment for Pavements (eLCAP)* operates at for the purposes of planning and early conceptual project evaluation. *ICE* functions at the corridor or higher level with very little input by the user. At the national level, researchers—including from the University of California Pavement Research Center (UCPRC)—have recently developed a spreadsheet-based LCA tool for the FHWA called *LCA Pave* that can be used by state transportation departments and contractors to perform project-level pavement LCAs (2,3). An effort was made to collect publicly available data to build libraries (material, construction equipment, transportation) in the tool. The data and models used to build the tool are mainly based on US averages.

There is a need for an LCA tool that models the details of the construction and maintenance life cycle of a pavement project at the conceptual-design stage or later in the project-design process. In addition, there is a need for a project-level LCA tool that uses LCIs specific to the materials and equipment typically used in California and by Caltrans. To address these needs, the web-based software *eLCAP* was developed. *eLCAP* is being designed so that it can also produce conceptual project-level evaluations with California-specific data in the future.

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<sup>1</sup> *ICE* is intended to inform planning and pre-engineering analysis.

## 1.2 Overview of eLCAP

*eLCAP* is a project-level life cycle assessment tool that uses California- and Caltrans-specific life cycle inventories and processes. *eLCAP* performs a formal *mass-balancing procedure* (discussed in Section 2.1) on a pavement LCA project model and then computes 18 different *impact category* values (identified by their variable names), among which are Global Warming Potential (GWP), Human Health Particulate Air, Acidification, and different forms of Primary Energy. *eLCAP* also generates a detailed *Microsoft Excel* report file to display graphs and tables of results.

*eLCAP* models the life cycle history of a *pavement project* by allowing a user to specify any number of construction-type events, occurring on a user-specified date, followed by an automatically generated Use Stage event that begins immediately afterward and lasts until the next construction-type event or the end-of-life date.

Construction-type events require user input specifications for materials (e.g., hot mix asphalt [HMA], portland cement concrete [PCC], aggregate base [AB], and in-place recycled [IPR] materials) and their associated quantities; transport types and their associated distances; and construction equipment (e.g., pavers, rollers, lighting) and their associated times of operation. *eLCAP* has built-in library versions for these processes based on California and Caltrans practices. These library-based processes allow a user to analyze a specific pavement project or create a user-defined process based on library versions and then customize the amounts and sources of inputs that go into that user-defined process. For example, the library process for Electricity Grid Mix uses 43.4% from Natural Gas, but a user can create a user-defined Electricity Process, based on the Electricity Grid Mix library process, which instead uses 20% from Natural Gas. Further, any custom, user-defined process setup—either by using the Manage User Processes page or within a project—becomes available globally to that user for any project.

Use Stage-type events, which are automatically generated for each user-defined construction-type event, have a start date immediately after the end of the construction event and an end date specified by the user. Currently, *eLCAP* is limited in that it only computes GHG for the Use Stage, using baseline fuel consumption for a very smooth pavement and excess fuel consumption from pavement roughness (in terms of the IRI). The tool models the environmental effects of “using” the pavement project by computing the GHG from traffic (cars and trucks) driving over the pavement during the time span of the Use Stage and including the effects of increasing the IRI and traffic with time.

Users interact with *eLCAP* via a web browser that accesses its user interface (UI). The main UI web page contains the controls necessary to define the life cycle of a pavement project: Construction, Maintenance/Rehabilitation, Materials, Transport, and Equipment. Data for a pavement project are grouped

into a *project trial*; there can be an unlimited number of project trials for a project, and a user can have an unlimited number of projects. All user data are stored in a database, currently *SQL Server*.

In addition, a user can save the data for a project trial to a local hard disk in a “json”-formatted file. These downloaded files can act as a backup to the user database or as project documentation; they can also be uploaded to *eLCAP* for processing.

### 1.3 Basic Results

One of the many objectives of *eLCAP* is to make the complicated process of LCA modeling and analysis as simple as possible. Another objective is to provide specific and easy-to-understand results. To that end, *eLCAP* generates an *Excel* spreadsheet that contains bar and pie charts for 18 impact categories, broken into the following categories: Material Production, Transport, Construction Equipment, and Construction. This report is generated for each construction-type event defined in the life cycle. The *Excel* spreadsheet also contains data tables for these categories’ impacts.

*eLCAP* generates several other, lower-level reports for each construction-type event:

- Detailed process-level results from the *balancing* operation (see Section 2.1), showing scaled input and output flows for every process in the pavement project model
- The input and output flows for the LCI for the pavement project
- The flows, the characterization factor, the LCI amount, and the resulting flow potential amounts for each impact category for each stage (e.g., Material Production) and for each impact method (e.g., TRACI 2.1, Primary Energy).

For Use Stage events, *eLCAP* generates a detailed report containing the following information for each lane in a route segment for each year of analysis in the Use Stage duration:

- Truck lane distribution factor
- Traffic volumes (cars and trucks)
- Equivalent single axel loads (ESALs)/year (for use in selecting IRI performance model parameters)
- ESAL category (for use in selecting IRI performance model parameters)
- IRI performance model parameters
- IRI
- GHG

## 1.4 Users

*eLCAP* has been designed using Caltrans terminology, units (with metric equivalents), and, to the extent possible, California-specific inventories reflecting Caltrans practices. This Caltrans version of *eLCAP* can be used for applications for other agencies, with these assumptions in mind, and can serve as the basis for customization for other agencies and other applications beyond California streets, roads, and highways.

*eLCAP* is designed to be used by engineers and planners who do not have extensive detailed knowledge of pavement materials, construction, transportation, use, and end-of-life treatments. For these users and for users with deeper knowledge working on projects for which very detailed information is not available, default data are available for the typical materials and processes used in California. *eLCAP* is also designed to be used by more advanced users with highly technical knowledge about pavements by allowing them to change processes; select more detailed descriptions of materials; and use their own materials designs, equipment orders of work, and traffic data. Advanced users with more in-depth knowledge about the inputs to pavement and LCA can develop their own material mix designs and electricity mixes; add or remove equipment and transport vehicles; add or edit hours per equipment use; and adjust other inputs.

As every project is unique, users will have to define the goals and scopes of their projects before running any analyses in *eLCAP*. The goal and scope include creating and providing a description of the project, identifying the location of the project, defining the dimensions of the road, and inputting the analysis period before even inputting the details of the life cycle stages.

## 1.5 Future Directions

Currently, *eLCAP* has 58 specific LCIs (exported from *GaBi* [*Ganzheitliche Bilanz*, or *GaBi*, is the LCA software from thinkstep AG® which is now owned by Sphera®]) and 43 user-addressable processes grouped into 21 types of models, such as HMA, PCC, Electricity, Paver, and Grinder (see Appendix A) for construction-type events (Materials and Equipment) and a Use Stage that computes GHG as a function of the IRI and traffic. The following are potential enhancements being considered for future versions of *eLCAP*:

- Additional materials
- Additional transports
- Additional pieces of equipment
- Use Stage to include mean profile depth and pavement deflection
- Additional impact categories for the Use Stage
- Comparisons by users of one Project Trial to another Project Trial



- *eLCAP* functioning at the conceptual project-level evaluation stage, similar to the FHWA's *ICE* tool (1)
- Updating of *eLCAP* database libraries with publicly available data

## **1.6 Software Ownership, Hosting, and Management**

*eLCAP* is a MicrosoftASP.NET/C# web application owned by the Regents of the University of California. The HTML (ASPX pages) and C# source files (and other support files, such as the Highway Log) are currently hosted on the servers of the UCPRC. The contractual agreement between Caltrans and the University of California allows Caltrans to move the hosting to a Caltrans web server at any time, gives Caltrans unlimited California state government use, and gives Caltrans the ability to modify the source code to create new state-owned software.

## **1.7 Notes on This Technical Memorandum**

The third-party critical review statement of the web-based *eLCAP* software and two accompanying documents, this technical memorandum and an LCI technical memorandum (4), is available in Appendix B of this document.<sup>2</sup>

It should also be noted that the *eLCAP* software discussed and depicted in this technical memorandum represented the most recent version available at the time of the writing. However, as the development of *eLCAP* is continual, the software's functions, user steps, and/or interface may be different at a later date.

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<sup>2</sup> A PDF document with the complete list of critical review panel comments is available to download at: <https://escholarship.org/uc/item/9f5181j1#supplemental>.

## 2 BALANCING, MODEL GENERATION, AND ASSESSMENT

*eLCAP*'s main function is to simulate (i.e., to model) the life span of a pavement section (i.e., a project) so it can be used to compute the environmental effects of traffic and of construction and maintenance (Use Stage). The software does this so that users can make informed decisions on the best course of action to pursue to minimize harmful environment effects and maximize pavement performance over the long term. This is important because sometimes what initially sounds like a good idea may turn out differently when all the processes in the life cycle—including extraction and production of materials, materials transportation, construction equipment use, maintenance, use, and end-of-life—are taken into consideration.

### 2.1 Balancing

*eLCAP* models a real-world pavement project as a series of *unit processes* or LCIs, with the output “flow” of one unit process or more going into another unit process as an “input” flow or flows, as Figure 2.1 illustrates. A unit process generates a *unit* amount of product flow (e.g., 1 kg of HMA). Each unit process has many inputs and outputs, and the outputs can be categorized as the main *product flow* and/or one or more *emission flows*.

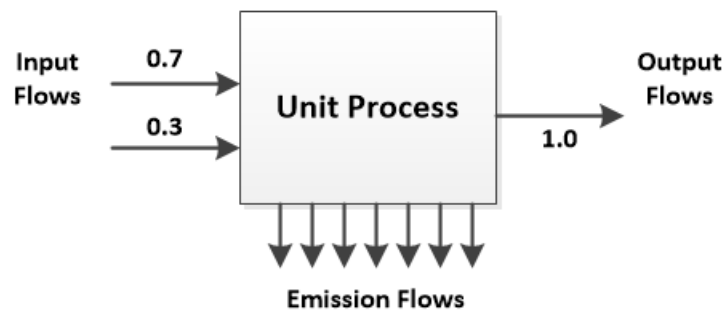
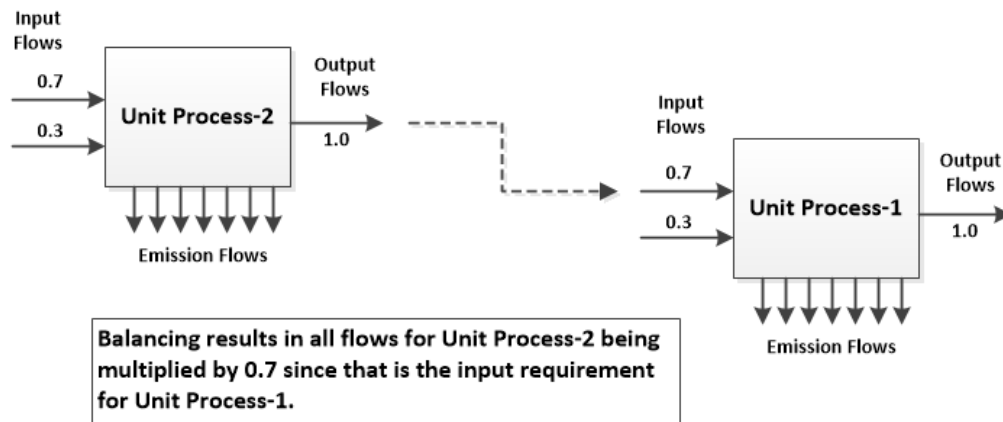


Figure 2.1: A unit process.

The *eLCAP* database currently contains over 50 different unit processes with over 1,600 different flows. A typical *eLCAP*-modeled pavement project may include several hundred-unit processes for one construction-type event, and there may be many construction-type events in the overall life cycle. These collected unit processes form the *LCA balance model* for the construction-type event.

Each unit process has *input quantity* requirements. For example, an *HMA unit process* needs to have 0.06 kg of bitumen and  $7.63 \times 10^{-3}$  MJ to produce 1.0 kg of HMA. Similarly, a *pavement project unit process* may need to have 100,000 kg of HMA (that is, it has an input quantity requirement of 100,000 kg of HMA).

Since each unit process generates a unit of product, a “scaling” or “balancing” procedure needs to be performed to get the final *balance model* in balance (an example is shown in Figure 2.2). This process starts at the pavement project unit process and traverses/climbs upstream for each input flow for each unit process in the model. All flows for a particular unit process are scaled by the quantity requirement of the unit process downstream. *eLCAP* accomplishes this balancing procedure by using a programming technique called *recursion*.



**Figure 2.2: Two-unit process with scaling.**

Once this balancing process is complete, each *input flow type* (e.g., CO<sub>2</sub>) for each process is summed. The same is done for the output flows, starting at the pavement project and traversing/climbing upstream for each input flow. The result of this summation process is an *LCI* for the pavement project that reflects all upstream effects.

The final step is to compute the results for the various impact categories. *eLCAP* computes 18 different impacts, most of which are based on the US Environmental Protection Agency’s Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) (5). Each impact category consists of a list of relevant flows, each with a specific “characterization” factor (e.g., for GWP, CO<sub>2</sub> has a factor of 1.0 and CH<sub>4</sub> has a factor of 25.0). The flows for the final LCI for the pavement project are used to compute the impact results for the Construction Stage.

From the above discussion, it is evident that the building blocks of any LCA are *processes* and the *flows* into and out of those processes. Another way to state this is that the building block of any LCA is *data*. Specifically, if process-level data are representative of what is being modeled (e.g., a pavement project), then the LCA should result in a good estimate of the environmental impact of what was included in the LCA. But if the process-level data are not representative—if perhaps some of the data are for industries

from a different county because “local” data are unavailable—then the LCA will not result in realistic assessments of what is being modeled.

The next sections discuss the various data items in an *eLCAP* LCA: processes, flows, and models.

## 2.2 Process Data

As previously mentioned, the basic building block of any LCA is the *unit process*, in which an object has material input needs and produces a product and emissions (i.e., output items). High-quality representative process-level data are key to obtaining representative results since LCA is basically an accounting activity—that is, data items (flows) are simply multiplied by factors and then added up.

*eLCAP* has over 50 unit processes in its database. This dataset was created using basic LCI data from *GaBi* (6) and tailoring them to the California environment. Some of the foreground data have also been acquired from the literature. The result is that the unit processes in *eLCAP* have been designed for LCA users in California. The development of the datasets that are used in *eLCAP* are explained in detail in the UCPRC LCI report (2).

Data from environmental product declarations (EPDs) cannot be used in *eLCAP* at this time. Material and mix EPDs do not provide mix design information or any foreground data (on energy use, for example). Therefore, they cannot be modeled or used in *eLCAP*.

### 2.2.1 Description and Format

A file format was developed for *eLCAP* to capture the data associated with a unit process so its database can be populated. The following data items are contained in a *process definition* file:

- Name of the process
- Description of the process
- Kind of process (as used in *GaBi*) (5)
  - “u-so”: a single operation process that does not reflect any upstream effects
  - “agg”: a process that reflects all upstream effects
- Flows (see Section 2.3)
  - Name of the flow
  - IO type: input or output
  - Amount
  - Unit
  - If the flow is the product flow
  - Name of a parameter if the amount is arrived at via a calculation

- Parameters
  - Name of the parameter
  - Comments
  - For “Free” or constant parameters
    - Value
  - For “Fixed” or formula-based parameters
    - A formula/equation
  - Units

A separate application was created to process these *process definition* files and to insert the unit process into the *eLCAP* database. The following shows sample lines from a process definition text file:

```
//Free parameters (constants)
Parameter, Name=Agg_Crushed, Comments="percentage of crushed aggregate", Value=47.0, Unit=%

//fixed parameters (formula based)
Parameter, Name=Agg_Crushed_norm, Formula="(Agg_Crushed/100.0) * Output_total", Comments=""

FlowItem, FlowName=Crushed stone [UCPRC Flows], IO=Input, Amount=0.0, Unit=kg,
IsReferenceFlow=false, ParameterName=Agg_Crushed_norm

FlowItem, FlowName="Hot Mix Asphalt (HMA) [UCPRC Flows]", IO=Output, Amount=1.0, Unit=kg,
IsReferenceFlow=true, ParameterName=Output_total
```

#### 2.2.1.1 Process Type: “agg”

An aggregated process or “agg”-type process is one that has all upstream effects included in it. It can be considered a “leaf” node in the balance model since nothing is upstream from it. Based on the scope of the study, it can be a cradle-to-gate process or a cradle-to-grave process; all environmental flows (inputs and outputs) caused by the reference flow for the product are included. Because it is aggregated, it does not describe which upstream processes are responsible for the flows. The “Crude Oil (agg)” process in Figure 2.3 is an “agg”-type process, which has no input flows shown. Further, once all the input flows to an “agg”-type process have been aggregated, it is impossible to disaggregate them back into the processes used to build the “agg”-type process. An “agg”-type process, exported from *GaBi*, typically has several hundred input and several hundred output flows since all flows from upstream processes have been aggregated into it.

From a user perspective, this type of process is the least flexible since it cannot be customized. But practically speaking, there must be “agg”-type processes at some point going upstream in the LCA model. The point where they appear depends on the sources of data and level of effort required to get the data.

### 2.2.1.2 Process Type: “u-so”

A unit process-single operation or “u-so”-type process is one that does not include any upstream effects; it has input flows that need to be connected to upstream models. It is the smallest element in the life cycle impact assessment (LCIA) for which input and output flows are quantified, and it is commonly referred to as *unit process*. The “Crude Oil Refinery (u-so)” process in Figure 2.3 is a “u-so”-type process. A “u-so”-type process exported from *GaBi* typically has a handful of input flows and very few output flows: the main product flow and a few emissions flows.

A “u-so” process is more flexible than an “agg”-type process since it allows flow-based connections to upstream models and thus permits an *eLCAP* user to customize the “u-so” process by changing the amounts of flows into the process and the actual source of the flows.

### 2.2.1.3 Parameters

The parameters “Free” and “Fixed” were added to the process definition file to add flexibility to them since sometimes flow amounts for a unit process are not constant but are a function of several parameters. For example, diesel consumption for a Transport is a function of miles per gallon, maximum payload, and the utilization ratio. A user could compute an amount to use for the flow, but changing the parameters is more intuitive and straightforward.

Parameters are either “Free” or “Fixed.” Free types are simply named constants to make the process definition file self-documenting. Fixed types are based on a formula.

## 2.2.2 *GaBi-Generated Processes*

Most of the Unit Processes in the *eLCAP* database are the result of their first being modeled in *GaBi*, tailored to California’s needs, and then taken through an export process that generates an *Excel* file. In arriving at a unit process in this way, minor manual modifications are made to the *Excel* file, which is then saved as a CSV file. As noted above, a separate application processes these *GaBi*-exported files and generates process definition files. *Flow definition* files (see Section 2.3) are also generated during this processing. The list of items in *eLCAP* for the energy and material processes are shown in Appendix C.

## 2.2.3 *Manually Created Processes*

*eLCAP* also has about 15 process definition files that are manually generated. These are necessary for unit processes that consist entirely of inputs and a single product output, such as AB (aggregate base). In this way, the manually generated unit process acts as a basic aggregator of input flows and does not generate any emissions itself.

## 2.3 Flow Data

Intimately associated with the unit process previously discussed are *flows*. *Flow objects* are used to model the flows of materials and emissions. Flows connect the input items of one unit process to the outputs of another unit process.

### 2.3.1 Description and Format

A file format was developed for *eLCAP* to capture the data associated with a flow so the application's database can be populated. The following data items are contained in a *flow definition file*:

- Name of the flow
- Description of the flow
- Reference Quantity (e.g., mass)
- Reference Unit (e.g., kg)
- Flow Property (used to convert a referenced flow in a unit process to units different from those used to define the flow)

### 2.3.2 GaBi-Generated Flows

Flow definition files are generated from the processing of *GaBi*-exported unit-process CSV files. Currently, over 1,600 flows have been generated from the *GaBi*-export process. The input and output flows for processes taken from *GaBi* cannot be generated by users in *eLCAP* because of the license agreement between thinkstep AG and the University of California, Davis.

### 2.3.3 Manually Created Flows

*eLCAP* also has about 25 flow definition files that are manually generated. This is necessary for unit processes that have a manually generated process definition file since the output flow for the process, the product flow, needs to be created for the aggregator-type process.

## 2.4 Models

The third concept used by *eLCAP* to build its LCA database is the *model*. An example model is shown in Figure 2.3 for “Crude Oil Refinery.” The figure shows that a model consists of a main unit process that produces the product (“Crude Oil Refinery [u-so]”) with a series of input flows.

The input flows can be satisfied by either “agg”-type unit processes or by another model. In the figure, the “agg”-type unit processes are represented by “Crude Oil (agg),” “Transport Ocean (agg),” and “Transport

Barge (agg),” which all have upstream effects included in them. The other input flows in the figure are connected to the outputs of other models (Natural Gas (Boiler), Electricity, Residual Fuel Oil, and Liquefied Petroleum Gas). Connecting an input flow to another model allows users to customize the upstream model in the UI. Users cannot customize an “agg”-type unit process.

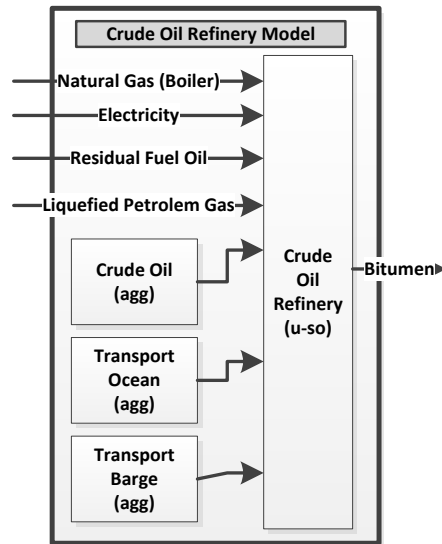


Figure 2.3: Example *eLCAP* model.

#### 2.4.1 Description and Format

Model definition files contain *named references* to unit processes, flows, and other models. Model definition files are processed into *eLCAP* memory at program start up. The following data items are contained in a model definition file:

- Name of the model
- Description of the model
- Named references to unit processes
- For a named reference that has input items (e.g., “Crude Oil Refinery[u-so]”) in Figure 2.3:
  - A named reference to a model
  - A named reference to a process in that model
  - A named reference to a flow in that process (this is usually the output product flow)

#### 2.4.2 User-Defined Models

A material mix design is represented by a model, and *eLCAP* users add mix designs (e.g., HMA and PCC) with a specific output quantity (e.g., 1000.0 tons) for a specific life cycle event. *eLCAP* has many built-in library mix designs that are available to the user. Users can create a user-defined mix design (a custom mix



design model) if the available library of mix design models does not satisfy a project requirement. For example, if the user needs to have an HMA mix design using a certain amount of electricity that is different than one of the library HMA models, the user can create a user-defined mix design model based on an existing HMA library model and change the amount of electricity input flow. (See Section 4.5 for a discussion on defining a user-defined mix design model.)

## 2.5 Processing and Generation of the LCA Database

The left side of Figure 2.4 shows the processing procedure carried out to generate the *eLCAP* LCA database. The steps in the procedure are as follows:

1. An LCA expert at the UCPRC builds a California-specific model in *GaBi* and exports flows for the main process in the model.
2. A separate software tool developed by the UCPRC, *DB Gen*, is used to process the *GaBi*-exported CSV files; this software tool reads these files and generates *process* and *flow definition* files.
3. *DB Gen* is next used again to process the generated *process* and *flow definition* text files and also the manually generated *definition* and *flow* files.
4. The above steps result in an XML database file that *eLCAP* loads when the application starts up. It has a structure shown at the center of Figure 2.4.
5. *Model definition* files are created. All sources of LCA data are now available for *eLCAP*.
6. A user accesses *eLCAP* via a web browser. *eLCAP* reads the LCA XML database file into memory and also reads and processes the model definition files into memory.
7. The structure for the in-memory version of the XML database file mimics the structure of the XML file.
8. When a user requests that an analysis be performed, *eLCAP* builds the *balance model* (see Section 2.1), balances it, and then computes the LCI for the construction-type event and the impact factors for it.

## 2.6 Model Generation

When a user requests that an LCA be performed, *eLCAP* starts a loop over all the *LcaEvents* (see Section 4.6.2) in the life cycle defined by the user. The first step in that loop, for each *LcaEvent*, is for user data to be translated into an LCA model via a *model generation activity*. This activity is simple for a Use Stage *LcaEvent* but complex for a construction-type event. Before the model generation activity, *eLCAP* must perform some initial/preparatory work to assist the Use Stage procedure: the tool converts the pavement project location on a route to a series of lane-based segments that have traffic (cars, trucks), a

WIM group, a value for ESALs, and a selected climate for each segment. This is necessary because the Use Stage has performance models that require these data.

### 2.6.1 Construction-Type Event

Figure 2.5 shows part of a construction-type model used to build the *balance model*. The process starts at the *pavement project model*, considers each named reference to a process, gets the actual process from the database, copies it, and adds it to the list of processes that will become the balance model. For each input flow for the process that produces the output product, the model that is referenced is obtained and the same process is followed. This continues until there are no more upstream models to address. A recursive implementation is used for this complex procedure. Once the balance model has been constructed, it can be balanced as discussed in Section 2.1.

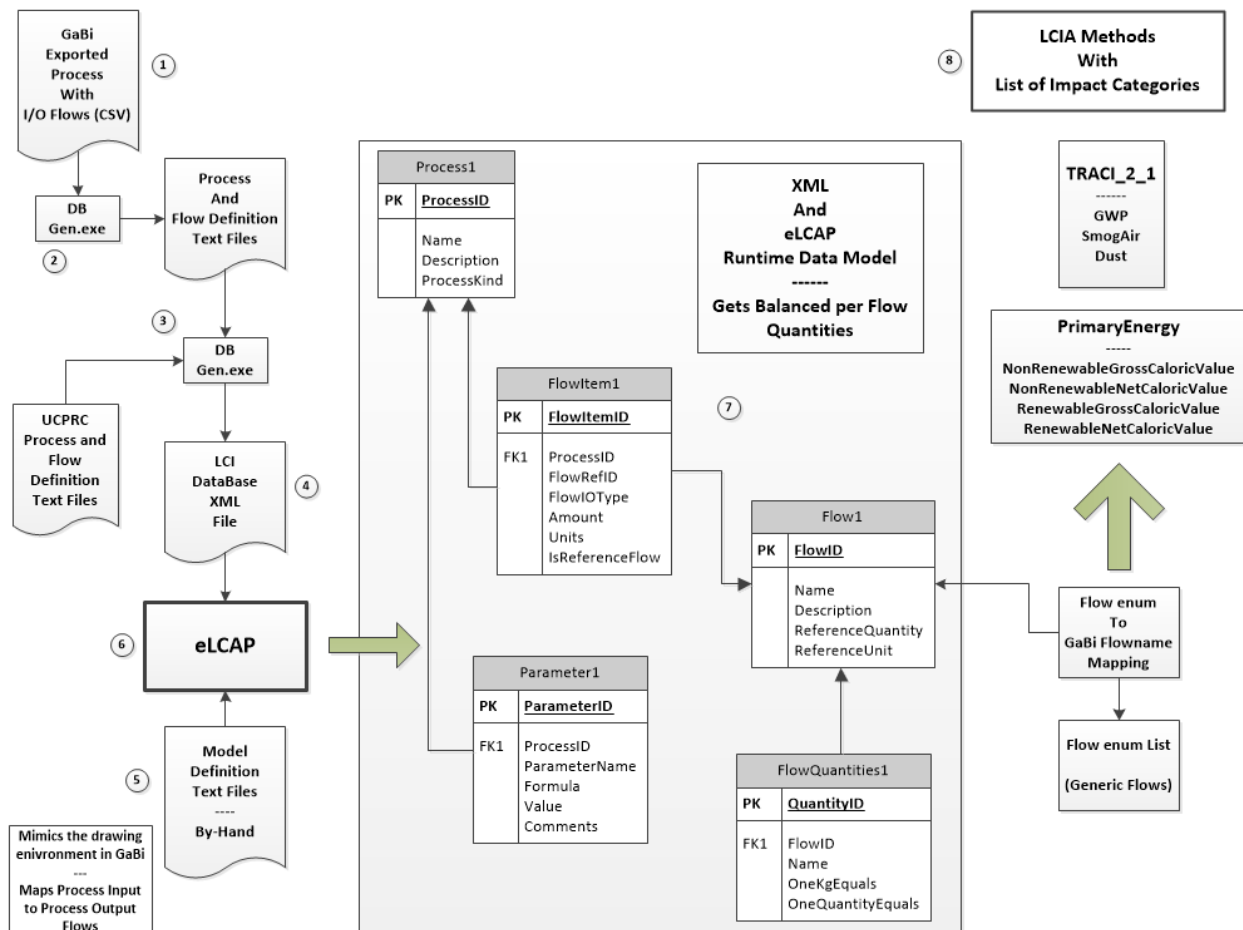


Figure 2.4: Overall *eLCAP* data processing and operation.

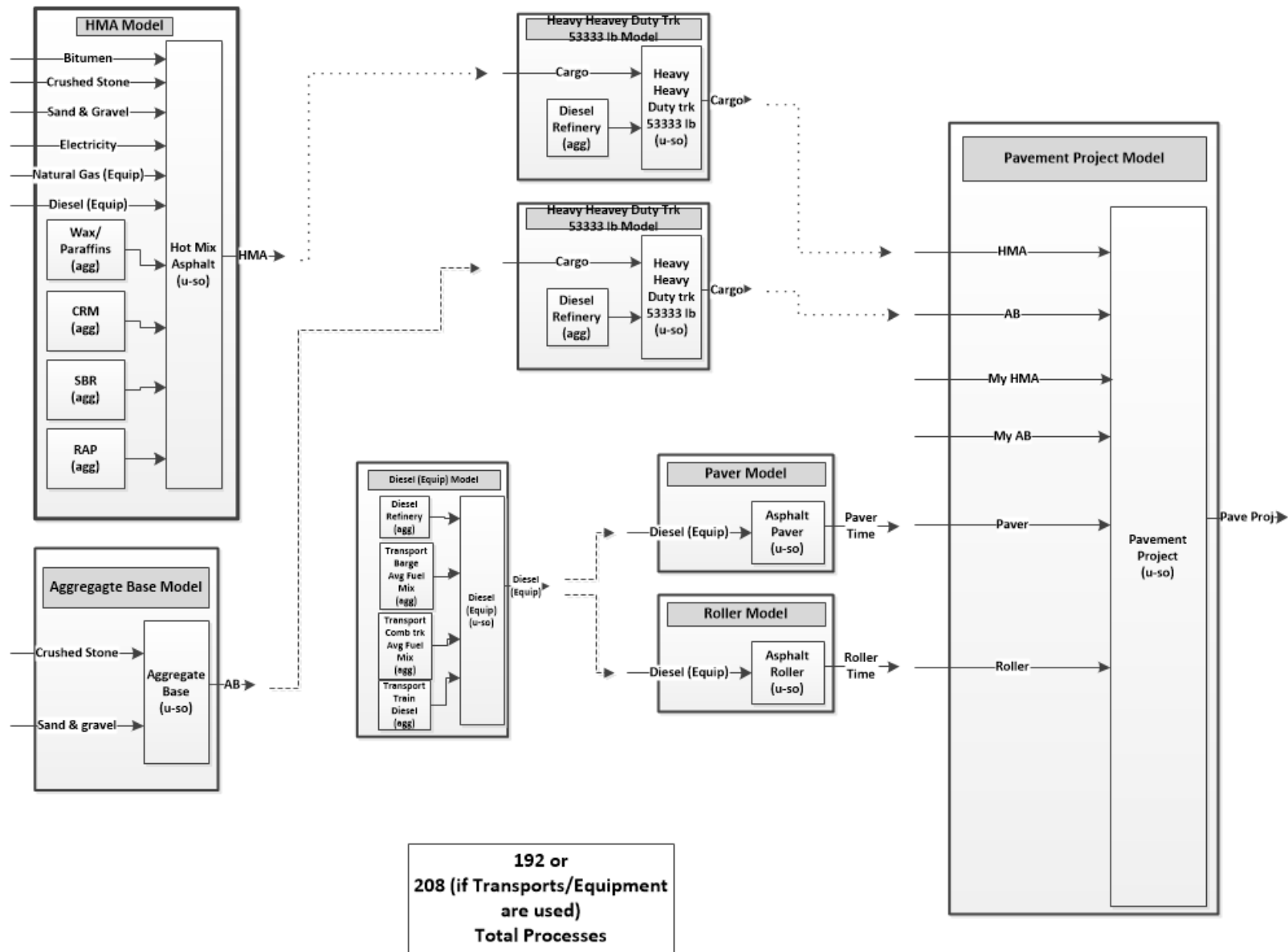


Figure 2.5: Pavement project model with other upstream models.

### 2.6.2 Use Stage Event

The model generation step for a Use Stage event is much simpler than for a construction-type event. The current Use Stage model computes the GHG generated from traffic driving over the pavement project for some user-defined time period. The GHG procedure used for this computation includes the effects of increasing IRI (and traffic) over time, so the Use Stage model-generation step obtains appropriate IRI performance model parameters for each lane segment based on Pavement Type, Treatment, Climate Zone, and ESALs (see details in Section 2.7.2).

## 2.7 Assessment (LCIA)

*eLCAP* internally generates an appropriate set of 18 *LCA impacts* (e.g., GWP, primary energy) associated with several *LCA methods* (e.g., TRACI 2.1 [4]) to allow the user to make decisions on the environmental effects of a pavement project over its life cycle. No user involvement is necessary.

*eLCAP* includes two methods for computing impact factors:

1. A method based on a list of flows with an associated characterization factor
2. A method based on a performance model (currently, an IRI model is the only one available)

*eLCAP* uses the first method for all impacts generated for *construction-type LcaEvents*, meaning all materials, construction, maintenance, and end-of-life processes. The second method is used for calculation of the GHG (GWP) emissions from pavement vehicle interaction associated with roughness in the use stage (the variable *Use Stage-type LcaEvents*), the only impact considered by *eLCAP* for the use stage at this time.

### 2.7.1 Flow-Based Impacts

As part of the *balancing* procedure in the balance model, the LCI for *appropriate processes* (see the following discussion) is generated using the methodology described in Section 2.2. The *LCI flow list* for a process and the list of *flows* (and characterization factors) for a particular impact of the process are used to compute the impact by simply matching up the flow names between the two lists, getting the balanced model LCI flow amount (which includes all upstream effects), multiplying it by a characterization factor, and summing over all flows defined for the impact.

The “appropriate processes” referenced previously are those that are needed for reporting to the user, such as Construction and Material Production processes. The stages that appear in the following list illustrate the

hierarchy of stages and processes for the examples shown (this is not a complete list of all the processes in *eLCAP*). Some of the stages are normally associated with LCA, such as Material Production, and others are “virtual” stages used to obtain the impacts computed for reporting purposes. Recycled materials that are not allocated impacts do not have materials production processes; they only have construction and transport processes. Reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA) handling in *eLCAP* is explained in the UCPRC LCI report (6) and summarized in Table A.1 and Table A.2 in Appendix A of this report.

1. Construction Stage
  - a. The Pavement Project Process
2. Material Production Stage
  - a. HMA Process
  - b. PCC Process
  - c. AB Process
3. HMA Production Stage
  - a. HMA Process
4. HMA Aggregate Stage
  - a. Crushed Aggregate Process
  - b. Natural Sand and Gravel Process
5. HMA Bitumen Stage
  - a. Bitumen Process
6. HMA Energy Stage
  - a. Electricity Process
  - b. Natural Gas Equipment Process
  - c. Diesel Equipment Process
7. PCC Production Stage
  - a. PCC Process
8. PCC Aggregate Stage
  - a. Crushed Aggregate Process
  - b. Sand and Gravel Process
9. PCC Cement Stage
  - a. Cement Process
10. PCC Energy Stage
  - a. Electricity Process

- b. Natural Gas Equipment Process
  - c. Diesel Equipment Process
- 11. Aggregate Base Production Stage
  - a. Aggregate Base Process
- 12. Aggregate Base Crushed Agg Stage
  - a. Crushed Aggregate Process
- 13. Aggregate Base Natural Agg Stage
  - a. Sand and Gravel Process
- 14. Transport Stage
  - a. Transport Process
- 15. Construction Equipment Stage
  - a. Paver Process
  - b. Roller Process

As shown, this list has 15 stages and many processes. There are many more stages and processes for other materials and equipment in *eLCAP*. Computing LCIs for a process is a computer-intensive activity since *eLCAP* needs to recursively climb the upstream tree, starting from a particular process and considering all the input flows into that process.

### 2.7.2 Performance Model-Based Impacts

*eLCAP* computes a single impact factor for Use Stage-type *LcaEvents*: GHG. Calculating that impact factor is done using an equation that accounts for traffic loads in each *lane segment* (cars and trucks) and uses an IRI performance model that predicts the increase of IRI over time (age from the date a treatment was applied). Details of the development of these equations are provided in the reports by Wang et al. (7,8,9). The approach that Wang et al. took to develop the use stage model for pavement LCAs was to first calculate the rolling resistance through the HDM-4 rolling resistance model (using pavement roughness and macrotexture and their effects on fuel use from National Cooperative Highway Research Program Report 720 [10]), and then use the resulting rolling resistance results in the vehicle tailpipe emission model *MOVES* (*Motor Vehicle Emission Simulator*) to get to the final vehicle emissions.<sup>3</sup> *MOVES* was developed by the US Environmental Protection Agency (11). A flow chart that shows the steps and parameters to calculate the effect of rolling resistance on vehicle fuel consumption is shown in Appendix D. The large set of

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<sup>3</sup> *MOVES* only gives tailpipe emissions (pump-to-wheel). Therefore, Wang et al. (9) used the *GREET* (*Greenhouse gases, Regulated Emissions, and Energy use in Technologies*) Model to add the well-to-pump emissions for the vehicle fuels to get life cycle emissions (well-to-wheel).

equations generated for different traffic speeds (congested, uncongested), road gradients, and other variables was simplified to equations for cars and trucks with different numbers of axles (two, three, four, and five or more) operating at constant highway speeds on roads with no vertical gradient.

Currently, *eLCAP* only calculates GHG emissions, mainly because *MOVES* only provides limited tailpipe emissions inventory for the combustion of fuels in the vehicles. Excess fuel consumption may also be caused by pavement structural responsiveness to different vehicle weights, which was also not modeled during the development of the GHG equations due to unavailable structural response models. In the near future, the UCPRC plans to update the GHG equations and expand *eLCAP* boundaries to include other midpoint indicators as well such as the structural response model in the Use Stage.

The equation for calculating GHG emissions from vehicles in each year is:

$$\begin{aligned}
 GHG_{Vehicle} (IRI) = & (IRI \times RoughnessFactor_{Car} + Const_{Car}) \times CarVolumeLane\ i \times LaneMile \\
 & + (IRI \times RoughnessFactor_{2Axle} + Const_{2Axle}) \times 2AxleVolumeLane\ i \times LaneMile \\
 & + (IRI \times RoughnessFactor_{3Axle} + Const_{3Axle}) \times 3AxleVolumeLane\ i \times LaneMile \\
 & + (IRI \times RoughnessFactor_{4Axle} + Const_{4Axle}) \times 4AxleVolumeLane\ i \times LaneMile \\
 & + (IRI \times RoughnessFactor_{5Axle} + Const_{5Axle}) \times 5AxleVolumeLane\ i \times LaneMile
 \end{aligned}$$

The variables used in the  $GHG_{vehicle}$  equation are described in Table 2.1. The values for *RoughnessFactor* and *Const* used in the  $GHG_{vehicle}$  equation are shown in Table 2.2. The emissions from this equation are summed over the analysis period (from the end of a construction-type event to the start of the next construction-type event) using the IRI predicted for the pavement at the middle of each year.

**Table 2.1: GHG Equation Variable Definitions**

<i>GHG<sub>Vehicle</sub></i>	GHG emissions from all vehicles in Lane <i>i</i> in a single year (metric tons of CO <sub>2</sub> -e)
<i>IRI</i>	IRI of the segment in Lane <i>i</i> (m/km), 1 m/km = 63 in./mi.
<i>LaneMile</i>	Total lane-miles of that lane in the segment (lane-mile)
<i>RoughnessFactor</i>	Averaged coefficient to convert the IRI to GHG emissions for cars and trucks due to rolling resistance; the unit is metric tonnes of CO <sub>2</sub> -e/(IRI [m/km] x mi.)
<i>Const</i>	Constant term in the equation, representing the GHG emissions due to other types of resistance that the energy needs to resist; the unit is metric tonnes of CO <sub>2</sub> -e/mi.)
<i>CarVolumeLane i</i>	Volume of cars in Lane <i>I</i> (readily available in the traffic table); the annual average daily traffic (AADT) is used and summed for the year
<i>2/3/4/5AxleVolumLane i</i>	Volume of trucks in each class in Lane <i>I</i> (readily available in the traffic table); the AADTT is used and summed for the year
<i>GHG<sub>VehicleAllYears</sub></i>	Total GHG emissions (metric tonnes of CO <sub>2</sub> -e) from vehicles running on Lane <i>i</i> in the segment in the whole analysis period

**Table 2.2: Roughness Factor and “Const” for GHG Equation**

Vehicle Classification	RoughnessFactor	Const
Car	0.003577	0.133451
Two-Axle Truck	0.003628	0.400894
Three-Axle Truck	0.0073	0.657537
Four-Axle Truck	0.012107	0.957231
Five-Axle Truck	0.012808	1.046075

The performance model equation for IRI as a function of the age of a treatment is the following:

$$IRI(t) = a + b*age**c \tag{2.1}$$

The parameters in Equation (2.1)—a, b and c—are selected based on *Pavement Type* (indicating surface type: Flexible or Rigid [jointed plain concrete at this time]), *Treatment*, an *ESAL category*, and a *Climate category*. A partial table of IRI performance model parameters is shown in Table 2.3. The full set of IRI performance model parameters is shown in Table C.1.



**Table 2.3: Excerpt from the Table of IRI Performance Model Parameters that Appear in Appendix C**

				<b>IRI</b> $(IRI_L + IRI_R)/2 = a + b * Age^c$ $Age = ((Average\_IRI - a)/b)^{(1/c)}$ (in./mi.)			
Pavement Type	Treatment	ESAL/yr <sup>a</sup>	Climate <sup>b</sup>	Node ID	a	b	c
Flexible Pavement	1. Full-Depth Reclamation	A	Severe	1	157.3	3.4	1.0
			Mild	2	88.8	2.0	1.0
		B	Severe	3	143.0	5.1	1.0
			Mild	4	88.3	2.2	1.0
		C	Severe	5	139.6	5.4	1.0
			Mild	6	87.8	2.5	1.0
	2. Thick Overlay or Reconstruct	A	Severe	7	157.3	3.7	1.0
			Mild	8	88.8	2.3	1.0
		B	Severe	9	143.0	5.4	1.0
			Mild	10	88.3	2.5	1.0
		C	Severe	11	139.6	5.7	1.0
			Mild	12	87.8	2.8	1.0
	3. Very Thin Overlay	A	Severe	13	89.5	3.8	1.0
			Mild	14	90.8	2.4	1.0
		B	Severe	15	77.3	5.5	1.0
			Mild	16	92.5	2.6	1.0
		C	Severe	17	76.4	5.8	1.0
			Mild	18	94.3	2.9	1.0

<sup>a</sup> ESAL/yr: A = <100,000; B = >100,000 and <500,000; C = >500,000

<sup>b</sup> Climate: North Coast: Severe; High Desert: Mild; Inland Valley: Mild; Central Coast: Mild; Desert: Mild; South Coast: Mild; High Mountain: Mild; South Mountain: Severe; Low Mountain: Severe

When a user defines the materials for a construction-type event, a selection is made for *Pavement Type* and *Treatment*. The other two data items needed to make the IRI model parameter selection are *ESAL Category* and *Climate Category*. Table 2.4 and Table 2.5 show how to obtain both categories from actual data.

The three ESAL categories—A, B, and C—are determined by the value of ESALs/year.

**Table 2.4: ESAL Categories**

ESALs/year	Category
<100,000	A
>100,00 and <500,00	B
>500,000	C

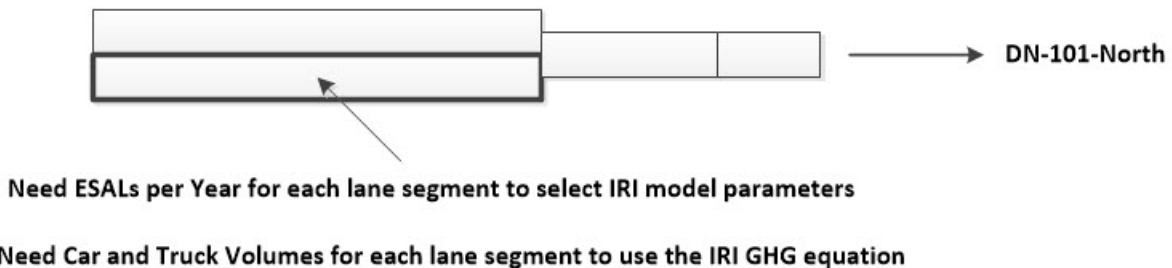
The two climate categories are determined from the *Climate Zone*.

**Table 2.5: Climate Categories**

Climate Zone	Category
North Coast	Severe
High Desert	Mild
Inland Valley	Mild
Central Coast	Mild
Desert	Mild
South Coast	Mild
High Mountain	Mild
South Mountain	Severe
Low Mountain	Severe

To assist in explaining the steps necessary to apply the GHG equation, the following discussion provides an example by using a pavement section on DN-101-North, from PM R1.000 to PM R5.000. The section has the lane segment configuration shown in Figure 2.6. Each rectangle in the figure represents a single lane segment. This section of DN-101-North begins with two lanes and then reduces to one lane, with three route segments from the beginning to the end of the section. The beginning two-lane route segment has two lane segments, and the two subsequent, single-lane route segments each have one lane segment.

*eLCAP* needs to obtain traffic data in each *lane segment* to use the GHG equation as described in Section 2.7.2.



**Figure 2.6: Example pavement project lane configuration.**

The first step in getting the traffic data for each lane segment is to determine the *WIM Group*. This is done using the steps shown below. The *WIM Group* is determined for a route segment, not for an individual lane, and traffic volumes are for both directions for the route where the project is located. Traffic data come from the *CalTrucks* database and are inflated from the date of traffic count collection to the day the *eLCAP* analysis is performed. A sample of data from the *CalTrucks* database is shown in Figure 2.7.

Determine the WIM group:

1. Get the *CalTrucks* record from *DB* (database) for *PM* (post mile) and *Leg* (e.g., in the entry “R4.569 B,” B represents a Leg and means that the traffic counts are from before the PM location at the center of the segment).
2. Calculate  $\text{Truck\_percentage} = \text{TotalTrucks\%}$  from DB record.
3. Calculate  $\text{Truck\_ratio} = (\text{TwoAxleVolume} + \text{ThreeAxleVolume} + \text{FourAxleVolume}) / \text{FiveAxleVolume}$ .
4. Calculate  $\text{GrowthRate} = \text{TwoAxle\%} * 7.07 + \text{ThreeAxle\%} * 4.8 + \text{FourAxle\%} * 6.27 + \text{FiveAxle\%} * 4.36$ .
5. Calculate  $\text{Inflated\_AADT} = \text{AADT} * (1.0 + \text{GrowthRate}) * (\text{yearNow} - \text{yearCollected})$ .
6. Use the flowchart shown in Figure 3.11 in *Estimation of Truck Traffic Inputs Based on Weigh-in-Motion Data in California* (13), which uses the data items above plus some special knowledge of routes in Caltrans districts and state counties to select the *WIM Group* that best represents the traffic patterns for the pavement project. This means that the *WIM Group* selected—for example, for DN-101-North—may actually be a WIM site in Southern California.

Route	Route S	District	Cour	Pc	Postmi	Leg	AADT	Total Tr.	Total Trucks %	2 axle	2 axl	3 axle	3 axle	4 axle	4 axle	5 axle	5 axle	Description	Yea	Ve
101		1 DN	R		4.638 B		4450	507	11.4	187	36.9	93	18.4	7	1.4	220	43.3	KLAMATH, JCT. 00	00	V
101		1 DN	R		4.638 A		4600	474	10.3	123	25.95	63	13.29	100	21.1	188	39.66	KLAMATH, JCT. 00	00	V
101		1 DN			24.41 B		4600	588	12.78	168	28.57	114	19.39	79	13.44	227	38.61	SANDMINE ROA 00	00	V
101		1 DN			24.41 A		6300	505	8.02	152	30.1	92	18.22	61	12.08	200	39.6	SANDMINE ROA 00	00	V
101		1 DN			27.01 B		26500	1325	5	700	52.8	208	15.7	13	1	404	30.5	CRESCENT CITY 00	00	E
101		1 DN			27.01 A		11000	1056	9.6	578	54.7	175	16.6	11	1	293	27.7	CRESCENT CITY 00	00	F

Figure 2.7: Sample from the *CalTrucks* traffic table.

*ESALs/year* is computed for each *lane segment* using the flowchart shown in Figure 2.8 and using the axle load spectra from the Caltrans database for the selected *WIM Group*. The traffic volumes used to compute *ESALs/year* for each lane segment need to be *lane-based*, so the traffic data from the *CalTrucks* database are distributed and transformed for a specific lane. The following procedure is used:

1. *CalTrucks* traffic volumes for the segment are divided by two to get directional traffic.
2. Truck lane distribution factors are used to distribute truck traffic to each lane.
3. Car volume per lane is computed using the passenger car equivalent approach, with a truck equal to 1.5 times a car.
4. Completing steps 1 through 3 yields final values for lane-specific AADT and Total Trucks.

Once this is complete for the lane segment, its *ESALs/year* can be computed using the flowchart in Figure 2.8.

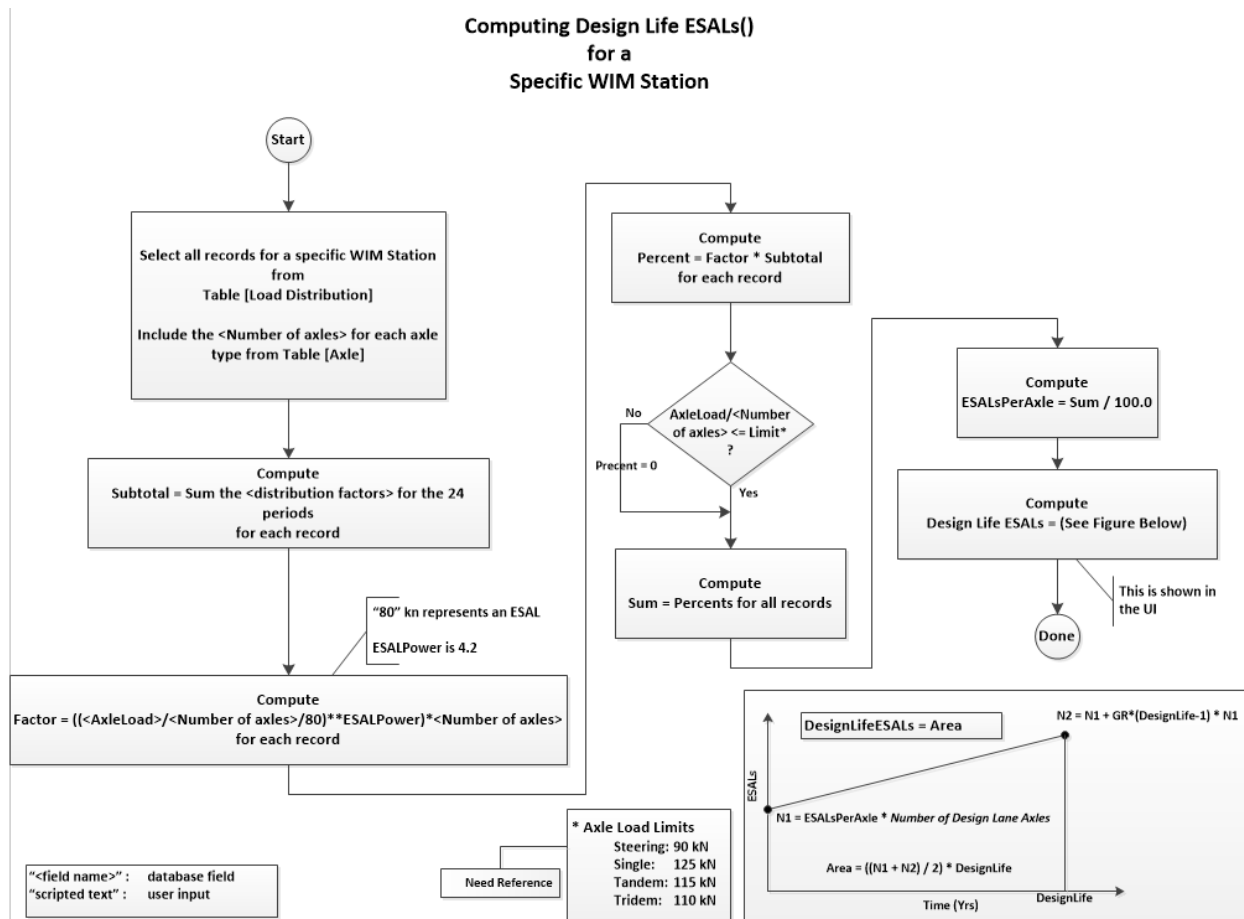


Figure 2.8: Flowchart for computing *ESALs/year*.

To assist in getting traffic data into the pavement project's lane segments, *eLCAP* constructs a segment and lane configuration map (see Figure 2.6) using lane count range data from the *Caltrans Highway Log*. The traffic point list shown in Figure 2.9 (the approximate location of the example pavement project section, DN-101-North, is also shown) is constructed and then traffic data are obtained for each lane segment based on the location of the center of the segment. However, before that step is done, additional segments are added to deal with the changes in traffic data to avoid having a traffic value change at the middle of a segment.

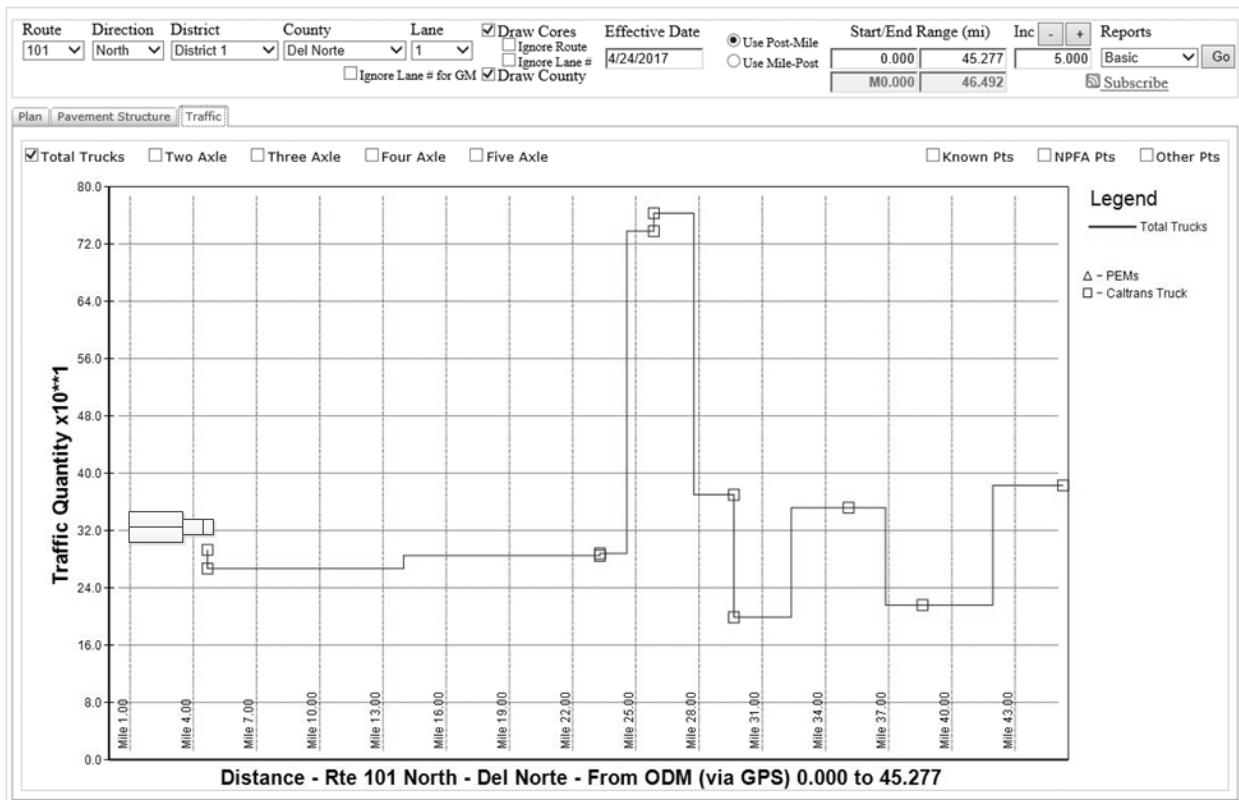


Figure 2.9: Plot of *Caltrucks* traffic data (directional).

*Climate zone* is obtained by using the *Caltrans Climate Zone* database, which divides the state into nine zones with post mile (PM) ranges for each route in each zone. The climate zone is determined for the *entire* pavement project.

Once *lane segment traffic volumes* and the climate zone have been determined, it is possible to select IRI performance model parameters using the table excerpt shown in Table 2.3 for each lane segment.

Figure 2.10 shows some detailed *eLCAP* Use Stage results for segments and lanes in DN-101-North for the first year of a 50-year Use Stage.

For each route segment, the segment length, climate category (the column labeled “C” and is “s” for “severe” for all four segments), WIM group (“1a” for all four segments), and number of lanes per segment (two lanes—i.e., one lane per direction) are shown.

For each lane, the lane distribution factor, traffic volumes, ESALs/year, ESAL category (the column labeled “E”), IRI performance model parameters, IRI, and, finally, the GHG are shown. Note that the ESAL category is the same on all segments, “A.” If any of the segments were to have more than one lane in one direction, the traffic would be spread across the lanes using lane distribution factors for cars and trucks.

Use Stage Data  
Starting Date: 1/1/2022 Ending Date: 1/1/2072 Analysis Period: 50.00 yrs  
Pavement Type: Flexible Treatment: HMA\_Thick\_Overlay  
Project Length: 1.000 miles Total Lane Miles: 1.000 miles Avg # Lanes 1-Dir: 1.00  
Project Center Climate Zone: North Coast Climate Category: severe  
Traffic Growth Rate: 0.0%

Use Stage GHG Due To IRI (Traffic Volumes Reflect Growth Rate Effects from Midpoint of Traffic Count Year to Date Shown in 'Date' Column)

Yr#	Date	Year	Seg#	Seglen (mi)	C	WIM Ln#	DF	AADT	CarVol	TrkVol	2-Axle	3-Axle	4-Axle	5-Axle	ESAL (k)	E	A	B	C	IRI (ipm)	GHG (kg)		
1	7/1/2022	0.5	1	0.035	s	1a	1	1.000	950	869	81	24	29	1	27	33	A	139.6	3.7	1.0	141.5	6.379301E+03	
				Segment Totals:				1.000	950	869	81	24	29	1	27								6.379301E+03
			2	0.190	s	1a	1	1.000	950	869	81	24	29	1	27	33	A	139.6	3.7	1.0	141.5	3.463049E+04	
				Segment Totals:				1.000	950	869	81	24	29	1	27								3.463049E+04
			3	0.023	s	1a	1	1.000	950	869	81	24	29	1	27	33	A	139.6	3.7	1.0	141.5	4.192112E+03	
				Segment Totals:				1.000	950	869	81	24	29	1	27								4.192112E+03
			4	0.752	s	1a	1	1.000	950	869	81	24	29	1	27	33	A	139.6	3.7	1.0	141.5	1.370638E+05	
				Segment Totals:				1.000	950	869	81	24	29	1	27								1.370638E+05
																						Year Total: 1.822657E+05	
																						Year Total Per Lane Mile: 1.822657E+05	

Note: Example page; results not associated with other figures.

Figure 2.10: Example Use Stage results.

## 2.8 Data Quality

### 2.8.1 Metadata

eLCAP includes fields for three kinds of metadata: (1) administrative, (2) descriptive, and (3) structural. A description of each item within each metadata field is presented in Table 2.6.

**Table 2.6: Metadata Fields Included in eLCAP (6)**

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

### 2.8.2 Data Quality Assessment

All data for materials, unit processes, energy resources, equipment, and transportation have been evaluated using a data quality assessment matrix similar to that used for the FHWA *PaveLCA* tool (2,3), which is in turn based on the pedigree matrix of the US Environmental Protection Agency (EPA) (14). This was done by the *PaveLCA* team working with a parallel FHWA project team that was developing a database framework for pavement LCA (15), which was partially informed by the framework in *eLCAP*. The US EPA’s pedigree matrix was enhanced for the FHWA tool to standardize the practice of data quality assessment for use in pavement LCAs. Table 2.7 shows the data quality assessment matrix that was used in *eLCAP*. The data quality matrix and scores for each item (material, equipment, fuel, etc.) are provided in *eLCAP* (see Section 3.7). More details on the data quality requirements and data validation can be found in the UCPRC LCI report (6).

**Table 2.7: Data Quality Assessment Matrix in eLCAP (6)**

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



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

### 3 USER INTERFACE

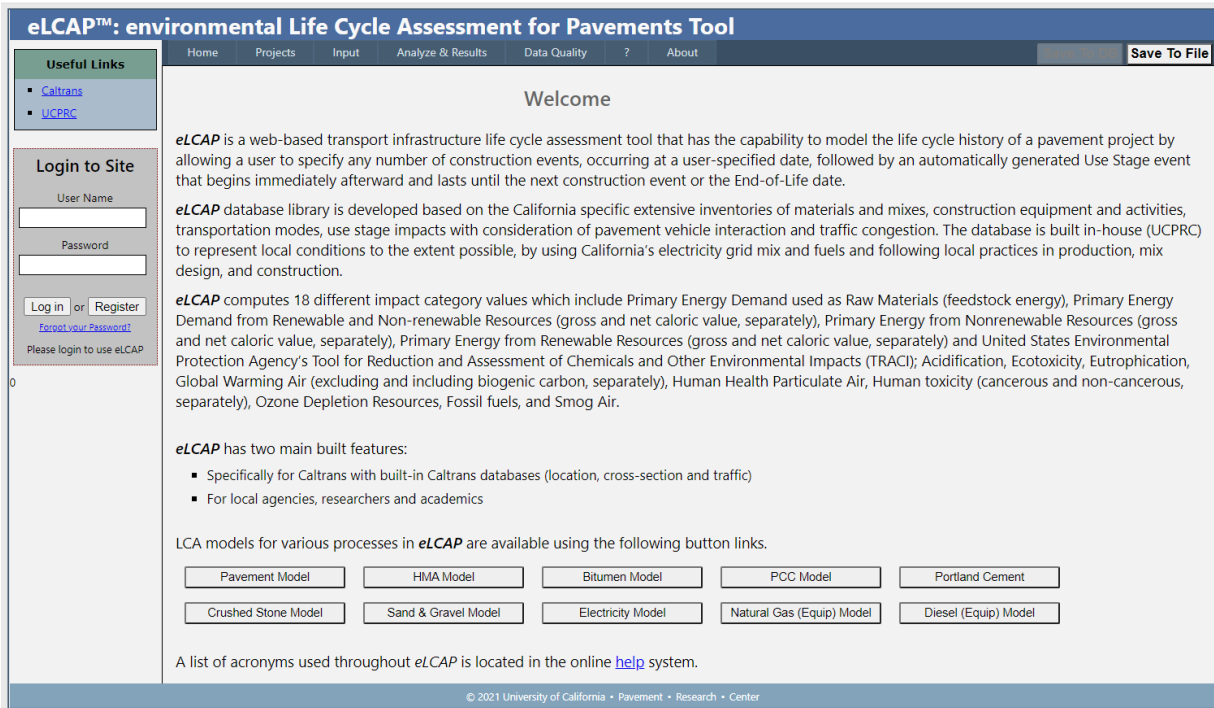
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This chapter discusses the user interface (UI) from a user's perspective. Chapter 5 discusses the UI from an architectural and software development perspective.

Figure 3.1 shows the *eLCAP* home page, which has a set of useful links and login controls on the left-side pane. The different pages in the UI are accessed via menu links, shown at the top in the figure. The buttons at the bottom are used to display PDF files of the various LCA models in *eLCAP*.

The following are the top menu items:

1. *Home*: This menu item is used to display the home page.
2. *Instructions*: This menu item is used to display the Instructions page, which contains information about how to use *eLCAP*.
3. *Projects*: This menu item is used to display the Projects and Project Trials Management page (see Section 4.2).
4. *Input*: This is a hierarchical menu with the following menu items:
  - a. *Manage User Processes*: Links to the page used to manage user-defined processes, such as a customized version of HMA (see Section 4.5).
  - b. *Project Information*: Links to the page used to specify the location of the pavement project on the highway system, to define the pavement cross section, and to review traffic counts (see Section 4.3).
  - c. *Life Cycle*: Links to the page used to define the life cycle of the pavement project, including events when construction/maintenance occurs, the list of activities, and the list of materials and equipment for each event (see Section 4.4).
5. *Analyze & Results*: This page is used to perform the LCA and obtain results (see Section 4.4.).
6. *About*: This menu item is used to display the About page which contains information about the application.



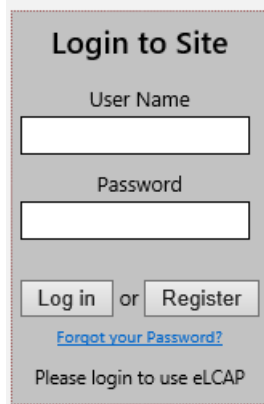
**Figure 3.1: The eLCAP home page.**

### 3.1 Authentication and Authorization

eLCAP requires users to be registered and approved before they can use the program. Once approval is granted, users are associated with a particular eLCAP user group or groups. Specific user permissions are controlled via user groups.

The eLCAP registration page is accessed by clicking the “Register” button shown in Figure 3.2 (it appears on the left side of the home page). Clicking that button brings up the dialog box shown in Figure 3.3. Once a user fills in all the empty fields and clicks “Create User,” both the user and the eLCAP administrator will receive an email. After receiving the email, the administrator can approve the user and assign them to the appropriate user group.

eLCAP also has a mechanism for obtaining a temporary password if a user forgets their password. To obtain a temporary password, a registered user just has to click the “Forgot your Password?” link on the home page (as shown Figure 3.2), and this will bring up the Password Recovery page shown in Figure 3.4. After entering a user name and clicking “Submit,” the user will receive an email containing a temporary password for logging in. The user can change the password to something else, as shown in Figure 3.5. Clicking the “Change your Password” link will bring up the registration page shown in Figure 3.6.



**Login to Site**

User Name

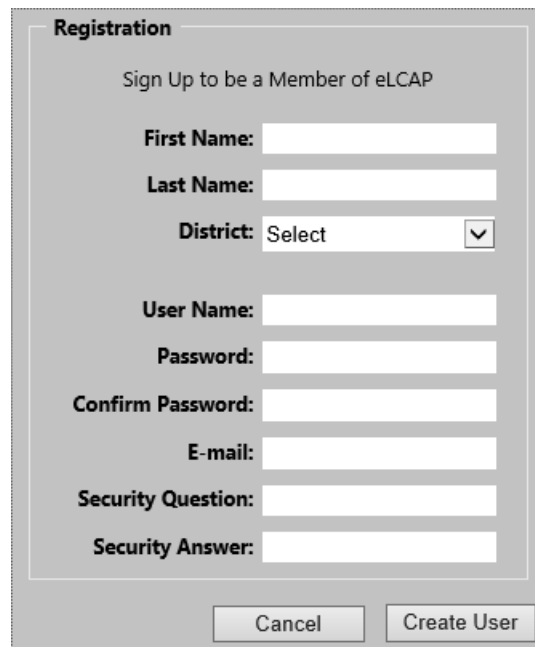
Password

or

[Forgot your Password?](#)

Please login to use eLCAP

**Figure 3.2: Accessing the registration page.**



**Registration**

Sign Up to be a Member of eLCAP

**First Name:**

**Last Name:**

**District:** Select

**User Name:**

**Password:**

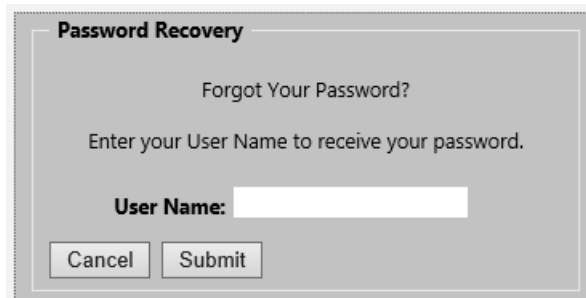
**Confirm Password:**

**E-mail:**

**Security Question:**

**Security Answer:**

**Figure 3.3: Registration page.**



**Password Recovery**

Forgot Your Password?

Enter your User Name to receive your password.

**User Name:**

**Figure 3.4: Password recovery page.**

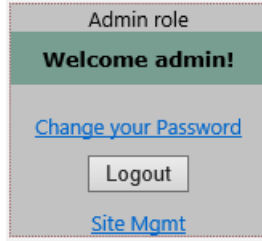


Figure 3.5: Accessing the password change page.

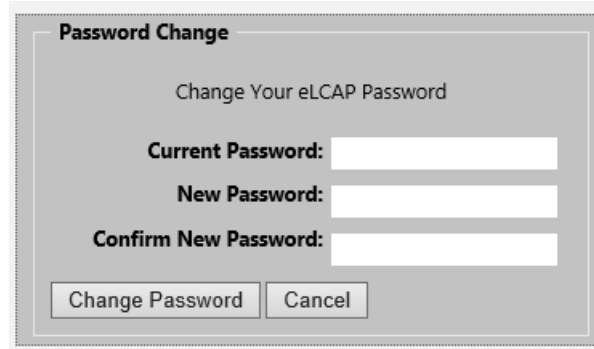


Figure 3.6: Password change page.

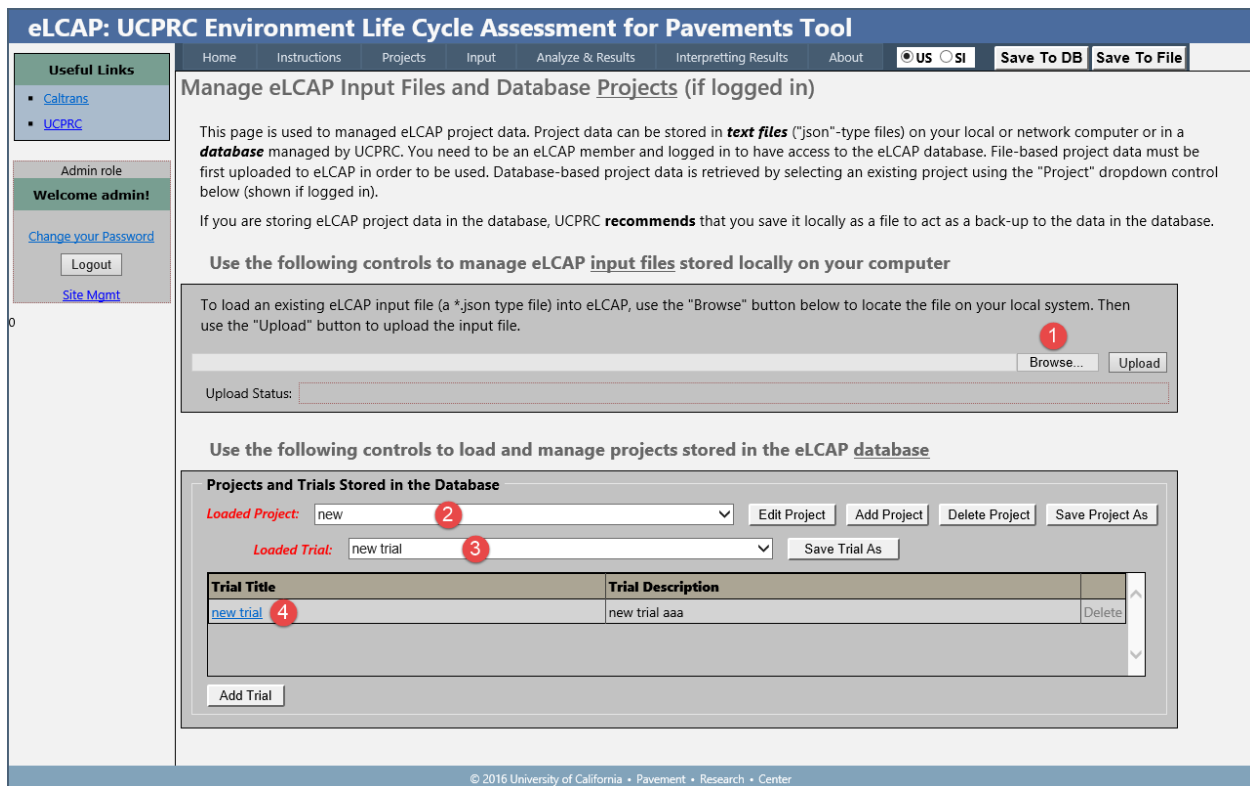
### 3.2 Projects and Project Trials Management

*eLCAP* uses the concepts of *projects* and *trials*. A user can create any number of projects, and a project can have any number of trials. A trial contains the data for the life cycle of a pavement project. User-defined processes (see Section 3.5), such as a custom HMA or custom Transport, are common across all trials. All user data are saved in an SQL database on a server.

*eLCAP* allows a user to generate a text file version of Trial data to act as backup to database data or for project documentation. These files may be uploaded to *eLCAP* and used to perform an LCA as well.

The Project and Trial Management page is shown in Figure 3.7. The corresponding number-labeled areas that appear in the figure are the following:

1. This button allows the user to browse a local hard disk for an *eLCAP* input file, and to upload, edit, and then run it.
2. This field shows the current project.
3. This field shows the current project trial.
4. This is a link to the trial, which allows the title to be edited and a description to be entered.



**Figure 3.7: Projects and Trials Management page.**

The buttons on this page allow users to perform the following activities:

1. *Edit Project*: Edits the current project. The kind of project (Caltrans or Local Agency) will be shown next to the name of the project.
2. *Add Project*: Adds a new project. A new trial will automatically be added to the new project.
3. *Delete Project*: Deletes the current project. If there is only one project, this button is disabled.
4. *Save Project As*: Creates a new project based on the current project.
5. *Save Trial As*: Creates a new trial for the current project based on the current trial.
6. *Add a Trial*: Adds a new trial to the currently selected project.
7. *Selected Trial Comparison Report*: Allows a user to select two or more trials and generate a report showing impact categories for each trial to assist in trial comparisons.

### 3.3 Project Information

The Project Information page is accessed via the Input menu. Hovering the mouse cursor over the Input menu will reveal three submenu items (see Figure 3.8), one of which is “Project Information.”

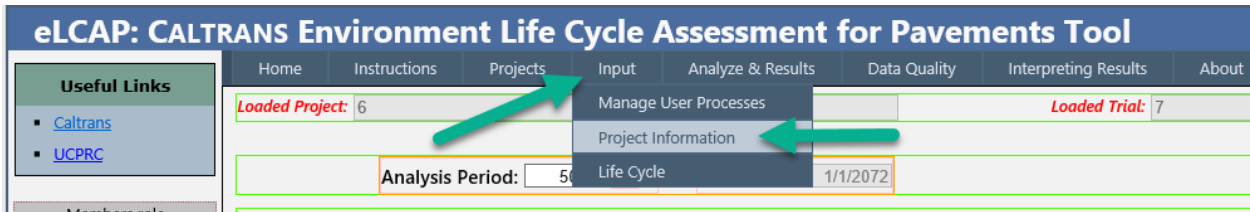


Figure 3.8: Menu item that opens the Project Information page.

Clicking “Project Information” will bring up the Project Information page (Figure 3.9). On this page, a user defines the location of the project and the pavement roadway cross section. The page also shows the one-way traffic counts (e.g., AADT, AADTT) for the center point of the project.

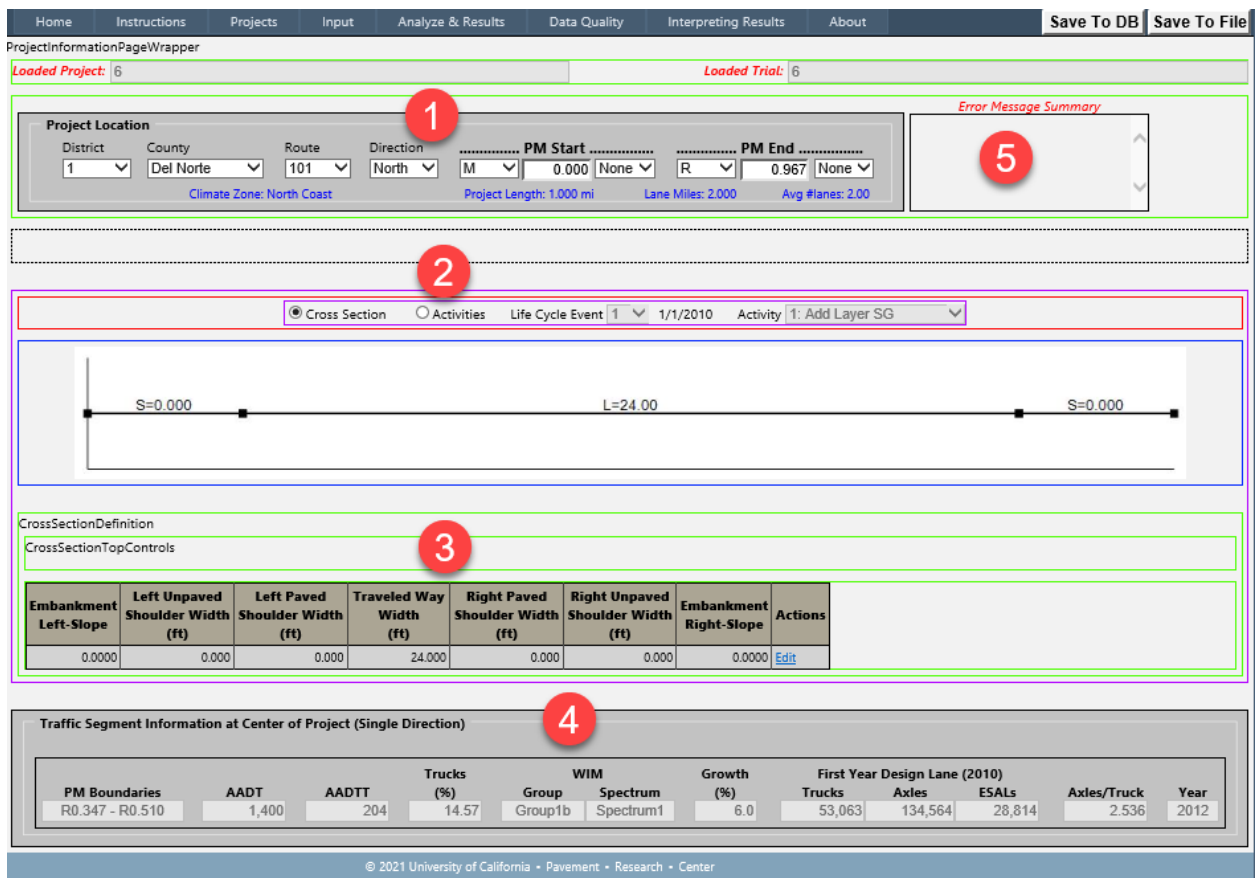


Figure 3.9: Project Information page.

The following list discusses the numbered items in Figure 3.9:

1. Controls for locating the project on the California highway system (District-County-Route-Direction, and Post Mile start and end).
2. Controls for viewing the cross-section or viewing activities (e.g., adding layers, removing material) per life cycle event and activity.
3. A one-line table for defining the various cross-section components for the left and the right roadway side (Embankment Slope, Unpaved Shoulder Width, Paved Shoulder Width) and a single field for defining the Traveled Way Width. The traveled way is initially populated when the project location is defined; this is possible because *eLCAP* has access to the Caltrans highway log.
4. A set of read-only fields that gives the single-direction traffic counts and traffic data for the center point of the project; this is possible because *eLCAP* has access to Caltrans traffic data.
5. An error message summary area that lists all the errors found on this page.

### 3.4 Life Cycle Definition

The Life Cycle page is accessed via the same Input menu used to access the Project Information page (as discussed in Section 3.3). Hovering the mouse cursor over the Input menu will reveal three submenu items (see Figure 3.10), one of which is “Life Cycle.”

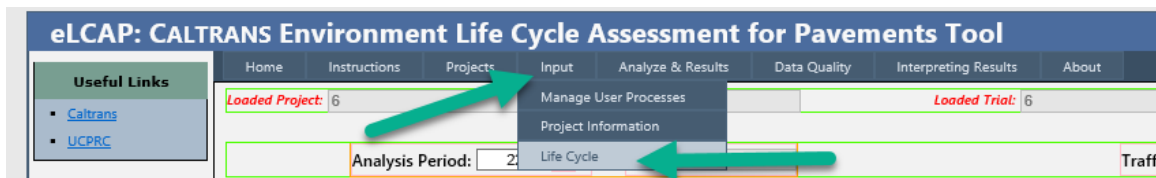


Figure 3.10: The menu item that opens the Life Cycle page.

Clicking “Life Cycle” will bring up the page where a user defines the series of construction events that will model the project’s life cycle. The top portion of the Life Cycle page, showing the Life Cycle grid, is shown in Figure 3.11. A Life Cycle Event is defined by the date of the event, the service life of the activities performed for the event, and the IRI roughness equation coefficients to use for the Use Stage that occurs between successive events. Each of the treatment options shown in the dropdown in Figure 3.11 has an associated set of IRI roughness equation coefficients that determines the rate of growth of IRI over time. See Section 2.7.2 for a discussion of the Use Stage. The full Life Cycle page is shown in Figure 3.12.

Selecting a treatment type for the Use Stage Roughness Equation tells *eLCAP* to do two things: (1) to include a use stage and (2) to select the IRI roughness equation coefficients associated with the selected



treatment. By default, “None” is selected, indicating that the user does not want to include a Use Stage for the life cycle event. A user should select the treatment that best represents the end result of the set of activities defined for the life cycle event. Major pavement treatment thickness definitions for the roughness equations include the following:

- Very Thin Overlay:  $\leq 0.1$  ft.
- Thin Overlay:  $> 0.1$  ft and  $\leq 0.2$  ft.
- Medium Overlay:  $> 0.2$  ft and  $\leq 0.5$  ft.
- Thick Overlay:  $> 0.5$  ft.

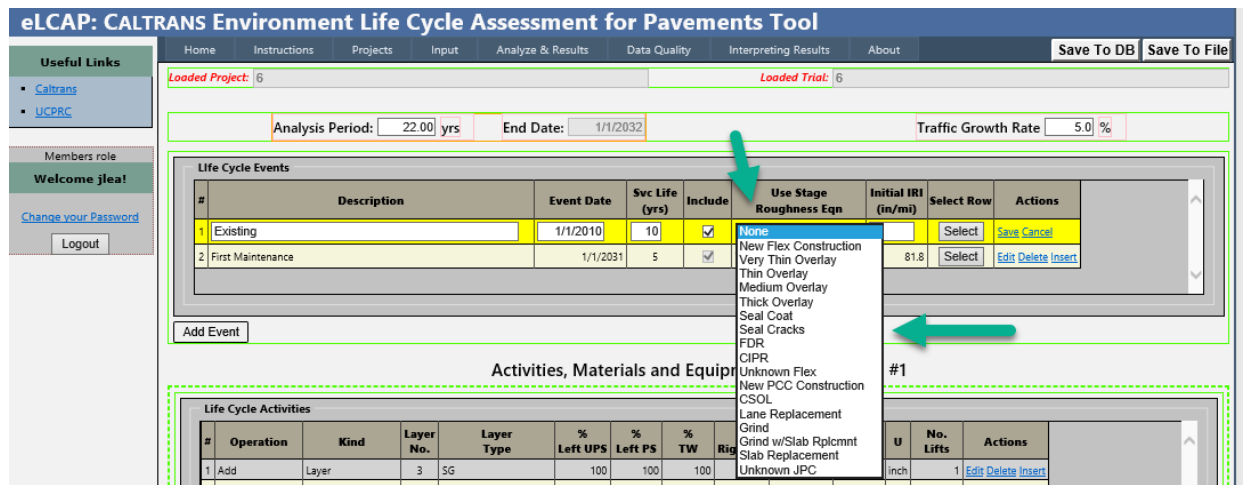


Figure 3.11: Selecting a treatment for the use stage roughness equation.

As shown in Figure 3.12, the Life Cycle page is divided into four panes:

1. *Life Cycle Events*: The grid in this pane allows a user to add any number of life cycle events. The associated activities, materials, and equipment for the selected event (highlighted in yellow in Figure 3.12) will appear in the lower three panes.
2. *Life Cycle Activities*: The grid in this pane allows a user to add any number of activities for the selected event. The following is the list of activities and the various options for each:
  - a. *Add*
    - i. Layer: HMA, PCC, AB, LCB, CTB-Class A, CTB-Class B, ATPB, CTPB, CCPR, FDR, PDR, AS, LTS, CSO, SG
    - ii. Seal Coat: Chip Seal, Slurry Seal, Fog Seal, Cape Seal, Sand Seal, Tack Coat, Prime Coat
    - iii. Reflective Coating: Bisphenol A, Polyester Styrene, Styrene Acrylate

- b. *Remove*
  - i. Mill asphalt
  - ii. Mill concrete
  - iii. Grind & Groove
  - iv. Cold plane
  - v. Excavate
  - vi. Haul Soil
- 3. *Materials and Transports to the Site:* The grid in this pane shows the *eLCAP*-generated materials, quantities, and means of transport for all the activities for the selected event; it also allows a user to manually add and delete materials.
- 4. *Equipment Used at the Site:* The grid in this pane shows the *eLCAP*-generated equipment and time of operation for each, for all activities for the selected event; it also allows a user to manually add and delete equipment.

When a life cycle event is added, the activities, materials, and equipment grids will be empty. *eLCAP* uses a default duration of 10 years between successive events to assist in constructing a life cycle. Users can edit the dates as necessary.

Each of the grids on the life cycle definition page consists of rows and columns. When the page first opens, the rows appear in *display* mode, allowing data items to be viewed but not edited. To enter *editing* mode to make changes, the user must click the “Edit” link in a particular row. After making changes, clicking “Save” will keep the changes and clicking “Cancel” will discard them.

When an activity is defined and saved, *eLCAP* will generate a default material to be used (e.g., a specific kind of HMA when adding an HMA layer) and a list of the construction equipment necessary to implement the activity. *eLCAP* will also compute the quantities of material using the project limits (post mile start/end and number of lanes), the cross section defined on the Project Information page, and the thickness (add layer or remove material) specified for the activity. *eLCAP* will also provide construction time estimates for each piece of equipment. The default material and the computed material quantities and equipment time estimates may be edited.

A user can delete any or all the items generated for an activity. In addition, a user can manually add materials and equipment. In fact, the user can skip defining any activities at all and directly add materials and their

associated quantities, and equipment and its associated times of operation. But, in most cases, defining activities for an event is more efficient than manually building lists of materials and equipment.

Clicking the links in the Source Name column in the two lower grids—Materials and Transports to the Site and Equipment Used at the Site—will display a form page with the data for the item. For example, if a user clicks the “HMA with 15% Binder Replacement, no Rejuv” in the Source Name column of the Materials and Transports to the Site grid, the HMA form page will be displayed. Listed on that form page will be all the input flows and their associated quantities needed to produce one unit of HMA. If the HMA is an *eLCAP* library material, no changes can be made to it; but if the HMA is a user-defined/custom HMA mix, changes can be made.

Home Instructions Projects Input Analyze & Results Data Quality Interpreting Results About Save To DB Save To File

Loaded Project: 6 **3** Loaded Trial: 6 **4** **1** **2**

Analysis Period: 22.00 yrs **5** End Date: 1/1/2032 **6** Traffic Growth Rate 5.0 % **7**

**Life Cycle Events**

#	Description	Event Date	Svc Life (yrs)	Include	Use Stage Roughness Eqn	Initial IRI (in/mi)	Select Row	Actions
1	Existing	1/1/2010	10	<input checked="" type="checkbox"/>	New Flex Construction	139.6	Select	Edit Delete Insert
2	First Maintenance <b>8</b>	1/1/2031	5	<input checked="" type="checkbox"/>	Thin Overlay	81.8	Select	Edit Delete Insert

**9** **10** **11** **12** **13** **14** **15**

Add Event **16**

**Activities, Materials and Equipment for LCA Event #1**

**Life Cycle Activities**

#	Operation	Kind	Layer No.	Layer Type	% Left UPS	% Left PS	% TW	% Right PS	% Right UPS	Thick (in)	No. Lifts	Actions
1	Add	Layer	3	SG	100	100	100	100	100	10.0	1	Edit Delete Insert
2	Add	Layer	2	AB	100	100	100	100	100	12.0	2	Edit Delete Insert
3	Add	Layer	1	HMA	N/A	100	100	100	N/A	6.0	2	Edit Delete Insert

**17** **18** **19** **20** **21** **22** **23** **24** **25** **26** **27** **28**

Add Activity **29**

**Materials and Transports To the Site**

#	Type	Source Name	Density	U	Quantity	U	Transport to Site	Distance	U	Actions
1	AB	Aggregate Base Mix	150.00	lb/ft3	8,181.4	ton	End Dump Truck	50.0	mile	Edit Delete Insert
2	AB	Aggregate Base Mix	150.00	lb/ft3	10,226.7	ton	End Dump Truck	50.0	mile	Edit Delete Insert
3	HMA <b>30</b>	HMA with 15% Binder Replacement, no Rejuv	150.00	lb/ft3	4,908.8	ton	End Dump Truck	50.0	mile	Edit Delete Insert

**31** **32** **33** **34** **35** **36** **37** **38** **39**

Add Material **40**

**Equipment Used at the Site**

#	Type	Source Name	Generated By	Time Est (hr)	Quantity	U	Actions
1	Light Tower	Light Tower	Add-Layer-SG	59.03	64.9	hr	Edit Delete Insert
2	Water Truck	Water Truck	Add-Layer-SG	0.19	0.2	hr	Edit Delete Insert
3	Front Loader	Front Loader	Add-Layer-SG	4.09	4.2	hr	Edit Delete Insert
4	Roller <b>41</b>	Roller Static	Add-Layer-SG	5.90	5.9	hr	Edit Delete Insert
5	Roller	Roller Padfoot	Add-Layer-SG	5.90	5.9	hr	Edit Delete Insert
6	Emulsion Truck	Emulsion Truck	Add-Layer-SG	0.20	0.2	hr	Edit Delete Insert

**42** **43** **44** **45** **46** **47**

Add Equipment **48**

Note: Numbers in red circles indicate interface elements, with explanations for each element in the text following this figure.

Figure 3.12: Life cycle definition page.

The following list discusses the numbered items in Figure 3.12:

1. Button to click for saving the trial data to the database. Data are saved automatically when the user goes to the “Analyze & Results” page.
2. Button to click to save the trial data to a file on the computer.
3. Field that shows the current project (i.e., the “Loaded Project”).
4. Field that shows the current trial (i.e., the “Loaded Trial”).
5. Field to set the analysis period.
6. End date, generated by *eLCAP*.
7. Field to set the traffic growth rate (traffic counts are used between events in the Use Stage).
8. Field to enter text that describes what the event is modeling in the life cycle.
9. Field to set the date for the event.
10. Field to set the service life of the event in years.
11. Checkbox used to tell *eLCAP* if the event should be included in the LCA.
12. Dropdown list to select the treatment type that best represents the end result of the event.
13. Field to change the default Initial IRI for the event.
14. Button used to select the event that will have its activities, materials, and equipment lists displayed in the lower three grids.
15. Buttons used to edit, delete, or insert an event.
16. Button used to add an event.
17. Dropdown list to select the operation for the activity (e.g., Add/Remove).
18. Dropdown list to select the kind of operation for the activity (e.g., Layer).
19. *eLCAP*-generated layer number.
20. Material type of the layer.
21. Percent of Left Unpaved Shoulder (UPS) width to include for the activity.
22. Percent of the Left Paved Shoulder (PS) width to include in the activity.
23. Percent of the Traveled Way (TW) width to include in the activity.
24. Percent of the Right Paved Shoulder (PS) width to include in the activity.
25. Percent of the Right Unpaved Shoulder (PS) width to include in the activity.
26. Thickness of the layer or the amount to remove in the activity.
27. *eLCAP* pre-populates this with the number of lifts required, per Caltrans rules.
28. Buttons used to edit, delete, or insert a life cycle activity.
29. Button to add a life cycle activity.
30. Field shows/selects the type of material for the activity.
31. Field shows/selects the source of the material; also used to select a custom material.

32. Field that is pre-populated with the density of the layer material.
33. Dropdown list to select the units for the density of the material.
34. Field shows/selects the amount of the material.
35. Field shows/selects the measurement units associated with the amount.
36. Field shows/selects the transport for bringing the material to the project.
37. Field shows/selects the distance for the transport of the material to the project site.
38. Field shows/selects the measurement units for distance.
39. Buttons used to edit, delete, or insert a material.
40. Button used to add a new material to the material grid.
41. Field shows/selects equipment type to be used at the site.
42. Field shows/selects the piece of equipment to be used.
43. *eLCAP*-generated field to indicate which activity generated the equipment.
44. *eLCAP*-generated estimate of how much equipment time will be needed.
45. Field shows/selects the amount of time that the equipment at the site will operate.
46. Field shows the measurement units (U) for the amount of time.
47. Button used to edit, delete, or insert a piece of equipment.
48. Button used to add a piece of equipment.

### 3.5 User-Defined Processes

*eLCAP* has many built-in materials, also referred to as *library materials*, that a user can select to define a construction-type event. The library materials are organized by type (e.g., HMA, PCC), and there are several individual processes per type. For example, there are three different types of HMA on which to base a user-defined, custom HMA.

Figure 3.13 shows the page for managing user-defined processes. The “Add New” button is used to add a new user-defined process for the type of material shown in the dropdown menu to the left of the button. The grid lists all user-defined processes.

The link in the Source Name column will display the edit form page for the process. The # Refs column indicates how many times the user-defined process is referenced by any trial. If the user-defined process is referenced, it cannot be deleted and the “Delete” button will be disabled.

## Manage User Definitions

This page is used to manage User Defined LCA objects, such as user defined HMA and PCC.

### User Defined Processes

#	Type	Source Name	Based on Model	Created	Modified	# Refs	
1	HMA	<a href="#">My Special HMA-1</a>	Hot Mix Asphalt (HMA) at Plant	2/14/17 11:37:58	2/14/17 11:37:58	0	<a href="#">Delete</a>

**HMA**  
PCC  
AB  
Cement  
Electricity  
Cargo  
Paver\_time  
Roller\_time

Add New

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**Figure 3.13: The page to manage user-defined processes.**

Clicking the “Add New” button when HMA is shown in the dropdown menu brings up the HMA edit form page shown in Figure 3.14. Once this page appears, the user supplies a unique name for the user-defined HMA and then selects one of the HMA types in the *eLCAP* library by using the “Based On” dropdown menu. Next, the user edits individual rows to customize the HMA. For example, a user might want to have a special HMA that uses 4% “Asphalt Content” instead of the library’s version of 6%, or the user might want to use a user-defined process (previously defined) for electricity for this new user-defined HMA.

Once a user-defined process has been created, it may be referenced when constructing the life cycle (see Section 3.4).

This form allows you to add a User Defined HMA Process by changing the input flow quantities into the HMA Process. The initial flow quantities come from the built-in Library HMA. Select the Edit link to edit one or more input flow quantity, specify a unique name for the User Defined HMA and select Save. Once saved, the User Defined HMA will be available to use wherever an HMA is appropriate.

Input Flows for:  Based On: Select  
HMA - Permeable - No RAP  
Hot Mix Asphalt (HMA) at Plant  
HMA with RAP - Hveem  
HMA with RAP - Superpave  
HMA with RAP  
RHMA - No RAP  
RHMA - Permeable - No RAP  
RHMA

Define Quantities for a New HMA  
HMA Reference Flow Amount: 1.000 kg

#	Type	Source Name	Quantity	Unit	
1	Parameter	Agg_Crushed	94.100	%	<a href="#">Edit</a>
2	Parameter	Agg_Natural	0.000	%	<a href="#">Edit</a>
3	Parameter	Asphalt_Content	5.900	%	<a href="#">Edit</a>
4	Parameter	Crumb_Rubber	0.000	%	<a href="#">Edit</a>
5	Parameter	Extended_Oil	0.000	%	<a href="#">Edit</a>
6	Parameter	Polymer_Modified	0.000	%	<a href="#">Edit</a>
7	Parameter	RAP	0.000	%	<a href="#">Edit</a>
8	Electricity	<a href="#">US-CA: Electricity Mix</a>	0.00763	MJ	<a href="#">Edit</a>
9	Natural_Gas	Natural Gas Combusted in Industrial Equipment	0.01033	m3	<a href="#">Edit</a>
10	Diesel_from_industrial_equipment	Diesel Combusted in Industrial Equipment	0.00000	m3	<a href="#">Edit</a>
<i>Total Percent</i>			100.000	%	

Save Cancel/Back

Figure 3.14: Adding user-defined HMA process page.

### 3.6 Default/Min/Max Values

*eLCAP* has a few default values that minimize user time when creating a new project trial. The following are the default values:

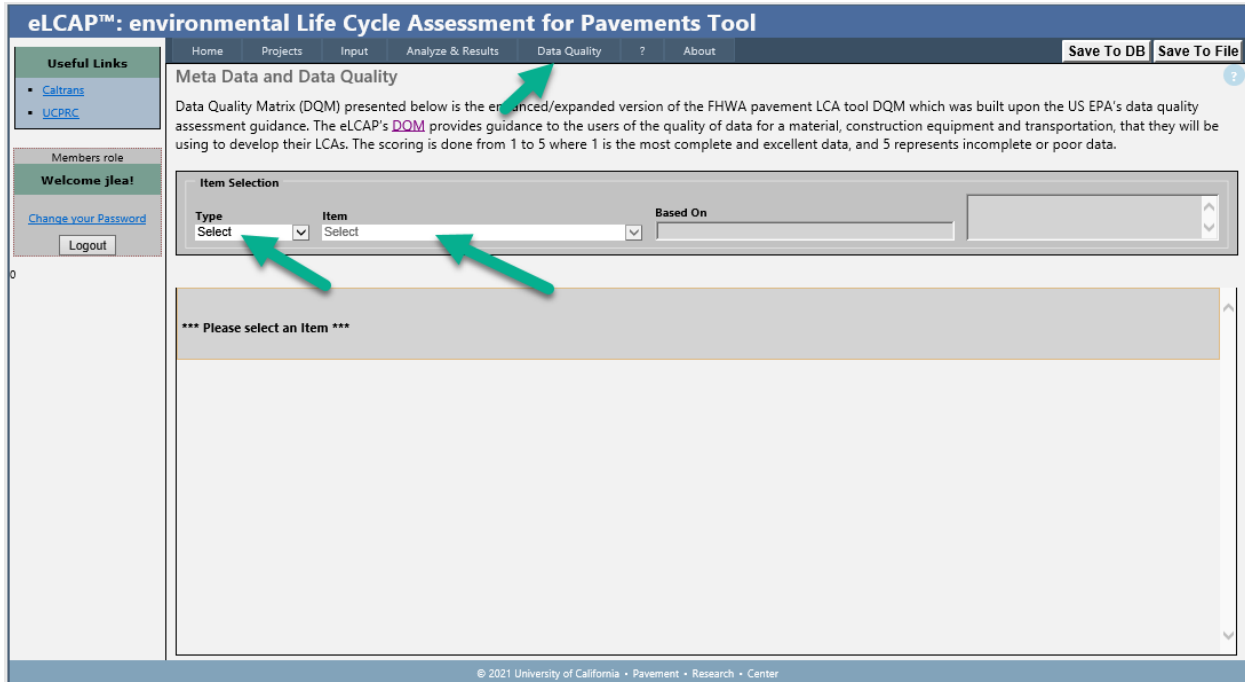
- Years added to the start of first life cycle event to establish the end-of-life date: **50 years**
- Construction time duration for a life cycle event: **6 months**
- Use Stage time duration between construction events: **10 years**
- Traffic Growth Rate: **0.0%**

*eLCAP* also makes range checks on data items so that unreasonable numbers/results are avoided. The minimum value is usually 0.0 and the maximum value is usually a large number so as not to constrain the user too much.

### 3.7 Data Quality Assessment

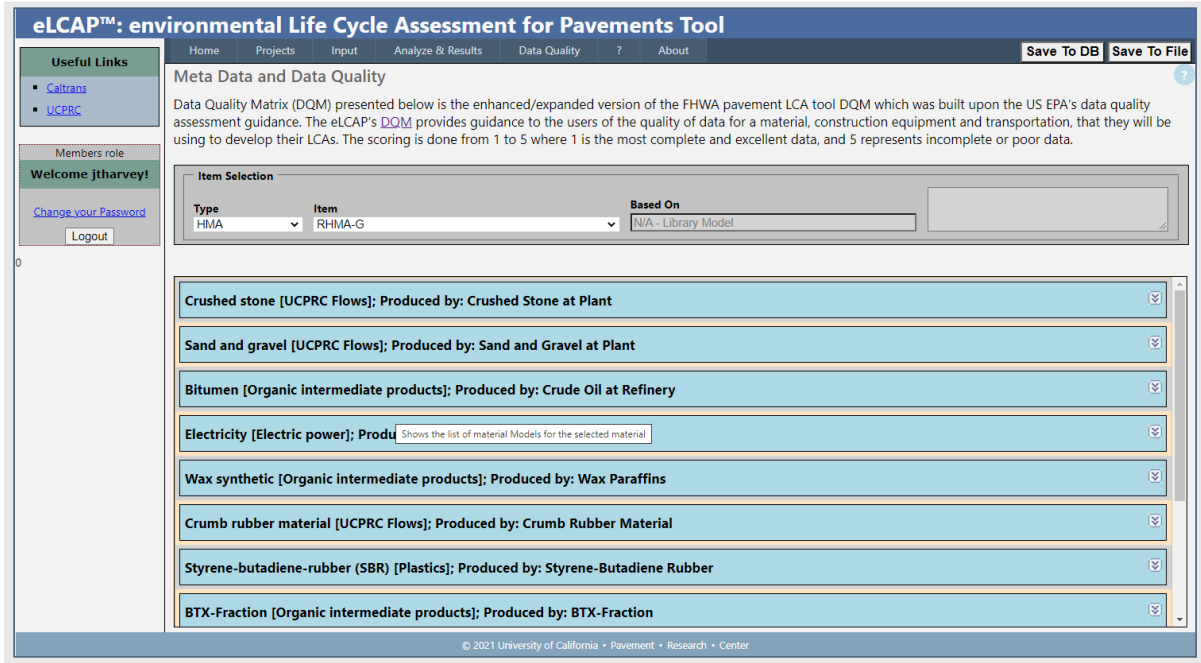
Metadata and data quality assessment information are available on the Data Quality tab as can be seen in Figure 3.15.





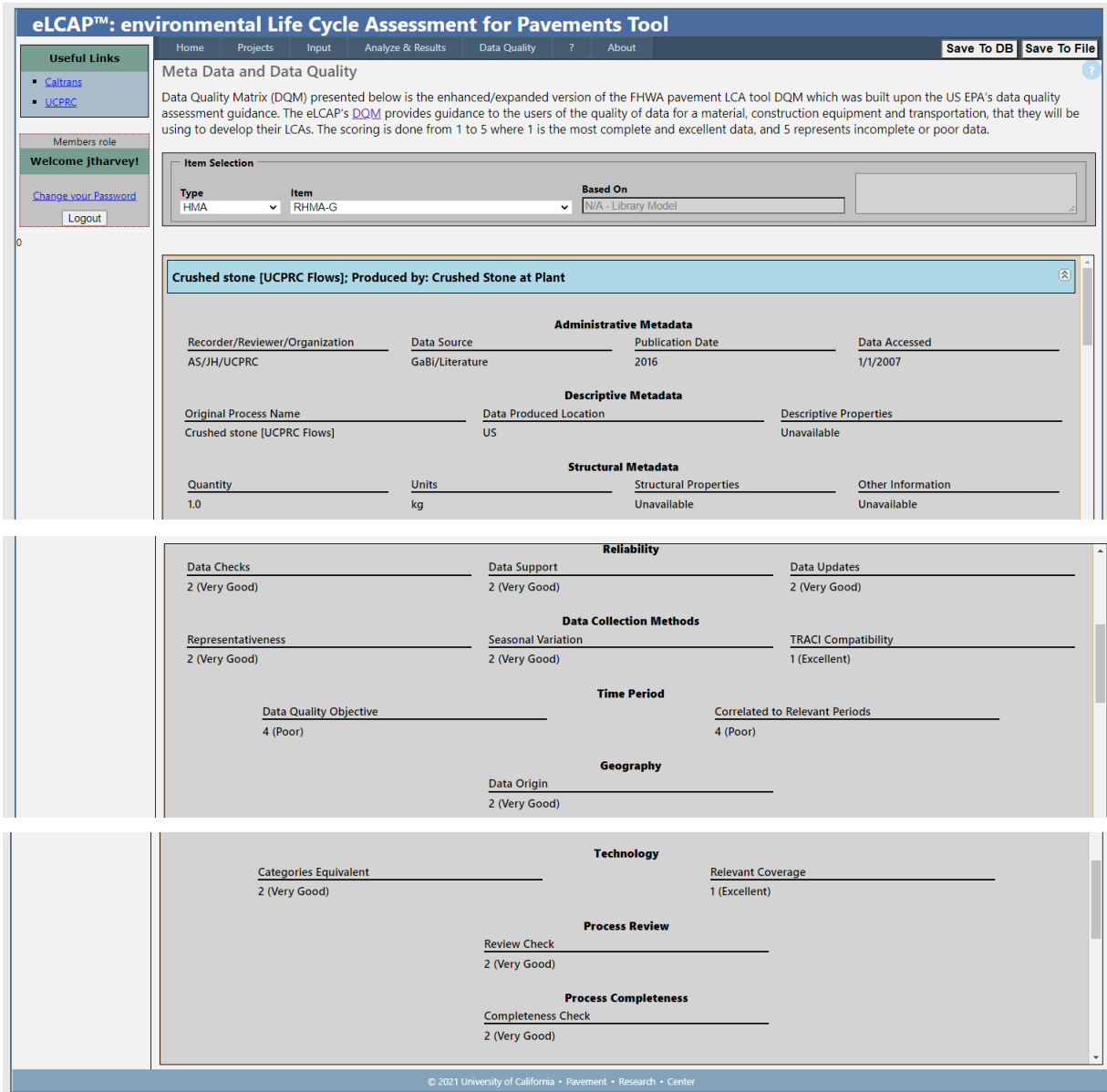
**Figure 3.15: Data Quality tab location on the *eLCAP* page.**

The type of process and the specific item (material, equipment, or transport) whose metadata and data quality are to be assessed are first selected on this page. If it is a composite material (made with different materials), the metadata and data quality for the component materials are accessed individually. Figure 3.16 is shown for the component materials of RHMA-G.



**Figure 3.16: Example showing metadata and data quality assessment information (embedded under blue boxes) for each ingredient of RHMA-G.**

Once an item is selected, the metadata and data quality assessment described in Section 2.8 can be seen, as shown in Figure 3.17.



**Figure 3.17: Example showing metadata and data quality assessment of crushed stone that is being used in the RHMA-G.**

### 3.8 Analyze & Results

The Analyze & Results page is used to perform an LCA and to obtain results. Figure 3.18 shows the Analyze & Results page. During a life cycle analysis, total GHG is displayed in the graph as it is computed for each construction-type event and each Use Stage event. Summary results appear in a scrollable window after the LCA is completed; there is a summary section for each construction-type event (Figure 3.18) and each Use Stage event in the life cycle (Figure 3.19). Report files (*Excel* and *PDF*) can be downloaded to a local computer by clicking the “Get Results” button.

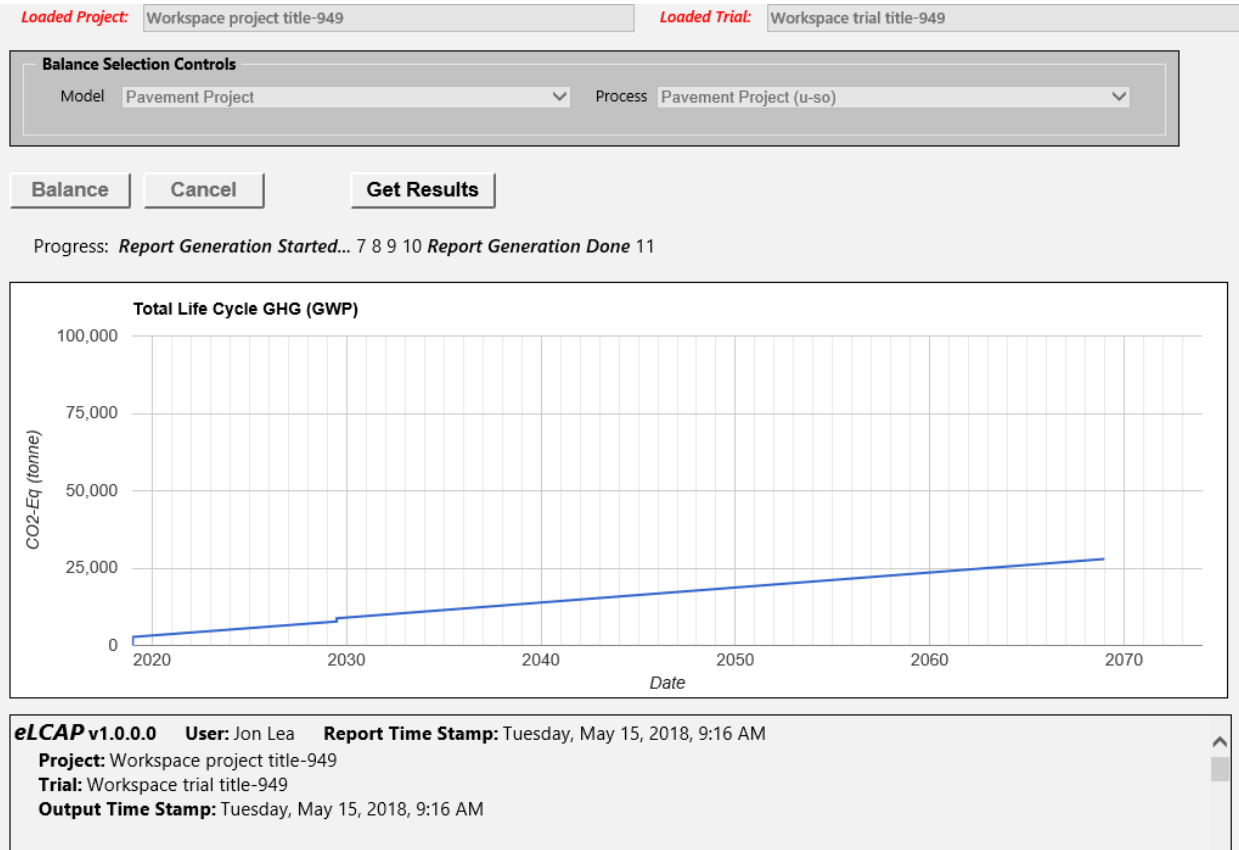
The read-only fields at the top indicate the Project and Trial that will be used for the LCA.

The Balance Selection Controls are for expert users and do not appear for most users. The Model dropdown menu is used to select the LCA model that will be used for the balancing, and the Process dropdown menu is used to select the process in the model that will be the starting point for balancing. The default selection for the model is “Pavement Project” and the default selection for the process is “Pavement Project (u-so).” See Section 2.1 for a discussion of balancing.

Balancing for a process (i.e., starting at and traversing/climbing upstream from the process) results in the generation of the LCI for the process. Expert LCA users may want to generate the LCI for a different process in the Pavement Project LCA model than the Pavement Project Process and these controls allow that to be done.

To initiate the LCA, the user clicks the “Balance” button. *eLCAP* will perform the LCA by looping over all the events (Construction Stage and Use Stage) in the life cycle, building an LCA model for each, balancing, and then performing the life cycle impact assessment (LCIA).

The “progress” message area immediately below the buttons on the page provides feedback to the user during the LCA. There are messages for each event. Construction-type events typically take more time to execute so the messages are easier to read; Use Stage events happen very quickly so the messages pass by quickly. For longer-executing events, there will be numbers visible in the message area as *eLCAP* sends second counts to the browser during the LCA.



Note: Example page; results not associated with other figures.

**Figure 3.18: Analyze & Results page.**

**Use Stage Event#1 Summary Results for Method: PaveM Conceptual**

Use Stage Data

Starting Date: 7/1/2018    Ending Date: 1/1/2068    Analysis Period: 49.54 yrs  
Pavement Type: Flexible    Treatment: Full\_Depth\_Reclamation

IRI Performance Data for GHG

Project Center Climate Category: severe

Impact Category	Value	Units
-----		
GHG, excl. biogenic carbon; Based on: PaveM_Eqns	2.418E+07	kg CO2e
Per Lane Mile	1.209E+07	kg CO2e

Note: Example page; results not associated with other figures.

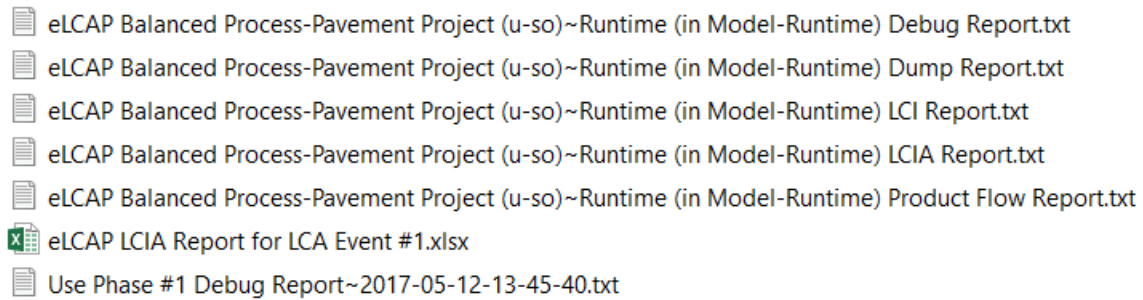
**Figure 3.19: Analyze & Results page showing Use Stage event summary results.**

The last messages shown for an LCA are “Report Generation Started” and “Report Generation Done.” When these appear, the “Get Results” button is enabled and generated report files can be downloaded.

The LCA may be stopped before it is complete by clicking the “Cancel” button.

### 3.8.1 Results Generation

A set of reports is generated automatically for each construction event–Use Stage pair of events. Detailed/debug level reports are generated (only available for Caltrans users) as well as a standard *Excel* report. The list of reports for a single construction event and a single Use Stage life cycle event is shown in Figure 3.20. The *Excel* file is the standard report, and all others are detailed/debug level reports. *eLCAP* computes and provides individual/separate *Excel* result files for each event in the project life cycle as well as the sum of the impacts from all the events (complete project).



**Figure 3.20: Generated reports ready for download.**

#### 3.8.1.1 Detailed/Debug Level Reports

Figure 3.20 shows the reports generated by *eLCAP* for a single construction event–Use Stage pair of events. The first five reports shown in the figure are detailed/debug level construction-type event reports. The first one listed is the most comprehensive of the reports. It gives input/output flows for every process in the Pavement Project Model (there can be hundreds of them) with the following data for each flow:

1. Flow name
2. Amount of flow “as collected”
3. Amount of the flow normalized to produce a unit value for the output product flow
4. Amount of the flow scaled as required by the Pavement Project Process to produce a single pavement project

Since the process of balancing starts at the Pavement Project Process and “climbs” upstream for each input flow into that process, the Pavement Project Process is the last one to be completed. Therefore, it appears at the end of the report. Figure 3.21 shows the sample results for that process.

The figure shows that there were 108 processes in the LCA model and that the Pavement Project Model has a single input flow (907.185 kg of HMA, which is a user input value of one ton of HMA) and one output flow (a pavement project).

Since the user specified one ton of HMA for the example pavement project, all flows in the HMA Process upstream from the Pavement Project Process are scaled by 907.185. The scaling is performed, recursively, upstream for each model attached to each input flow in each process.

Process (108) Information for: Pavement Project (u-so)-Runtime      This Process is FIXED;    Model Scale Factor: 1.000  
 This is a Pavement Project (u-so) Process

All Techsphere and Nature flows are scaled by: 1.000000e+00

Flows	As Collected	Normalized to *	Normalized to #	
			Techsphere Flows	Nature Flows
-----				
<b>Inflows</b>				
Hot Mix Asphalt (HMA) [UCPRC Flows]-1	907.185 kg	907.185 kg/pcs	907.185 kg/pcs	
<b>Outflows</b>				
Pavement Project [UCPRC Flows]*#	1.000 pcs	1.000 pcs/pcs		1.000 pcs/pcs

*Note:* Example page; results not associated with other figures.

**Figure 3.21: Debug level report results for the Pavement Project Process.**

Figure 3.22 shows some of the detailed information in the Use Stage event report.

The top section shows the three route segments for the example of DN-101-North, from PM R1.000 to PM R5.000. The second section shows some high-level Use Stage data. The third section shows route segment and lane data for the first year on the Use Stage. The information in this section is discussed in Section 2.7.2.

Segment List AFTER Project Limit Trimming (Traffic Volumes are for BOTH Directions)

MgmtSegment List for Pavement Project Get Segments										
Event	Beg Segment CODM(m)	Boundary SODM	PM	Lanes	Segment AADT	Trks Yr	Event	End Segment CODM(m)	Boundary SODM	PM
BegProj	0.0	763.637	M0.000	2	4450	507 00	LaneRange	0.0	767.317	R3.647
LaneRange	0.0	767.317	R3.647	1			Traffic	0.0	768.308	R4.638
Traffic	0.0	768.308	R4.638	1			EndProj	0.0	768.670	R5.000

Use Stage Data

Starting Date: 1/1/2019 Ending Date: 7/1/2029 Analysis Period: 10.50 yrs  
 Pavement Type: Flexible Treatment: Full\_Depth\_Reclamation  
 Project Length: 5.033 miles Total Lane Miles: 8.713 miles Avg # Lanes 1-Dir: 1.73  
 Project Center Climate Zone: North Coast Climate Category: severe  
 Traffic Growth Rate: 0.0%

Use Stage GHG Due To IRI (Traffic Volumes Reflect Growth Rate Effects from Midpoint of Traffic Count Year to Date Shown in 'Date' Column)

Yr#	Date	Year	Seg#	Seglen (mi)	C	WIM	Ln#	DF	AADT	CarVol	TrkVol	2-Axle	3-Axle	4-Axle	5-Axle	ESAL (k)	E	A	B	C	IRI (ipm)	GHG (kg)	
1	7/1/2019	0.5	1	3.680	s	1b	1	0.190	1,152	1,104	48	17	8	0	20	24 A	157.3	3.4	1.0	159.0	7.343863E+05		
							2	0.810	1,072	868	204	75	37	2	89	101 B	143.0	5.1	1.0	145.6	1.006404E+06		
				Segment Totals:			1.000		2,224	1,972	252	92	45	2	109							1.740790E+06	
			2	0.991	s	1b	1	1.000	2,225	1,972	253	93	46	3	110	124 B	143.0	5.1	1.0	145.6	4.707014E+05		
				Segment Totals:			1.000		2,225	1,972	253	93	46	3	110								4.707014E+05
			3	0.362	s	1b	1	1.000	2,300	2,063	237	61	31	50	94	117 B	143.0	5.1	1.0	145.6	1.787601E+05		
				Segment Totals:			1.000		2,300	2,063	237	61	31	50	94								1.787601E+05
				Year Total: 2.390251E+06																			
				Year Total Per Lane Mile: 2.743316E+05																			

Note: Example page; results not associated with other figures.

Figure 3.22: Debug level report results for the Use Stage.

3.8.1.2 Standard Excel Report

The following sections show some of the results for the standard *Excel* report.

**Sample Project-Level bar chart.** Figure 3.23 shows 6 of the 18 computed impact categories, with each chart showing results for “Material Production,” “Transport,” “Construction Equipment,” and “Construction.”

**Sample Material-Level bar chart.** Figure 3.24 shows 2 of the 18 computed impact categories, with each chart showing several different types of grouped results.

**Sample result table.** Figure 3.25 shows the Project Totals table.



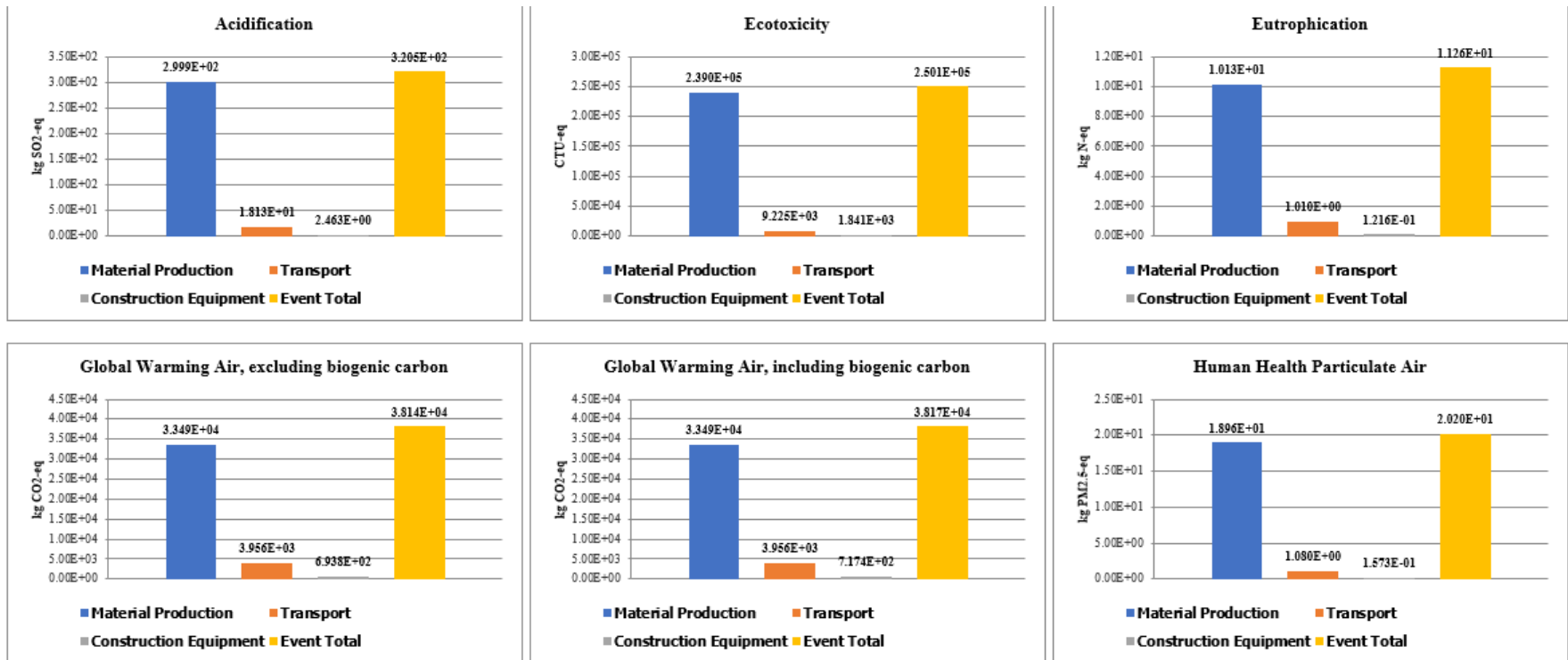


Figure 3.23: *Excel* report example showing bar charts.

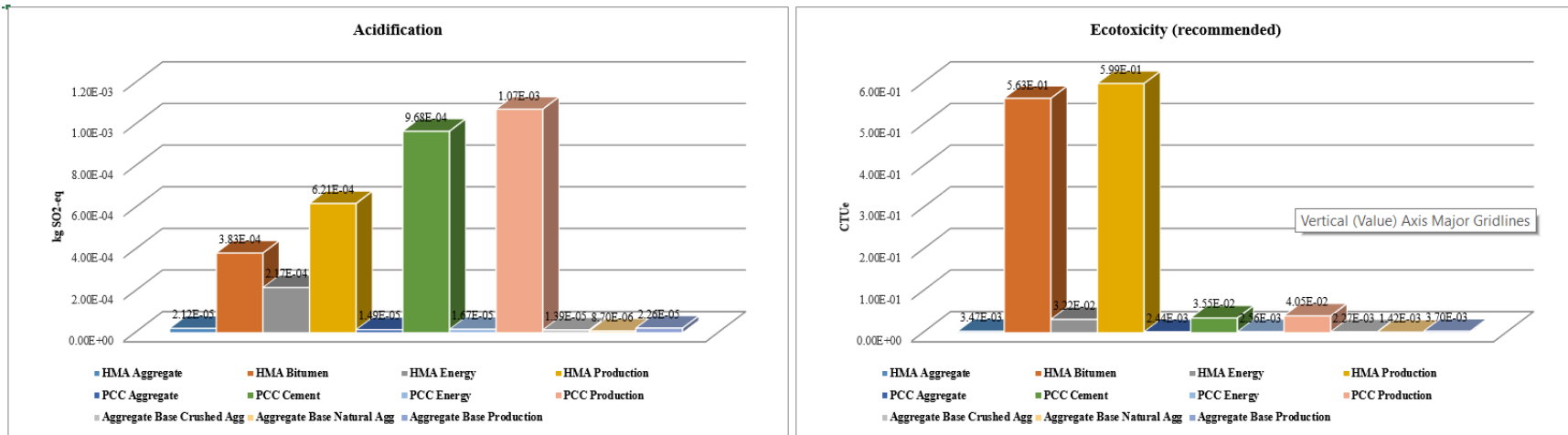


Figure 3.24: Excel report example showing 3D bar charts.

Event Totals

Selected Impact Categories and Inventories	Units	Material Production	Material Production as % of Event Total	Transport	Transport as % of Event Total	Construction Equipment	Construction Equipment as % of Event Total
Acidification	kg SO2-eq	2.9987E+02	93.57%	1.8134E+01	5.66%	2.4633E+00	0.77%
Ecotoxicity	CTU-eq	2.3904E+05	95.58%	9.2246E+03	3.69%	1.8414E+03	0.74%
Eutrophication	kg N-eq	1.0130E+01	89.95%	1.0098E+00	8.97%	1.2163E-01	1.08%
Global Warming Air, excluding biogenic carbon	kg CO2-eq	3.3492E+04	87.81%	3.9564E+03	10.37%	6.9378E+02	1.82%
Global Warming Air, including biogenic carbon	kg CO2-eq	3.3492E+04	87.75%	3.9564E+03	10.37%	7.1743E+02	1.88%
Human Health Particulate Air	kg PM2.5-eq	1.8965E+01	93.88%	1.0799E+00	5.35%	1.5734E-01	0.78%
Human Toxicity, cancer	CTUh	2.5038E-05	95.63%	9.1169E-07	3.48%	2.3278E-07	0.89%
Human Toxicity, non-cancer	CTUh	1.2913E-02	95.50%	5.0719E-04	3.75%	1.0145E-04	0.75%
Ozone Depletion	kg CFC 11-eq	4.7026E-06	96.42%	1.4553E-07	2.98%	2.9048E-08	0.60%
Resources, fossil fuels	MJ surplus energy	1.9834E+05	96.05%	6.8026E+03	3.29%	1.3578E+03	0.66%
Smog Air	kg O3-eq	3.2315E+03	85.84%	4.8070E+02	12.77%	5.2398E+01	1.39%
Primary Energy Demand used as Raw Materials (feedstock energy)	MJ	8.6095E+05	100.00%	0.0000E+00	0.00%	0.0000E+00	0.00%
Primary Energy Demand from Renewable and Non-renewable Resources (gross calorific value)	MJ	1.5216E+06	96.02%	5.2510E+04	3.31%	1.0481E+04	0.66%
Primary Energy Demand from Renewable and Non-renewable Resources (net calorific value)	MJ	1.4141E+06	96.00%	4.9068E+04	3.33%	9.7944E+03	0.66%
Primary Energy from Non-renewable resources (gross calorific value)	MJ	1.5080E+06	95.99%	5.2510E+04	3.34%	1.0481E+04	0.67%
Primary Energy from Non-renewable Resources (net calorific value)	MJ	1.4005E+06	95.97%	4.9068E+04	3.36%	9.7944E+03	0.67%
Primary Energy from Renewable Resources (gross calorific value)	MJ	1.3624E+04	100.00%	0.0000E+00	0.00%	0.0000E+00	0.00%
Primary Energy from Renewable Resources (net calorific value)	MJ	1.3624E+04	100.00%	0.0000E+00	0.00%	0.0000E+00	0.00%

Figure 3.25: Excel report example showing data table.

## 4 ARCHITECTURE

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*eLCAP* implements the well-known three-layer architecture to support separation of functionality and to promote code reuse:

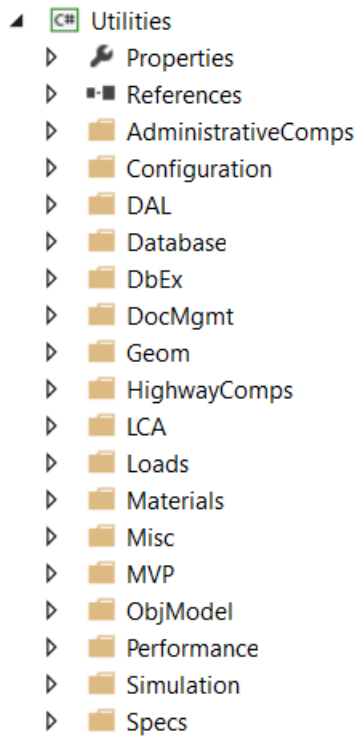
- User Interface, UI
- Business Logic Layer, BLL
- Data Access Layer, DAL

Any given lower-level layer (e.g., Data Access) does not know anything about the layers above it (e.g., Business and the UI). In addition, any given upper-level layer (e.g., UI) communicates with lower-level layers (e.g., Business) using an API (data in a layer is private to that layer and API functions provide access to its data and operations on its data). And in general, an upper-level layer communicates only with the layer immediately below it, but there are exceptions.

The UI is designed to be as “thin” as possible with all business-type activities handled in the BLL. Error checks are made in the UI to provide the best possible feedback for the user, but error checks are also made in the other layers. Implementing a user-friendly UI tends to be a time-consuming activity since it is crucial to the acceptance and overall use of the application.

The BLL consists of a large set of classes. Currently, there are around 800 C# classes/interfaces in the BLL. The BLL lives in a dynamic link library (DLL) named “Utilities.” The BLL models the business domain of the UCPRC and is organized as shown in Figure 4.1. Almost all classes in the BLL inherit from a base class, *UCPRCBase*, which contains member data needed by all classes in the BLL and virtual functions implemented by all classes.

The BLL is general (i.e., not specific to LCA) so it is used in applications other than *eLCAP*. The *eLCAP*-specific part of the architecture is the UI; the BLL and the DAL can be used by any application. The size of the Utilities DLL in debug configuration is around 3 MB.



**Figure 4.1: Groups of classes in the Utilities DLL.**

The BLL accesses the DAL with high-level, domain object-level data requests, and it is agnostic about the specific data storage type and location. The details of the specific data storage and location of that storage are specified in the configuration file, *web.config*, and the lowest-level set of DAL functions. The architecture of the DAL implements the Factor Pattern and Data Provider Pattern to make it relatively straightforward to change data storage types in the future and to allow every specific data object (e.g., a table) to be stored in separate data stores and locations; all data tables need not be stored in the same physical database.

The basics of the Factory Pattern and Data Provider Pattern used for the DAL are that data access is provided to upper-level classes via an “abstract” class. This class defines abstract functions (usually to get or update database data) that must be implemented by a concrete implementation, such as a class containing functions to access an SQL Server. The specific concrete class to use at runtime for a particular table of data is set in the configuration file or can be set by some other means. The Factory Pattern implemented in the DAL is shown in Figure 4.2. The Provider Pattern is similar but slightly simpler.

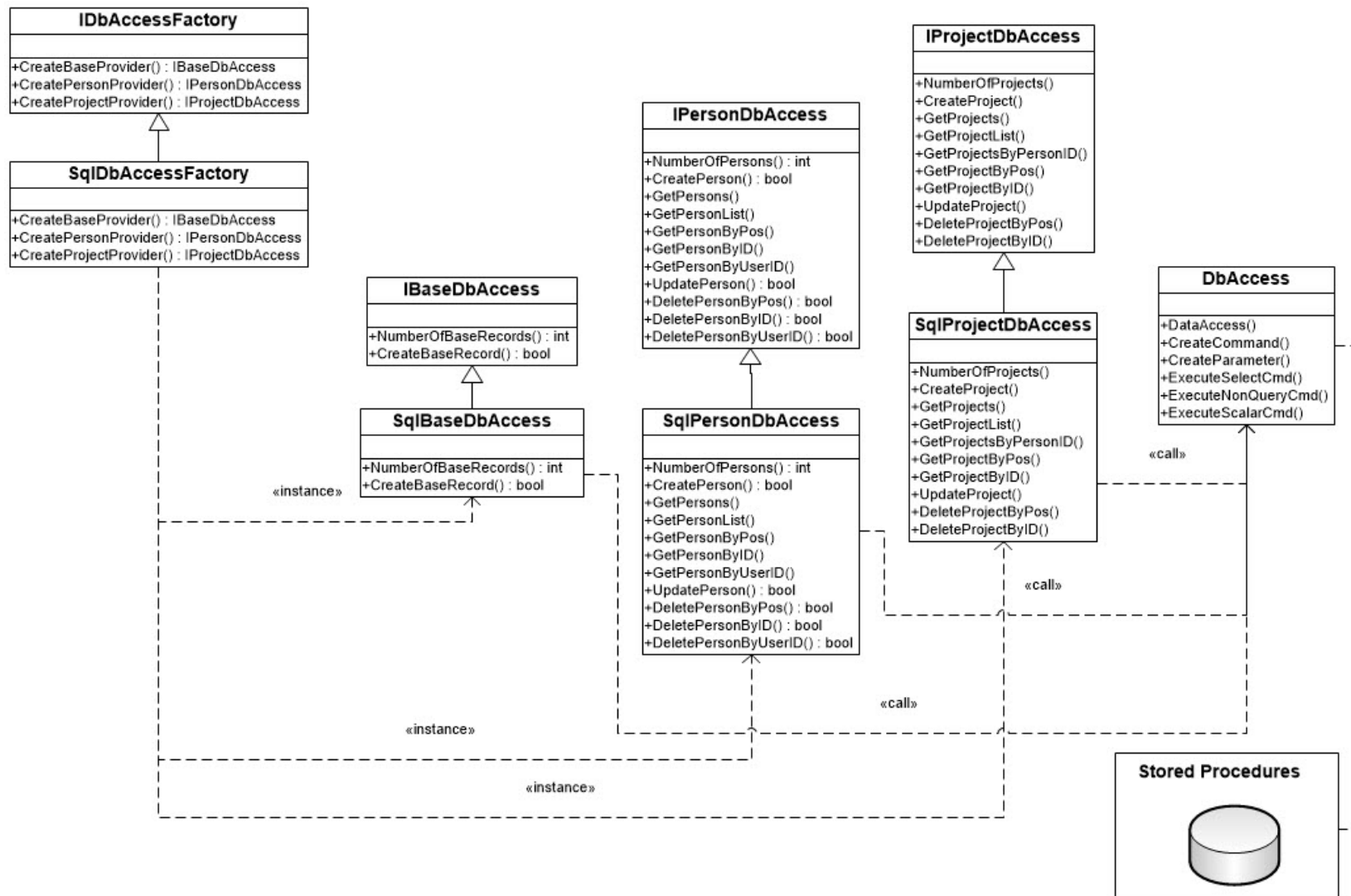


Figure 4.2: Factory Pattern implemented in DAL.



*eLCAP* is an ASP.NET (web) C# application so its internal organization is influenced by ASP.NET and it also makes use of many services of the .NET runtime environment. Currently, *eLCAP* is built to the 4.5.1 version of .NET runtime. Development is done using *Visual Studio* (2013).

*eLCAP* also makes use of several third-party libraries (see Section 4.7). These libraries are managed by the *Visual Studio* included *NuGet* package manager.

#### **4.1 ASP.NET Concepts**

The UI in *eLCAP* is implemented using ASP.NET, a mature Microsoft web technology initially released in 2002 as *Active Server Pages* (ASP) that later turned into ASP.NET. It is a server-side web framework built on the .NET Common Language Runtime (CLR) and currently supports many different programming models, such as MVC. ASP.NET can be used with any programming language supported by the CLR; the UI in *eLCAP* uses C#. The CLR consists of many thousands of classes and provides an extensive array of services to the application developer.

A web application is, by HTTP design, a stateless machine; each request to a web server results in the web server constructing completely new versions of all controls and the page itself. The web application does not “remember” what happened on an earlier request. This is very different from a desktop application, in which state is maintained during a user’s interaction with it. ASP.NET provides several techniques to maintain state between multiple page requests in order to provide needed UI functionality. *eLCAP* uses the ASP.NET *Session State* facility to maintain a finite amount of program state. In general, one tries to minimize the amount of Session State since it consumes valuable web resources, but maintaining state is necessary in any user-friendly UI.

Client-side programming can easily be done using JavaScript downloaded to the browser at runtime. *eLCAP* makes use of this in various ways to extend the functionality of the server controls and to provide a more responsive UI.

##### *4.1.1 HTML (aspx, server controls, CSS), C# Code Behind, and Event and Error Handling*

The basic pattern in ASP.NET is that visual controls such as data fields, radio buttons, check boxes, and tables (grids) are implemented using ASP.NET “server”-side controls located in \*.aspx files (very similar to HTML files and HTML controls) and user events (for example, clicking a check box or entering data in a field are “handled” or trapped in C# “code behind” files). The C# functions that respond to user interactions provide the main UI functionality and the interaction with the BLL to set and get data and

perform any needed UI operations using the facilities of the BLL. The ASP.NET server controls, when loaded by the ASP.NET web server (IIS), emit standard HTML and any necessary JavaScript to the web browser.

The visual aspects of the server and HTML controls and pages are handled using standard CSS. ASP.NET allows for formatting of controls within the server-side controls themselves in the aspx file, but it is performed in *eLCAP* via CSS for greater flexibility and to follow web standards.

Error trapping and handling is a complex and detailed activity. The first layer of error trapping and handling is done using ASP.NET server Validation controls to perform range checking and data existence. These Validation controls are implemented in JavaScript that is generated by the ASP.NET engine. The second layer of error trapping and handling is done in the C# code behind, and messages are presented to the user as necessary by the code behind code. The third layer of error trapping is done in the BLL; standard C# exceptions are “thrown” by BLL functions and “caught” by the UI code with subsequent issuing of user messages.

#### 4.1.2 *Master and Content Pages*

The UI in *eLCAP* uses a facility in ASP.NET called “Master” and “Content” pages. A Master aspx page is where common page look and feel and functionality are placed while specific page content is placed in separate Content pages. A Content page inherits the controls and code from a Master page. This method minimizes coding by having common things in one place and provides a simple mechanism to have a consistent look and feel across all pages in a web application.

#### 4.1.3 *Web.config*

A critical file in the world of ASP.NET is *web.config*. This is an XML-formatted file that contains many sections, and it is where users are able to control many aspects of the application without having to rebuild and redeploy the application. ASP.NET detects that this file has been edited and reloads it automatically. Since *web.config* is an XML file, control of the application is done using “name-value” pairs (e.g., “<add key=”my important key” value=”key value” />”).

The main sections of *web.config* used in *eLCAP* are:

- *ConnectionStrings*: This section is used to specify connection parameters to database sources. Items such as the server url, type of security used by the database server, name of the database, user login credentials, and specific data provider (SQL, OLEDB, etc.) used to access the data are defined.
- *AppSettings*: This section is used to define application data that can easily be changed by simply editing *web.config* on the web server. Items such as directory locations of runtime files, email



settings, and fully qualified names of classes used by the DAL to access specific tables of data are defined.

- *Authentication, RoleManager, Membership and Profile*: These sections are used to control user authentication and authorization and to keep track of user profiles (e.g., which Caltrans district a user is in).
- *Page Protection*: This section allows specific pages of the application to be protected so that only specific authorized users or specific groups of users can access them.

## 4.2 Authentication, Authorization, Profiles, and the Database

The design and implementation of *eLCAP* included user access controls via standard login procedures. ASP.NET has built-in support for user authentication and authorization and group membership. An SQL Server database is provided by ASP.NET, called *aspnetdb*, which is used to store all user access/login data. The database schema is shown in Figure 5.1. ASP.NET provides customizable login controls (see Section 3.1) for registration, log in, and password recovery.

*eLCAP* adds some custom fields to the Registration control to gather data that is not part of the built-in control. Data items such as First Name, Last Name, and Caltrans District have been added, and they are stored in a user profile in the *aspnetdb* database. In addition, the most recently used project and project trial are stored in the user profile so *eLCAP* can open up the last used project trial when starting a new *eLCAP* session.

## 4.3 Automatic Email Generation

*eLCAP* sends email to users and the system administrator for a variety of reasons. When a person registers to become a member of *eLCAP*, an email is sent to the system administrator so they can verify the person and then authorize and put the person in the appropriate user group.

In addition, if the application crashes during use, an email containing a variety of debug information is sent to the system administrator (for later debugging) and a “user-friendly” page is shown to the user.

## 4.4 Units

Unit conversion in engineering applications is an ongoing issue but one that needs to be addressed at the very beginning of design and development. *eLCAP* uses the services of a unit conversion subsystem called *EngrUnits* that converts between many different types of units. Currently, there are seven different quantities in *EngrUnits*: area, energy, force, length, mass, time, and volume. Each quantity contains many

variations of the units. For example, length has 20 different units (e.g., kilometer, meter, mile, league, yard, chain, twip).

To get a conversion factor to convert miles to feet:

```
milesToFeet = Length.Factor(Length.Type.Mile, Length.Type.Foot);
```

 (4.1)

#### 4.4.1 Base and Client

The *EngrUnits* subsystem forms the basis of a slightly higher, application-specific, and more convenient method of performing unit conversion. *eLCAP* sets up a base set of units forming a consistent set of units for all internal computations. This set of base units is known only to *eLCAP*. All data that are given/specified to the internal data structure in *eLCAP* are converted to base units using the services of the *EngrUnits* subsystem. The BLL has a class, called *Units*, that has a set of units for the base and a set of units for the client (the UI); *eLCAP* establishes the set of base units and set of client units during startup.

Whenever the UI needs to specify data to its internal project data structure or BLL data structures, it gets a conversion factor. For example, to get a conversion factor to convert client data (mile) to base data, the following is used:

```
clientToBase = Length.Factor(Length.Type.Mile, Units.BaseLengthUnits);
```

 (4.2)

The reverse is done when data are extracted from *eLCAP*'s internal data structure and displayed in the UI.

For cases where a particular item in the UI is not part of the client set of base units, the above approach will not work and the approach in Equation (4.1) is used. For example, if a client unit for length is *meters* but a particular data item exposed to the user is in *kilometers*, then Equation (4.1) is used.

#### 4.4.2 Per Data Item

*eLCAP* is an LCA tool and works with flows of materials and chemicals. So it must deal with a wide range of different units in the UI (and also the actual database of processes and flows) since quantities of materials (e.g., HMA) might be known to the user in tons or tonnes, kilograms (kg) or grams (g), pounds (lb.), or something else. Therefore, *eLCAP* allows the user to select, from a list of units, a specific unit for a specific data item. For example, when defining a construction-type event, a user may know the amount of AB in kilograms but the amount of HMA in tons.

To avoid forcing a user to convert one or both to whatever the UI wants for quantity, *eLCAP* allows the user to specify AB in kilograms and HMA in tons. To support this, *eLCAP* maintains a unit specification for the quantity data item (and others), and during the balancing process (see Section 2.1) all flow quantities are converted to the same base unit using Equation (2) above.

#### 4.4.3 UI and C# Code

ASP.NET provides several methods of making the localization process as simple as possible (i.e., to minimize the time for it to happen).

For UI controls, the following is used:

```
Text="<%$ Resources:GlobalResources, EndOfLifeLabelPartB_G %>">
```

ASP.NET will look in a string resource file named *GlobalResources.?.?.resx*, where “??” is the two-letter ISO language code (e.g., “en,” “es,” “fr,” for the string labeled “EndOfLifeLabelPartB\_G”) and assign that string to the Text of the control.

For getting a string in code, the following is used:

```
Text = Resources.GlobalResources.EndOfLifeLabelPartB_G
```

### 4.5 User Real-Time Feedback: SignalR

*eLCAP* is web application, and, as such, it is constrained by web protocols. One constraint is that a single *response* is sent by a server when it receives a *request* from a client browser. Clicking a button is a request; sending a message from the server to show the user is a response. This model works perfectly well for most web applications. However, it does not work when the request results are in a long-running execution of the application. Performing an LCA is a long-running activity, and user feedback is necessary for a user-friendly UI.

Sending user feedback during a long-running web application requires the use of real-time web technology. The specific real-time technology used by *eLCAP* is called SignalR. It is basically a point-to-point, bidirectional connection technology, similar to chat applications, that allows the server to send content to the client browser as it happens in real-time, independent of a web request.

SignalR uses WebSockets, when available, as the communication technology and older protocols as necessary. SignalR provides a very simple, high-level API for doing server-to-client Remote Procedure Calls (i.e., call JavaScript functions in the browsers from server-side .NET code) in the ASP.NET application.

Clicking the “Balance” button on the Analyze & Results page results in calling a function, located in a special class in *eLCAP*, which deals with real-time, client-to-server and server-to-client communication. All messaging to the client browser during the LCA is done using SignalR.

## 4.6 Main Classes

As mentioned earlier, the BLL contains over 800 classes/interfaces, and it is neither practical nor instructive to discuss all of them here. This section briefly touches on the more important classes.

### 4.6.1 Base Class

Most of the classes in the BLL derive from the base class *UCPRCBase*. This class is shown in Figure 4.4. It is very convenient to have classes derive from a base class for a variety of reasons.

<b>UCPRCBase</b>
-m_ID : string
-m_dirty : bool
-m_id
-m_addedBy : string
-m_addedDate : Date
-m_modifiedBy : string
-m_modifiedDate : Date
+OmTypeFromBLL()
+BLLTypeFromOmType()
+CloneMe()
+PreSerializationTasks()
+PostSerializationTasks()
+PropertyHasChanged()
+Recompute()
+Dump()

**Figure 4.4:** The base class, *UCPRCBase*.

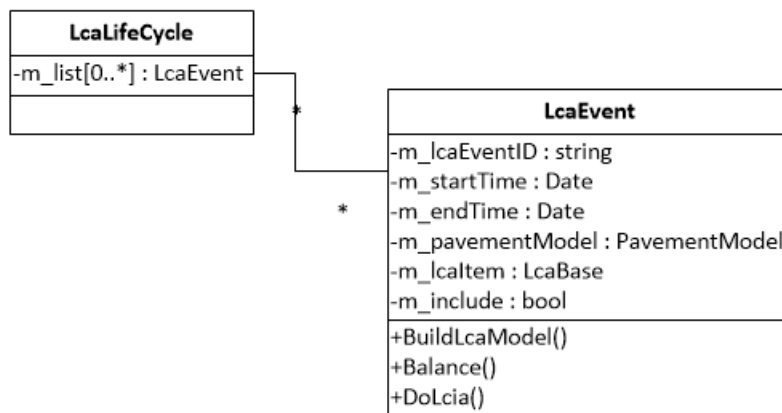
### 4.6.2 Life Cycle

The pavement project life cycle is modeled by two classes, *LcaLifeCycle* and *LcaEvent*, as shown in Figure 4.5. An *LcaEvent* object is added to the list of *LcaEvents* in *LcaLifeCycle* for each construction-type event defined by the user, and then *eLCAP* adds another one after it to represent the Use Stage. The

*m\_pavementModel* data member in *LcaEvent* either contains a *PavementProjectModel* or a *PavementUseModel* object.

The *BuildLcaModel()* function in *LcaEvent* translates either a *PavementProjectModel* object into a *PavementLca* object or a *PavementUseModel* object into a *PavementUseLca* object. The “Lca”-named objects are the objects that know how to do an LCA analysis. The *PavementLca* object does the balancing of flows for the generated process based model (see Section 2.7.1); the virtual *Balance()* function for *PavementUseLca* does nothing since the Use Stage is based on performance models (see Section 2.7.2).

When a user requests that *eLCAP* perform an analysis, *eLCAP* iterates through the *LcaEvent* list in *LcaLifeCycle* calling *BuildLcaModel()*, *Balance()* and *DoLcia()*.



**Figure 4.5: Life cycle classes.**

Other modeled classes include *LcaBase*, *PavementLca*, and *PavementUseLca* classes, shown in Figure 4.6; model and process-related classes shown in Figure 4.7; and LCIA assessment-related classes shown in Figure 4.8.

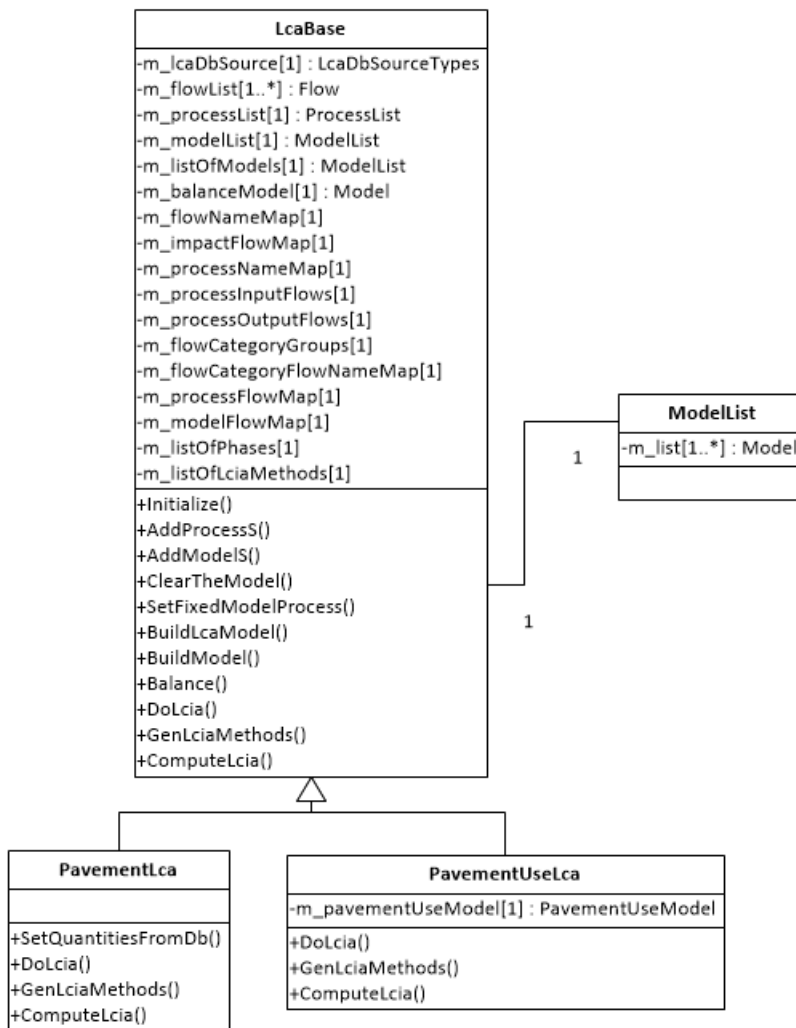


Figure 4.6: *LcaBase*, *PavementLca*, and *PavementUseLca* classes.

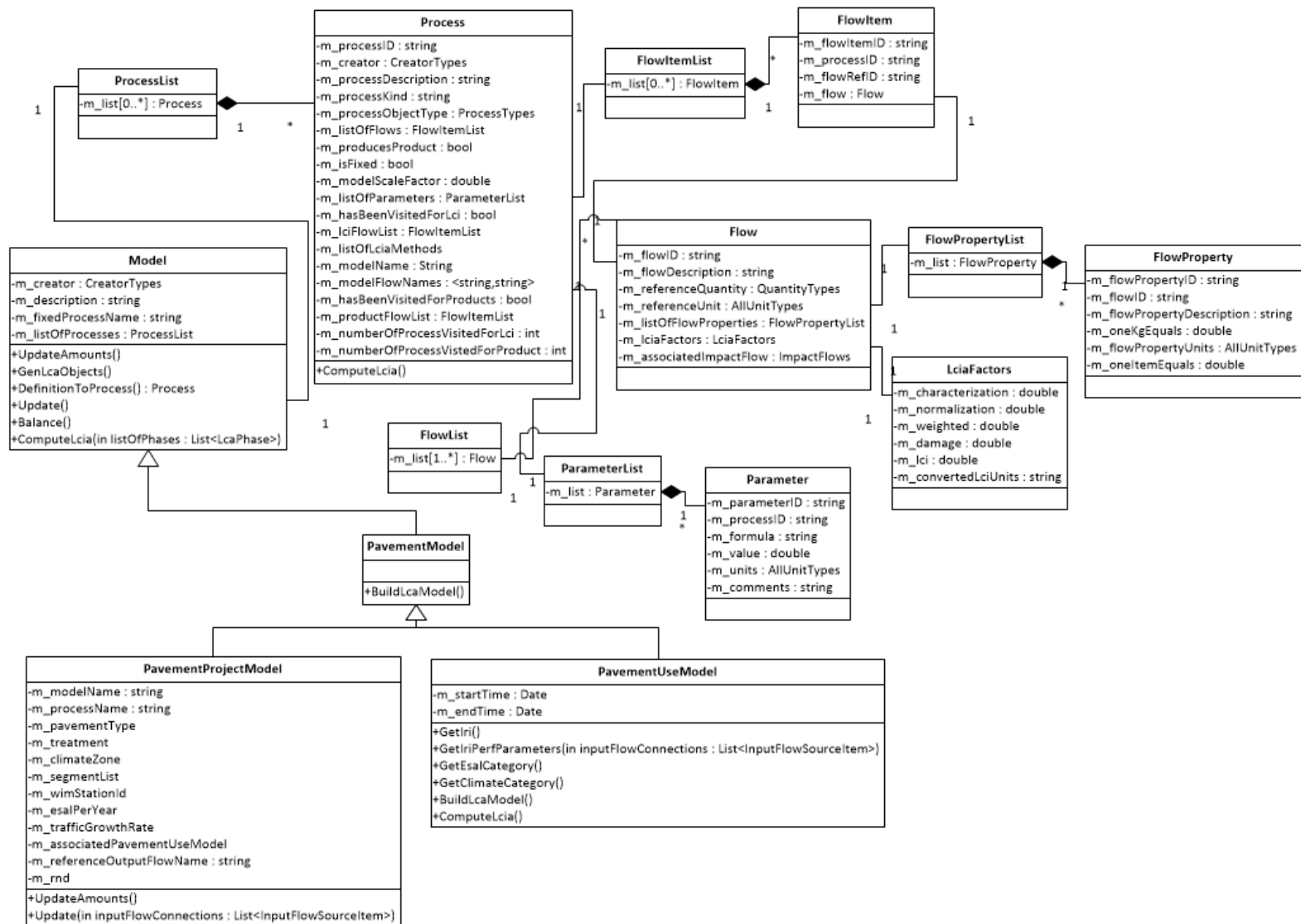


Figure 4.7: Model and process-related classes.

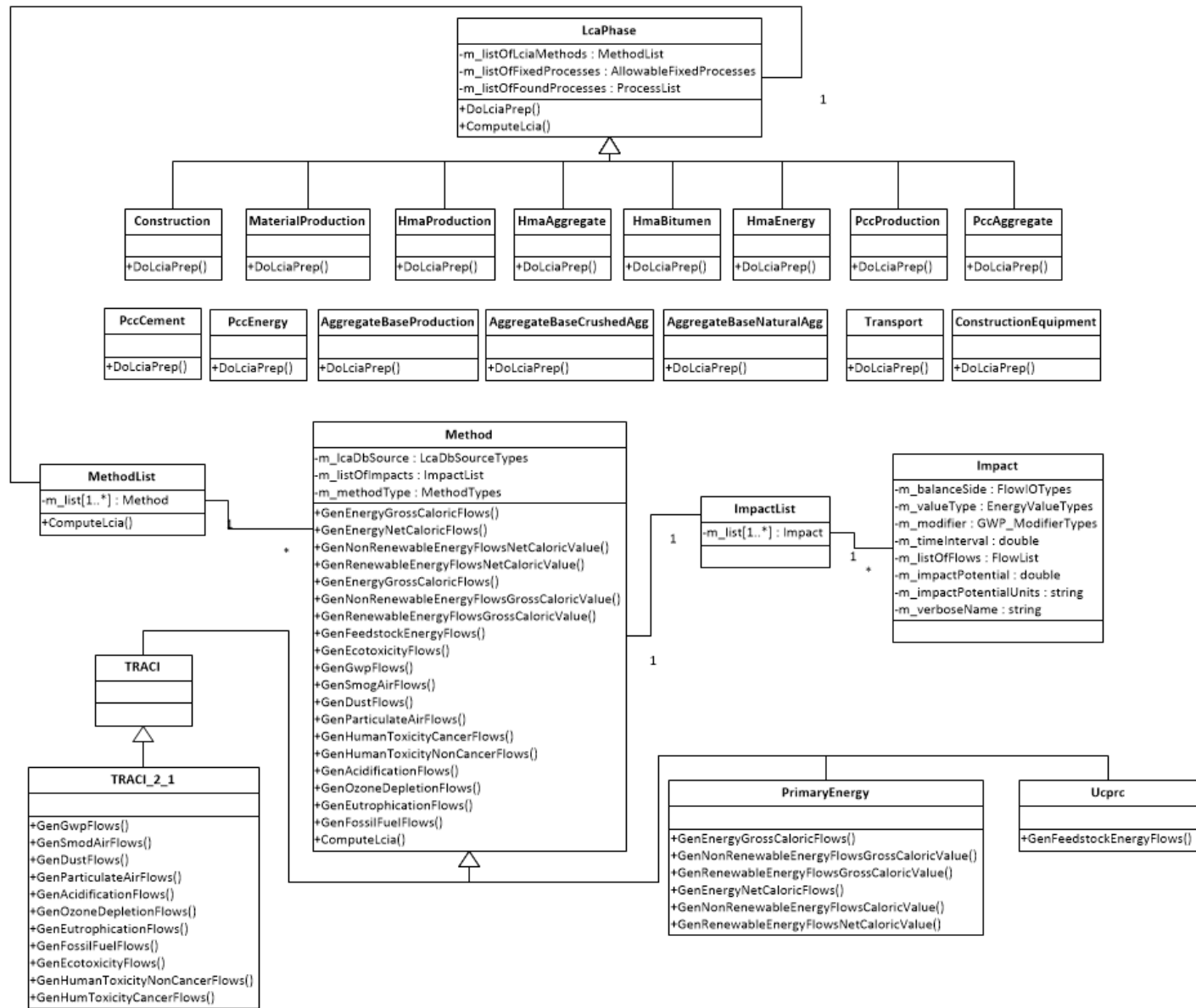


Figure 4.8: LCIA assessment-related classes.



## 4.7 Third-Party Libraries

*eLCAP* uses a few third-party libraries managed by *Visual Studio's NuGet* Package Manager:

- *AjaxControlToolkit*: The ASP.NET AJAX Control Toolkit is an open-source project built on top of the Microsoft ASP.NET AJAX framework. It is a joint effort between Microsoft and the ASP.NET AJAX community that provides a powerful infrastructure to write reusable, customizable, and extensible ASP.NET AJAX extenders and controls, as well as a rich array of controls that can be used out of the box to create an interactive web experience.
- *SharpZipLib*: Zip file services.
- *MathNet.Numerics*: Math.NET Numerics provides methods and algorithms for numerical computations in science, engineering, and everyday use. Covered topics include special functions, linear algebra, probability models, random numbers, interpolation, integration, regression, optimization problems, and more.
- *Newtonsoft.json*: json file serialization and deserialization support.
- *Spire.xls*: Excel file generation services.
- *Mathos.Parser.MathParser*: Expression parsing services.
- *Select.HtmlToPdf*: HTML-to-PDF file services.

## 4.8 Application/Session Startup

*eLCAP* performs several activities when a user starts a new web browser session:

- UI control Session State variables are initialized.
- UI language Session State variables are initialized.
- Base and Client units are set.
- Some main classes are initialized.
- Permissions for user groups (Roles) are set.
- Directory locations for runtime files are set.
- Support files are read into memory using .NET tasks.
  - Caltrans Highway Log
  - Caltrans Route Direction

## **4.9 Software Development**

### *4.9.1 The Environment*

All development for *eLCAP* is done using *Visual Studio* 2013 and targeting the version 4.5.1 of the .NET runtime.

### *4.9.2 NuGet*

Third-party libraries are managed using *NuGet* provided by *Visual Studio*.

### *4.9.3 Source Control*

All source files are managed by the source control system “Subversion” (svn) and using the client visual tool called *TortoiseSVN*.

## 5 DATA ACCESS

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*eLCAP* makes use of data from several sources. It makes three formal database connections—*SQL Server*, *MS Access*, and the login database—and it loads its LCA XML database file directly into memory for performance reasons. As discussed in Chapter 4, *eLCAP* uses either a Factory Pattern (for the XML data) or the Provider Pattern (for all other data except login) to access the data. Access to login data is provided by a .NET API.

### 5.1 Database Connections

Database connection specifications are defined in the ASP.NET configuration file, *web.config*.

#### 5.1.1 MS SQL Server

Project, Project Trial, User-Defined Processes, and IRI Performance Model parameters data are stored in a *MS SQL Server* database having the schema shown in Figure 5.1. *eLCAP* connects to *SQL Server* using the connection string shown in Figure 5.2.

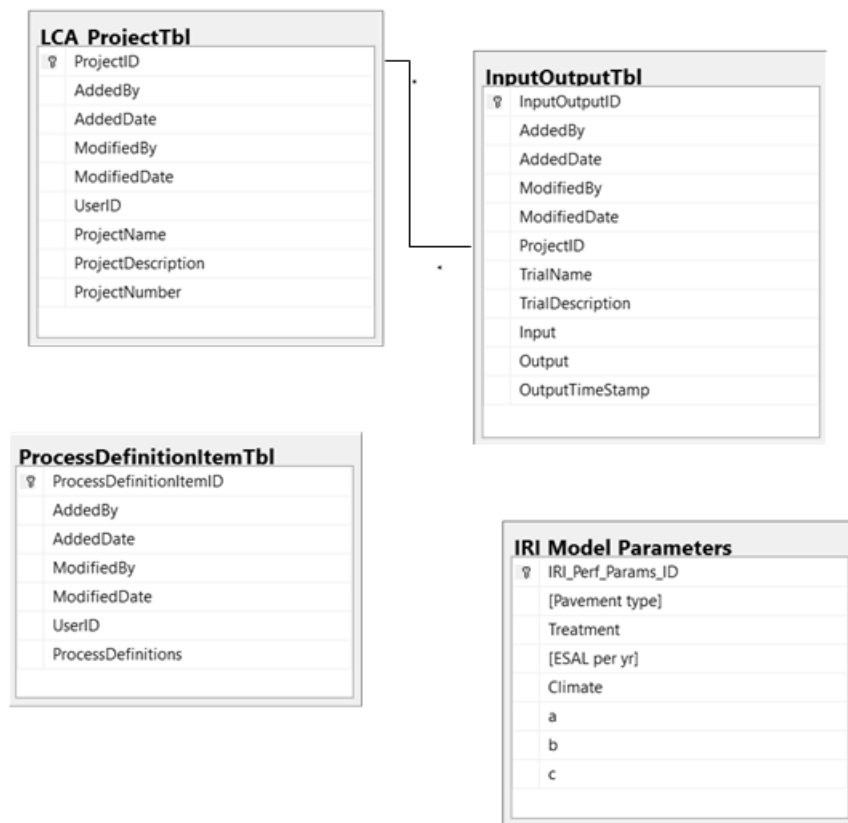


Figure 5.1: *eLCAP* database schema.

```
<add name="eLCAP"
      connectionString="Server=dev.ucprc.ucdavis.edu;
      Integrated Security=false;
      Database=eLCAP_1_0;
      User ID=An eLCAP User;
      Password=myPwd"
      providerName="System.Data.SqlClient" />
```

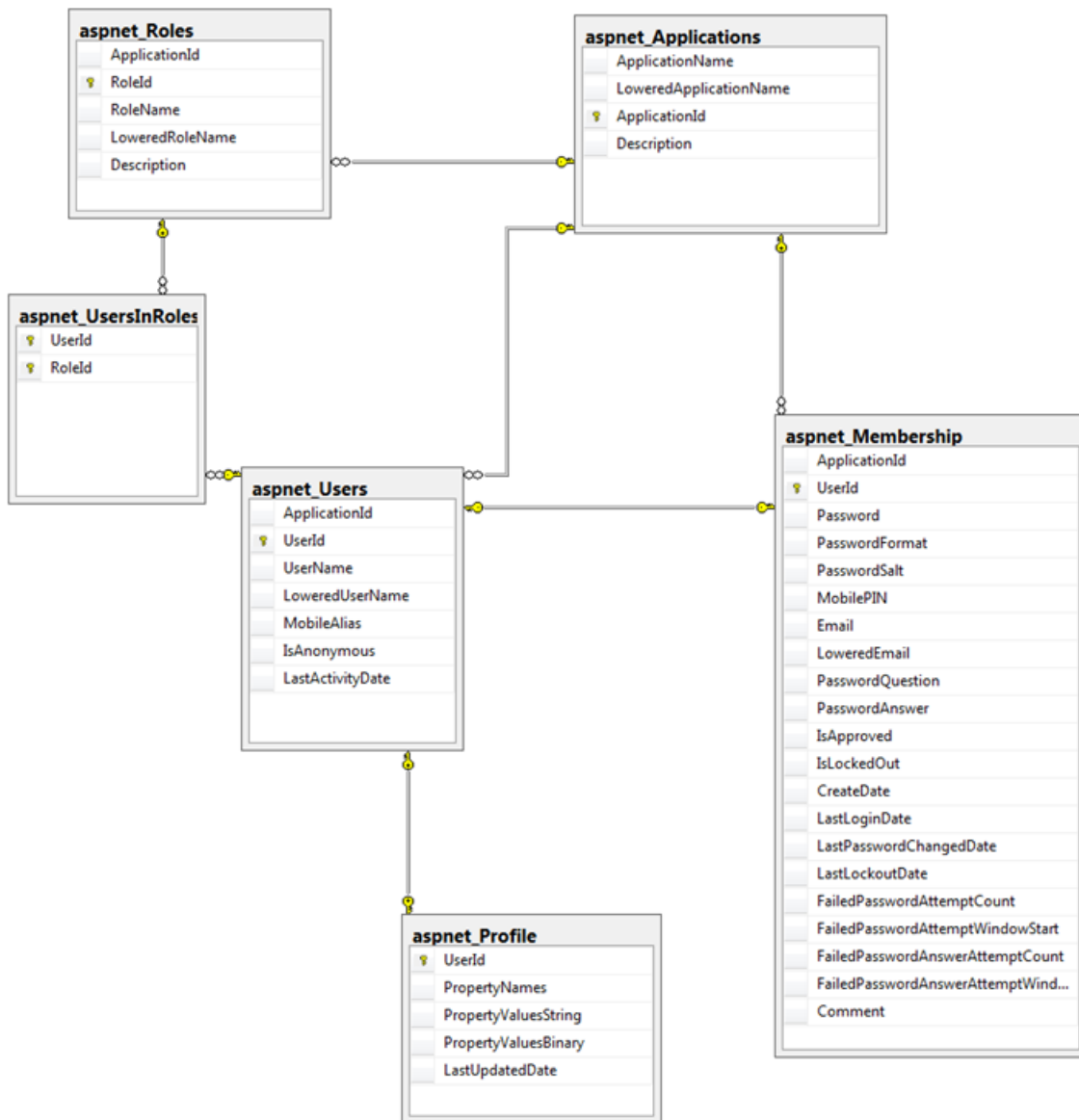
**Figure 5.2: *SQL Server* project data connection string.**

All project trial data are managed by a class that is serialized to a json string and stored in the table named “InputOutputTbl” in the field named “Input.” The same is done for output but it is placed in the field named “Output.” The json string is deserialized back into the class when the data are loaded from the database.

User-defined process data are stored, as json strings, in the table named “ProcessDefinitionsItemTbl” in the field named “ProcessDefinitions.”

IRI performance model parameter data are stored in the table named “IRI Model Parameters.” The data for this table originate from a CSV file that is imported into the *SQL Server* table.

Login data are also stored in a *SQL Server* database; its schema is shown in Figure 5.3 and the connection string is shown in Figure 5.4. The basic login database is created by running a command outside of *Visual Studio*.



**Figure 5.3: ASP.NET user authentication, authorization, and profile database schema.**

```
<add name="LocalSqlServer"
connectionString="Server=dev.ucprc.ucdavis.edu;
Integrated Security=false;
Database=aspnetdb;
User ID=Login User;
Password=myPwd"
providerName="System.Data.SqlClient" />
```

**Figure 5.4: *SQL Server* login connection string.**

### 5.1.2 MS Access

Traffic, WIM, and climate data are stored in an MS Access database having the schema shown in Figure 5.5, Figure 5.6, Figure 5.7, and Figure 5.8, with the connection string shown in Figure 5.9.

Field Name	Data Type
Route	Number
Route Suffix	Short Text
District	Number
County	Short Text
Postmile Prefix	Short Text
Postmile	Number
Leg	Short Text
AADT Total	Number
Total Trucks	Number
Total Trucks %	Number
2 axle volume	Number
2 axle percent	Number
3 axle volume	Number
3 axle percent	Number
4 axle volume	Number
4 axle percent	Number
5 axle volume	Number
5 axle percent	Number
Description	Short Text
Year	Short Text
Verify/Estimate	Short Text

Figure 5.5: MS Access traffic database schema.

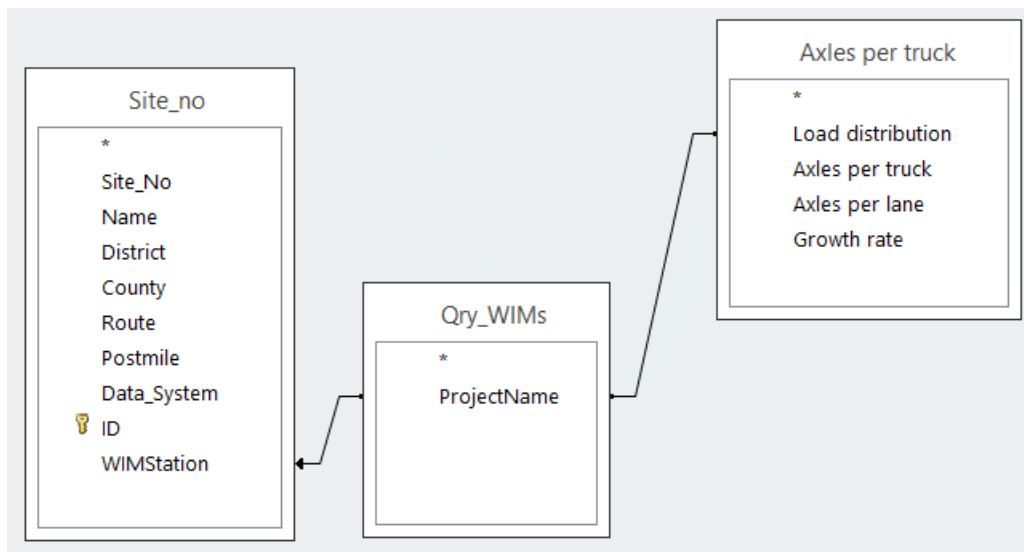
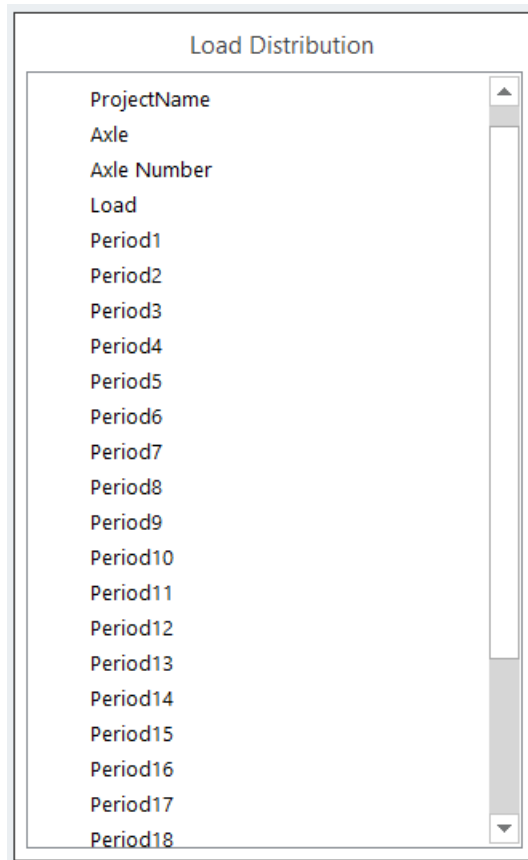


Figure 5.6: MS Access WIM database schema.



**Figure 5.7: MS Access axle load spectra (24 hours) database schema.**

Field Name	Data Type
District	Number
County	Short Text
Route	Number
Postmile	Short Text
Climate	Short Text

**Figure 5.8: MS Access climate database schema.**

```
<add name="CalMEConnectionString"
connectionString="Provider=Microsoft.Jet.OLEDB.4.0;
Data Source=|DataDirectory|\CalME.mdb"
providerName="System.Data.OleDb" />
```

**Figure 5.9: MS Access connection string.**

## 5.2 XML Database File

*eLCAP*'s LCA database is an XML file that is read into memory when the application starts up. This is done for performance reasons since access to it occurs frequently. The file is constructed as discussed in Section 2.5. The schema for the file, and the in-memory version of it, is shown in Figure 5.10. Data are accessed using the DAL, as usual, for any data source used by *eLCAP*.

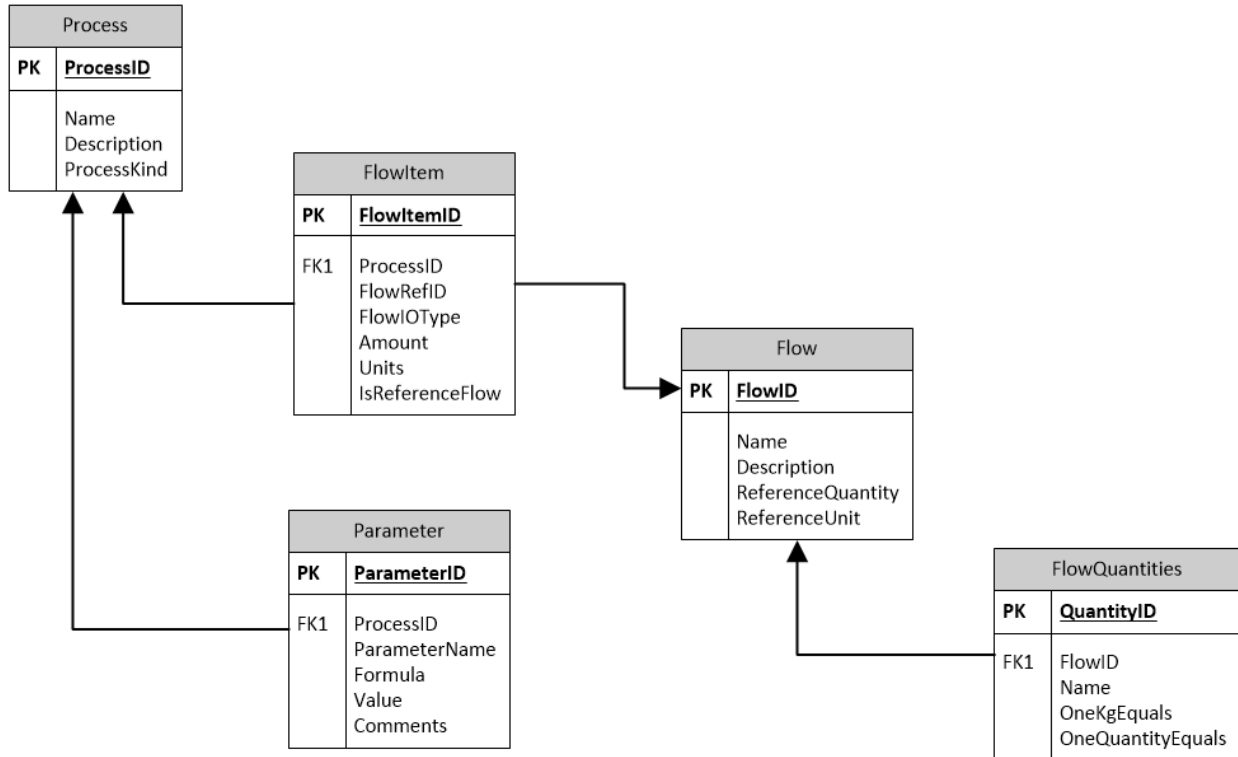


Figure 5.10: XML file schema.



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# APPENDIX A: PROCESS MODELS

The following figures show the *process models* used in *eLCAP*. A process model contains a process that produces a product, such as *HMA* or a *pavement project*, and other “agg”-type processes. The main product-producing process has a series of input flows that connect to either the “agg”-type processes in the model or to other models.

The figures in this appendix usually contain more than one process model. This is done to provide information about the source of the input flows for the process model in the figure.

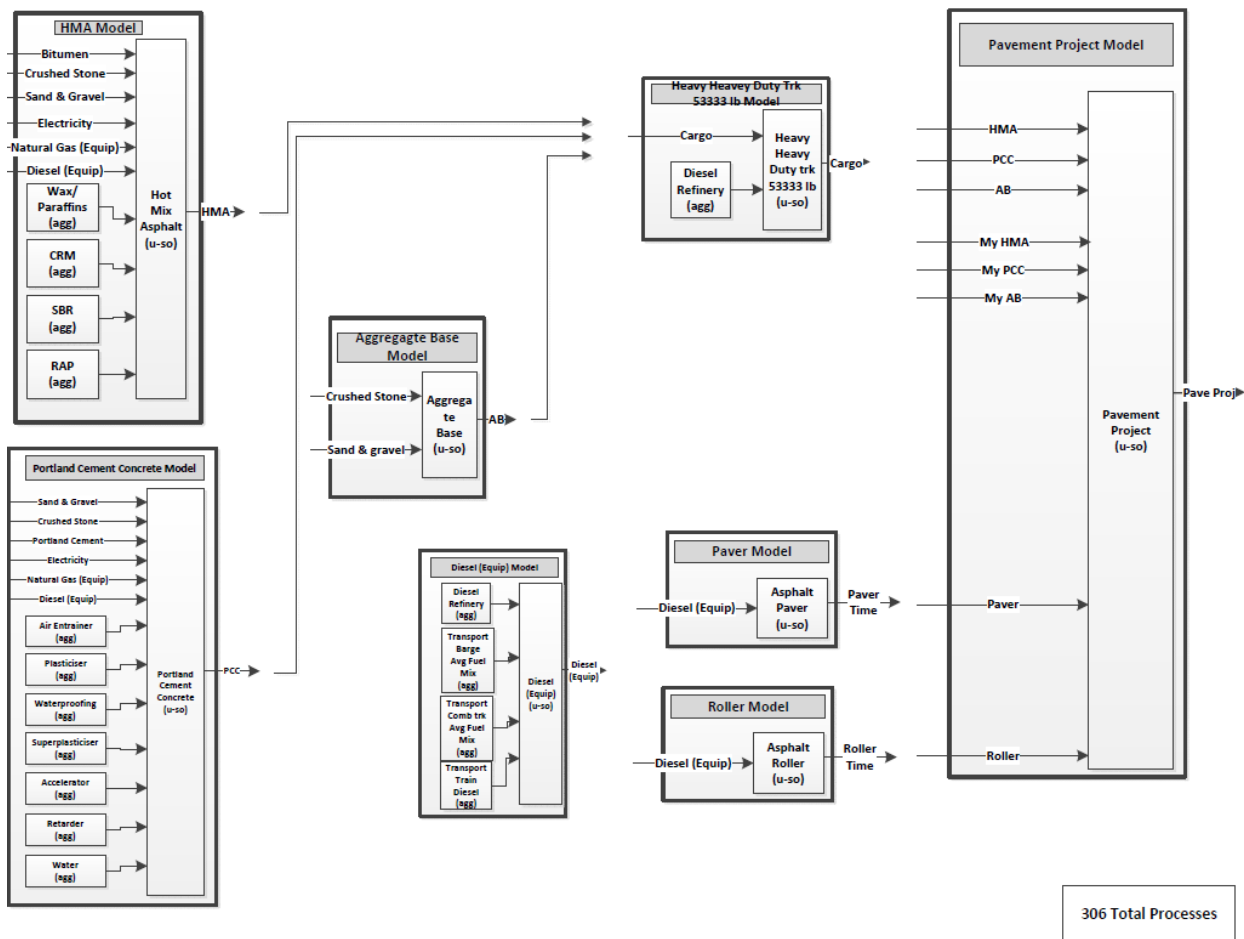
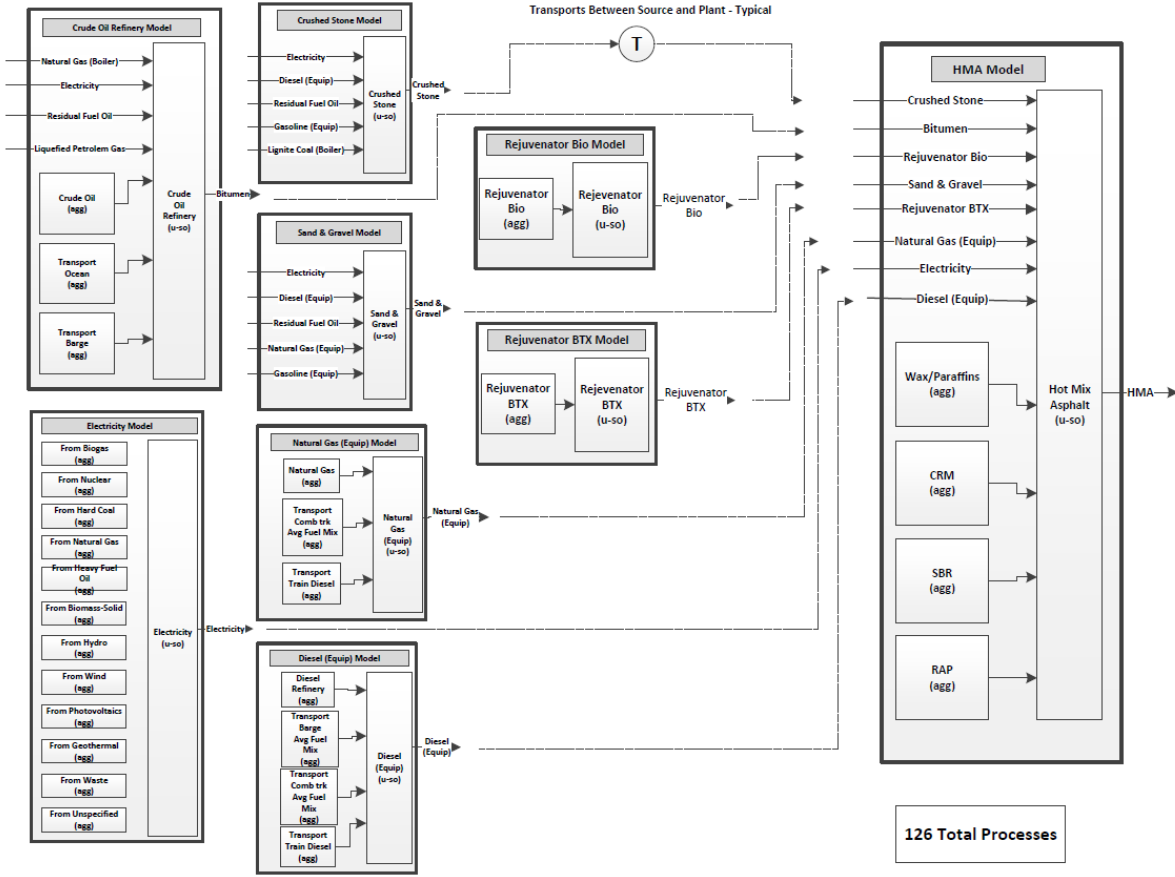


Figure A.1: Pavement project process model.



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**Figure A.2: HMA process model.**

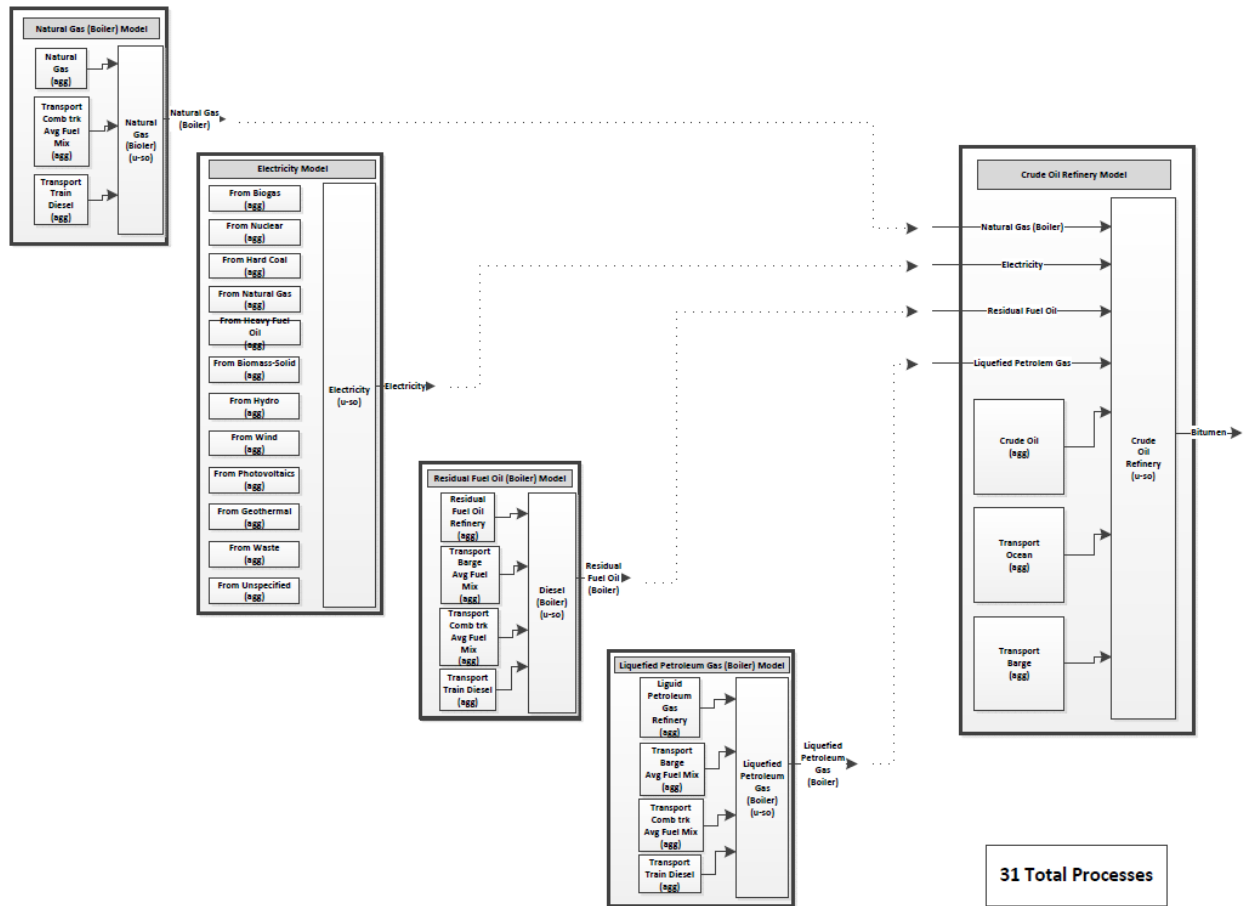


Figure A.3: Bitumen (crude oil) process model.

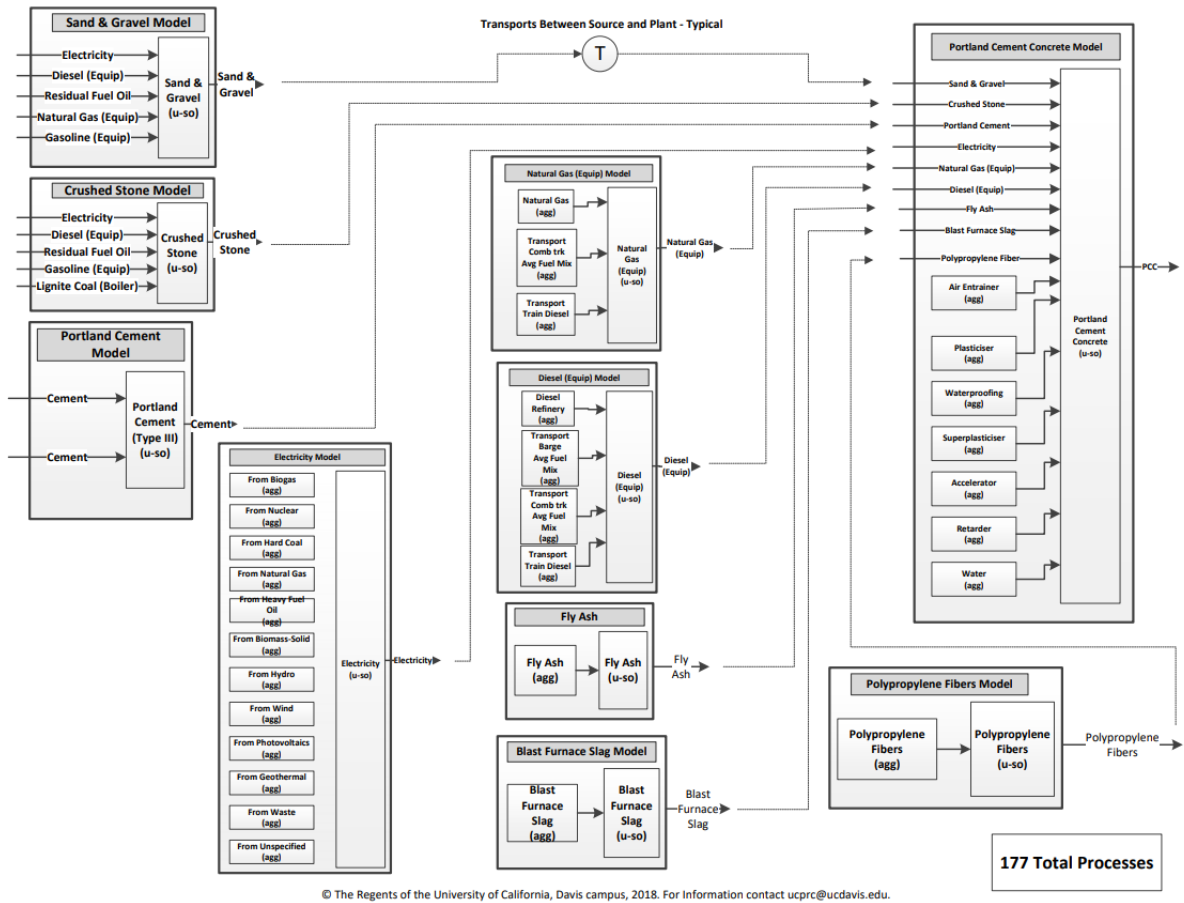


Figure A.4: Portland cement concrete (PCC) process model.

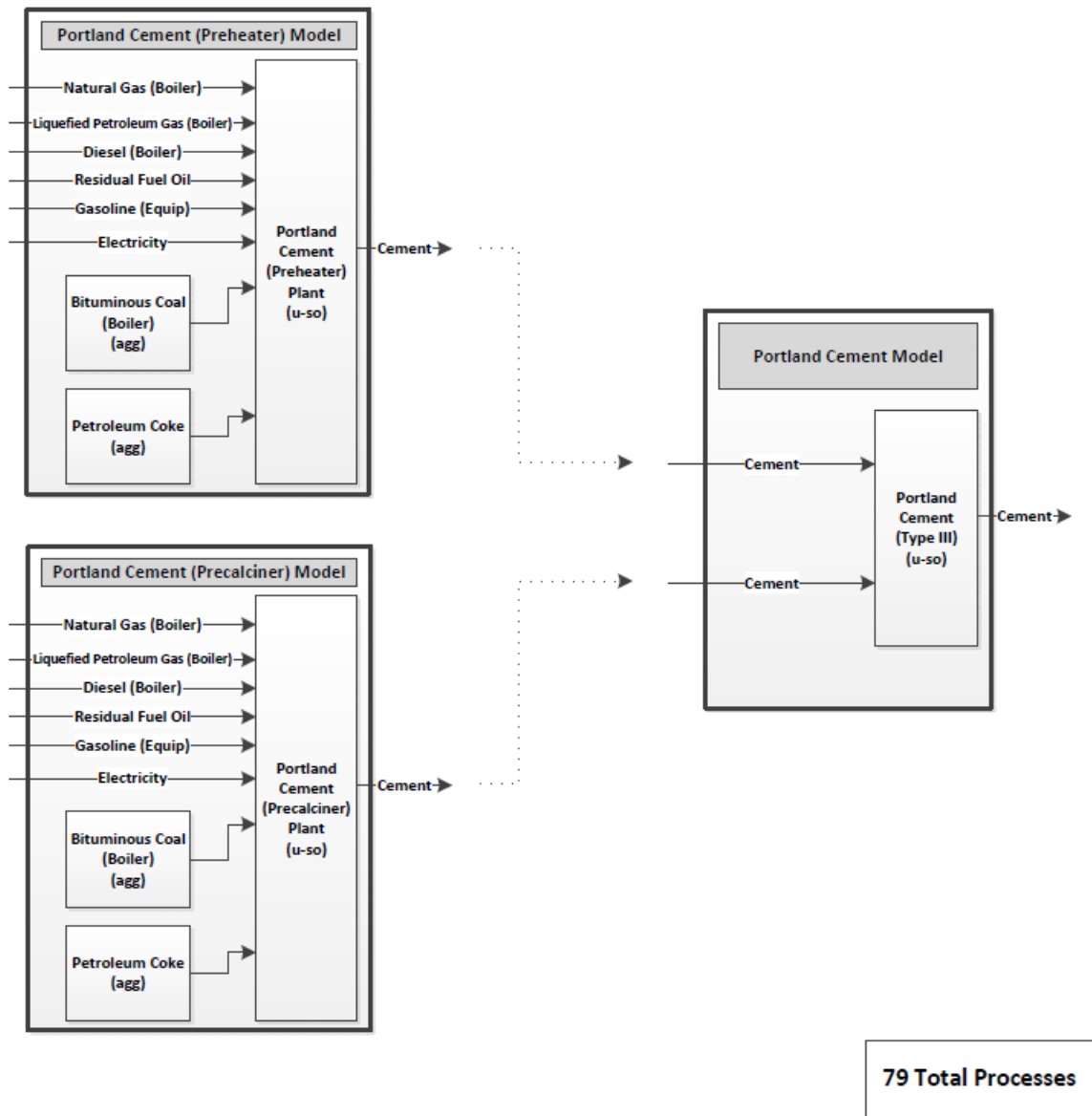


Figure A.5: Hydraulic cement process model.

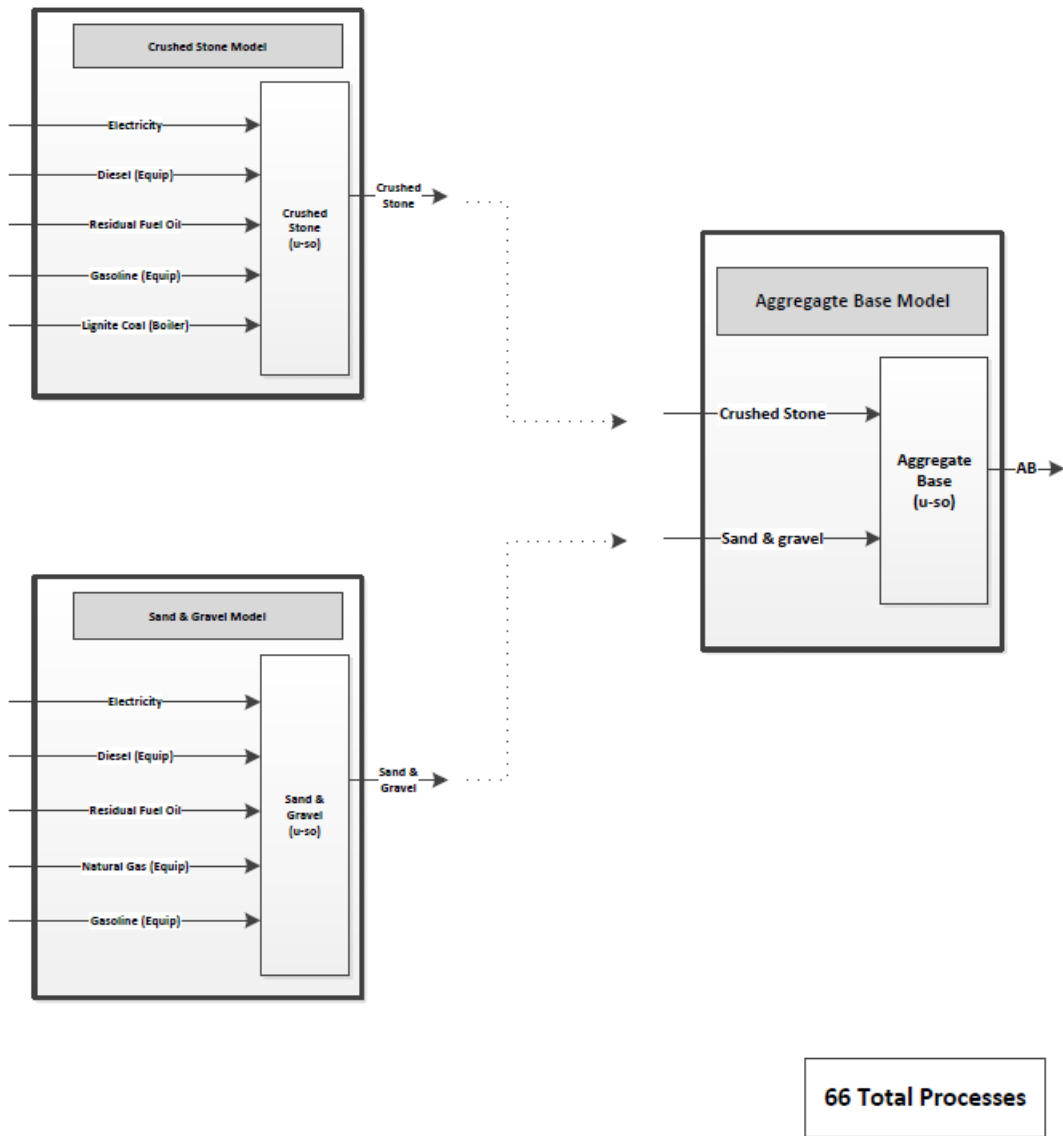


Figure A.6: Aggregate base (AB) process model.



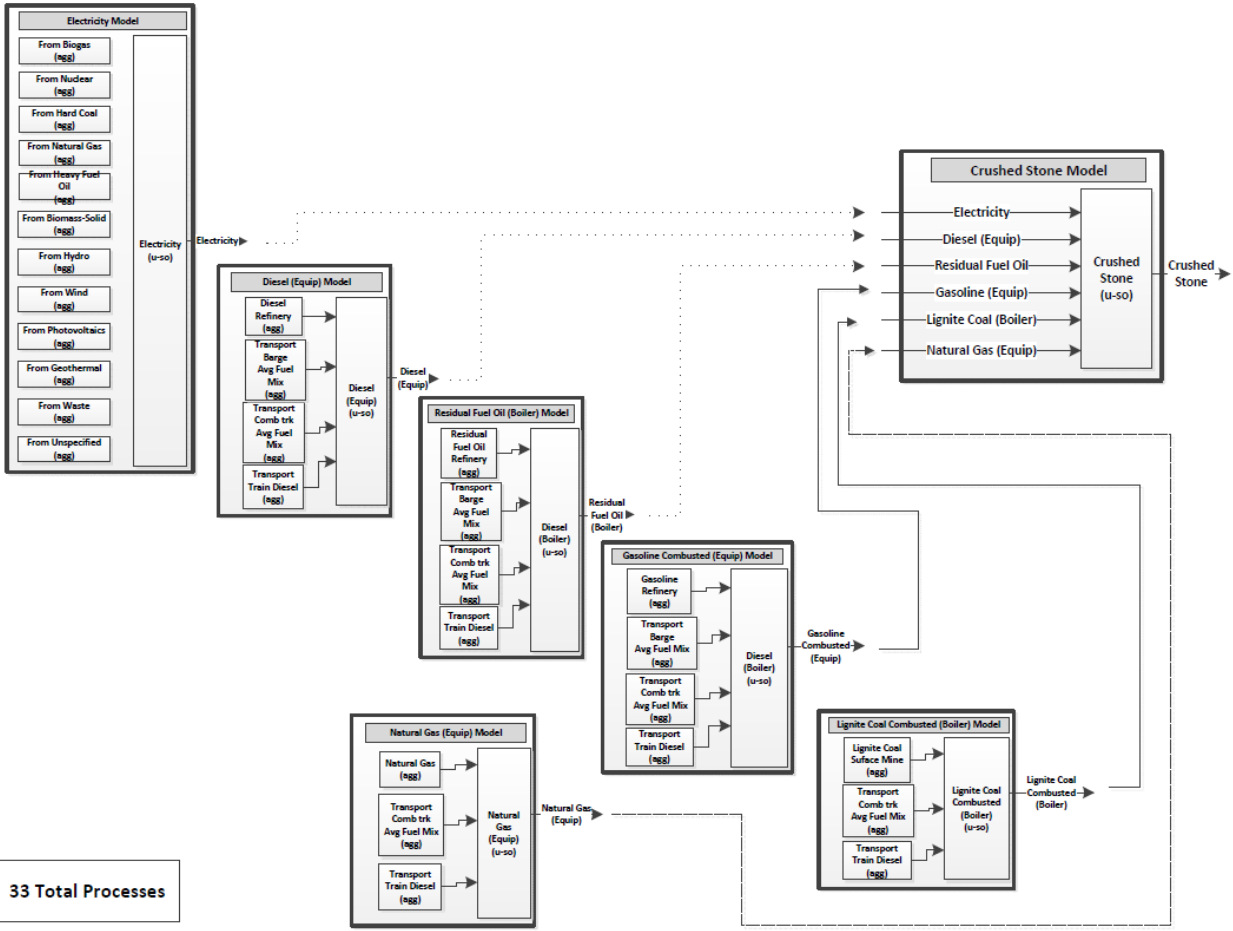


Figure A.7: Crushed stone process model.

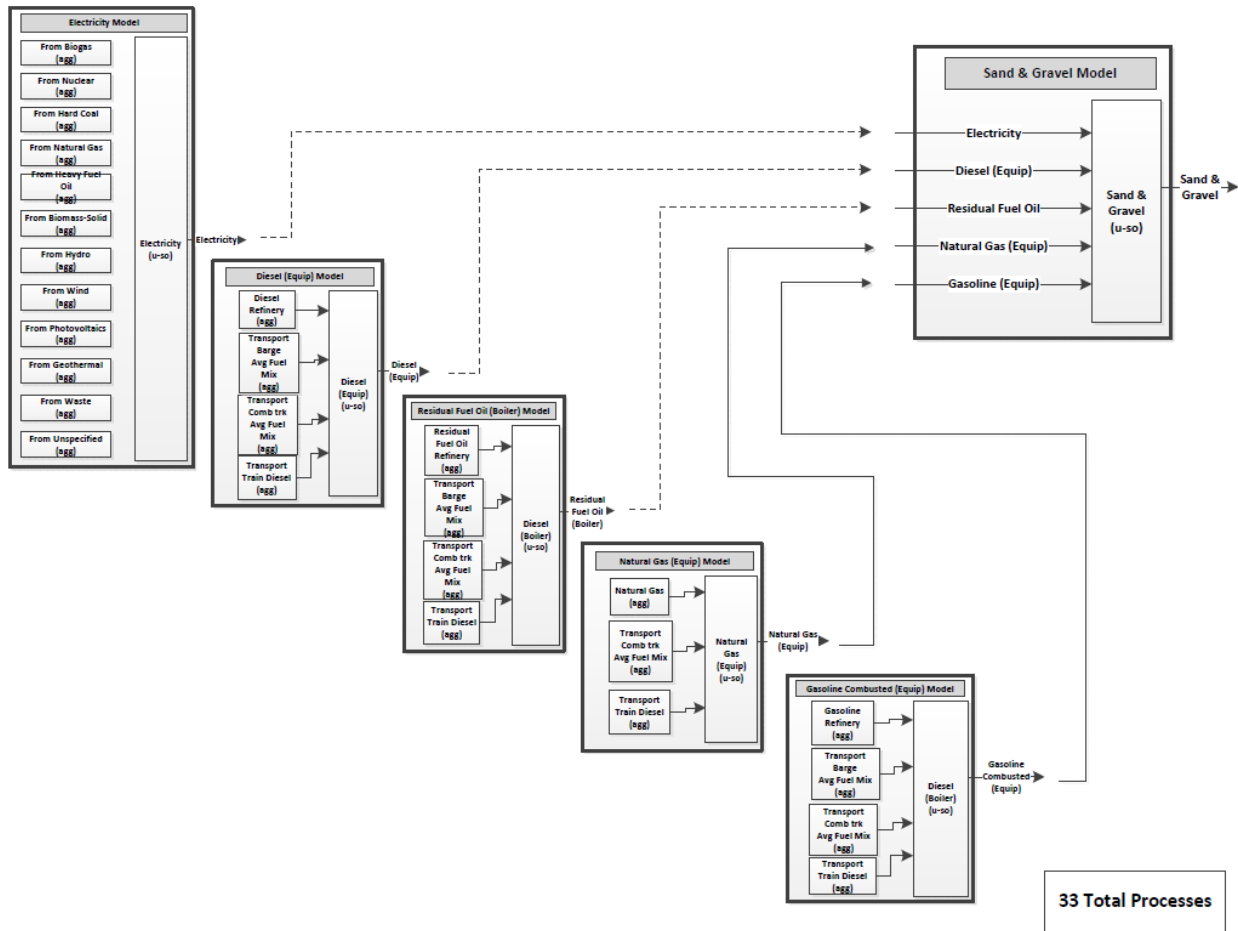


Figure A.8: Sand & gravel process model.

**Table A.1: Reclaimed Asphalt Pavement (RAP) Allocation and Handling in eLCAP**

Recycling Types	RAP Type	RAP Name	Comments	Equipment	Transport Vehicles
<b>In-Place Recycling OR Cold Central Plant Recycling (CCPR)</b>	In-place	RAP (IPR/CCPR)	Zero burden as all processing is covered in the ADD LAYER process (FDR/PDR and CCPR equipment processes and transport).	—	—
<b>In-Plant Recycling (existing RAP stockpiles at the plant)</b>	Unfractionated	RAP	RAP has already been produced in another project and has been stockpiled at the mixing plant. The production, milling, and transport burdens of RAP are allocated to the previous project that produced it.	—	—
	Fractionated	RAP with fractionation	RAP is produced in an earlier project and is stockpiled at the mixing plant. The production, milling, and transport burdens of RAP are allocated to the previous project. However, because fractionation is required in the project for which it is being used, fractionation impacts are allocated to the RAP amount being used.	<ul style="list-style-type: none"> <li>• Conveyor belt</li> <li>• Front loader</li> <li>• Fractionation</li> </ul>	—
<b>In-Plant Recycling (RAP stockpiled at a different site and transported to the plant)</b>	Unfractionated	RAP from different site	RAP is produced and stockpiled at a different site or plant. The production, milling, and transport to current site burdens of RAP are allocated to the previous project. However, because RAP is to be transported to the mixing project plant location, transport to mixing plant impacts are allocated to the RAP amount being used.	<ul style="list-style-type: none"> <li>• Front loader</li> </ul>	<ul style="list-style-type: none"> <li>• End dump truck</li> </ul>
	Fractionated	RAP from different site (with fractionation)	RAP is produced and stockpiled at a different site or plant. The production, milling, and transport to current site burdens of RAP are allocated to the previous project. However, because RAP is to be transported to the mixing project plant location and required fractionation, transport and fractionation impacts are allocated to the RAP amount being used.	<ul style="list-style-type: none"> <li>• Conveyor belt</li> <li>• Front loader</li> <li>• Fractionation</li> </ul>	<ul style="list-style-type: none"> <li>• End dump truck</li> </ul>

Recycling Types	RAP Type	RAP Name	Comments	Equipment	Transport Vehicles
<b>In-Plant Recycling (RAP produced and used in the same project)</b>	Unfractionated	RAP	Milling/handling and transportation of RAP are covered in the REMOVE LAYER process. Therefore, the RAP production burden is already part of the project analysis.	—	—
	Fractionated	RAP with fractionation	Milling/handling and transportation of RAP are covered in the REMOVE LAYER process. Therefore, the RAP production burden is already part of the project analysis. However, because fractionation is required in the project it which it is being used, fractionation impacts are allocated to the RAP amount being used.	<ul style="list-style-type: none"> <li>• Conveyor belt</li> <li>• Front loader</li> <li>• Fractionation</li> </ul>	—
<b>In-Plant Recycling (RAP produced but not being used in the current project)</b>	Unfractionated	RAP	Milling/handling and transportation of RAP are covered in the REMOVE LAYER process. Therefore, the RAP production burden is already part of the project analysis.	—	—
	Fractionated	n/a	n/a	n/a	n/a

**Table A.2: Recycled Concrete Aggregate (RCA) Allocation and Handling in eLCAP**

Recycling Types	RAP Type	RAP Name	Comments	Equipment	Transport Vehicles
<b>In-Place Recycling OR Cold Central Plant Recycling (CCPR)</b>	In-place	RCA (IPR/CCPR)	Zero burden as all processing is covered in the ADD LAYER process (in-place).	<ul style="list-style-type: none"> <li>• Front loader</li> <li>• Portable crushing &amp; sizing equipment</li> </ul>	—
<b>In-Plant Recycling (existing RCA stockpiles at the plant)</b>	Unfractionated	RCA	RCA has already been produced in another project and has been stockpiled at the mixing plant. The production, demolition, and transport burdens of RCA are allocated to the previous project that produced it.	—	—
	Fractionated	RCA with fractionation	RCA is produced in an earlier project and is stockpiled at the mixing plant. The production, demolition, and transport burdens of RCA are allocated to the previous project that produced it. However, because fractionation is required in the project it is being used, fractionation impacts are allocated to the RCA amount being used.	<ul style="list-style-type: none"> <li>• Conveyor belt</li> <li>• Front loader</li> <li>• Portable crushing &amp; sizing equipment</li> <li>• Fractionation</li> </ul>	—
<b>In-Plant Recycling (RCA stockpiled at a different site and transported to the plant)</b>	Unfractionated	RCA from different site	RCA is produced and stockpiled at a different site or plant. The production, demolition, and transport burdens of RAP are allocated to the previous project that produced it. However, because RCA is to be transported to the current project plant location, transport impacts are to be allocated to the RCA amount being used.	<ul style="list-style-type: none"> <li>• Front loader</li> </ul>	<ul style="list-style-type: none"> <li>• End dump truck</li> </ul>
	Fractionated	RCA from different site (with fractionation)	RCA is produced and stockpiled at a different site or plant. The production, demolition, and transport burdens of RCA are allocated to the previous project that produced it. However, because RCA is to be transported to the mixing project plant location and required fractionation, transport and fractionation impacts are to be allocated to the RCA amount being used.	<ul style="list-style-type: none"> <li>• Conveyor belt</li> <li>• Front loader</li> <li>• Portable crushing &amp; sizing equipment</li> <li>• Fractionation</li> </ul>	<ul style="list-style-type: none"> <li>• End dump truck</li> </ul>

Recycling Types	RAP Type	RAP Name	Comments	Equipment	Transport Vehicles
<b>In-Plant Recycling (RCA produced and used in the same project)</b>	Unfractionated	RCA	Removal of concrete and transport of RCA are covered in the REMOVE LAYER process. Therefore, RCA production, demolition, and transport burdens are already part of the project analysis.	—	—
	Fractionated	RCA with fractionation	Removal of concrete and transport of RCA are covered in the REMOVE LAYER process. Therefore, RCA production, demolition, and transport burdens are already part of the project analysis. However, because fractionation is required in the project it is being used, fractionation impacts are allocated to the RCA amount being used.	<ul style="list-style-type: none"> <li>• Conveyor belt</li> <li>• Front loader</li> <li>• Portable crushing &amp; sizing equipment</li> <li>• Fractionation</li> </ul>	—
<b>In-Plant Recycling (RCA produced but not being used in the current project)</b>	Unfractionated	RCA	Removal of concrete and transport of RCA are covered in the REMOVE LAYER process. Therefore, RCA production, demolition, and transport burdens are already part of the project analysis.	—	—
	Fractionated	n/a	n/a	n/a	n.a

## **APPENDIX B: SUMMARY OF CRITICAL REVIEWS COMPLETED IN 2021**

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### **Critical Review Statement**

#### **Review of the *eLCAP* Software and Documentation**

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

Valid as of: July, 2021

#### **Scope of the Critical Review**

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

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

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

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

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

#### **Critical Review Process**

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

#### **Evaluation**

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

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

aimed for, with the goal of developing defensible results consistent with the stated goals and scope of the project.

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

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

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



Arpad Horvath



Jeremy Gregory



Amlan Mukherjee



## APPENDIX C: LIST OF ENERGY AND BASIC MATERIALS IN ELCAP

Table C.1: Data Sources and Data Quality Checks for Different eLCAP Items/Processes (see also /4/)

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

UCPRC Items List	Components/Processes in GaBi	Source	Data Quality Checks
	US: Electricity from biogas (UCPRC) (agg)	<i>GaBi</i> : The inventory is partly based on primary industry data, partly on secondary literature (several sources) data.	Well documented. Compliance with ISO14040-14044 reported in <i>GaBi</i> model documentation (dependent internal review). No evaluation scores in the external review section.
	US: Electricity from waste (UCPRC) (agg)	<i>GaBi</i> : The inventory is mainly based on industry data and is completed, where necessary, by secondary data.	Well documented. Compliance with ISO14040-14044 reported in <i>GaBi</i> model documentation (dependent internal review). No evaluation scores in the external review section.
<b>Diesel</b>	Diesel, combusted in Industrial Equipment ( <i>USLCI</i> ) (u-so)	<i>GaBi</i> : The original datasets and documentation can be found online: <a href="https://www.lcacommons.gov/nrel/search">https://www.lcacommons.gov/nrel/search</a>	Most of the data in the <i>USLCI</i> database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
	Diesel, at refinery ( <i>USLCI</i> ) (agg)	<i>GaBi</i> : This is a cradle-to-gate inventory generated by PE from unit process data in the <i>USLCI</i> database.	Most of the data in the <i>USLCI</i> database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
	Diesel, combusted in construction Equipment (CARB <i>Off-Road</i> ) (u-so)	The resulting four emissions values from Off-Road are replaced in Diesel, combusted in industrial equipment model.	Internally reviewed by the UCPRC.
	Diesel, combusted in transport (EMFAC) <sup>b</sup> (u-so)	The resulting 10 emissions values from EMFAC are all considered to be the emission LCI output of diesel combusted in transport vehicle.	Internally reviewed by the UCPRC.
<b>Natural Gas</b>	Natural Gas, combusted in Industrial Equipment ( <i>USLCI</i> ) (agg)	<i>GaBi</i> : The original datasets and documentation can be found online: <a href="https://www.lcacommons.gov/nrel/search">https://www.lcacommons.gov/nrel/search</a> .	Most of the data in the <i>USLCI</i> database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
<b>Aggregate</b>	Aggregate (crushed) (u-so)	Aggregate production data were acquired from Table 10 of Marceau et al. 2007. <sup>c</sup>	The data on which the LCI is based and the LCI results have been peer reviewed by the Portland Cement Association membership and its relevant allied groups.
<b>Sand and Gravel</b>	Aggregate (natural) (u-so)	Aggregate production data were acquired from Table 9 of Marceau et al. 2007. <sup>c</sup>	The data on which the LCI is based and the LCI results have been peer reviewed by the Portland Cement Association membership and its relevant allied groups.
<b>Virgin Asphalt Binder</b>	Bitumen, at refinery <i>USLCI</i> /ts (u-so)	Asphalt binder production is based on the <i>USLCI</i> database developed by the National Renewable Energy Lab (NREL) and thinkstep. UCPRC replaced US electricity mix with California electricity mix in the asphalt binder model.	Most of the data in the <i>USLCI</i> database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
<b>Asphalt Emulsion</b>	Bitumen Emulsion, at plant Eurobitume (u-so)	Using input data from Chapter 6 of the Eurobitume 2012 report. <sup>d</sup> Bitumen emulsion model was developed in <i>GaBi</i> .	Eurobitume 2012 is critically reviewed by ESU-services Ltd. According to ISO 14040 and 14044. Critical review report provided as Appendix 5 in the Eurobitume 2012 report. <sup>d</sup>

UCPRC Items List	Components/Processes in GaBi	Source	Data Quality Checks
<b>Portland Cement</b>	Portland Cement, at plant (agg)	Portland cement model developed based on the Portland Cement Association report. UCPRC replaced electricity mix with California electricity grid mix in the cement model.	The data on which the LCI is based and the LCI results have been peer reviewed by the representatives of the Portland Cement Association members and cement and concrete industries. No indicators of data quality were assessed in the report as (stated in the Portland Cement Association report) data quality indicators complying with ISO 14041 has not yet been developed.
<b>Cement Admixtures</b>	Cement Admixtures (Accelerator) (agg)	Directly obtained from <i>GaBi</i> . The source of the input/output data is from European Federation of Concrete Admixture Associations.	—
	Cement Admixtures (Air Entraining) (agg)		
	Cement Admixtures (Plasticizer) (agg)		
	Cement Admixtures (Retarder) (agg)		
	Cement Admixtures (Superplasticizer) (agg)		
	Cement Admixtures (Waterproofing) (agg)		
<b>Hydrated Lime Dry Slacked</b>	Lime Hydrate (Ca(OH) <sub>2</sub> ) slaking, ts (agg)	Directly obtained from <i>GaBi</i> . The data set covers all relevant process steps/technologies over the supply chain of the represented cradle-to-gate inventory. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.	Well documented. Compliance with ISO14040-14044 reported in <i>GaBi</i> model documentation (dependent internal review). No evaluation scores in the external review section.
<b>Paraffin (Wax)</b>	Wax/Paraffins at refinery, PE (agg)	The data set covers the entire supply chain of the refinery products. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.	Well documented. Compliance with ISO14040-14044 reported in <i>GaBi</i> model documentation (dependent internal review). No evaluation scores in the external review section.
<b>Quicklime</b>	Quicklime, at plant, <i>USLCI</i> /ts (agg)	Directly obtained from <i>GaBi</i> . Data based on <i>USLCI</i> database and thinkstep.	Most of the data in the <i>USLCI</i> database has undergone some sort of review. The database as a whole has not yet undergone a formal validation process.
<b>Crumb Rubber Modifier</b>	CRM production, at plant, Corti (agg)	Data obtained from Corti et al., <sup>e</sup> which is a peer reviewed published journal article.	Primary data has been acquired and generated by the authors of the journal article.

<sup>a</sup> *USLCI*: U.S. Life Cycle Inventory Database; ts: thinkstep

<sup>b</sup> EMFAC: EMISSION FACTOR

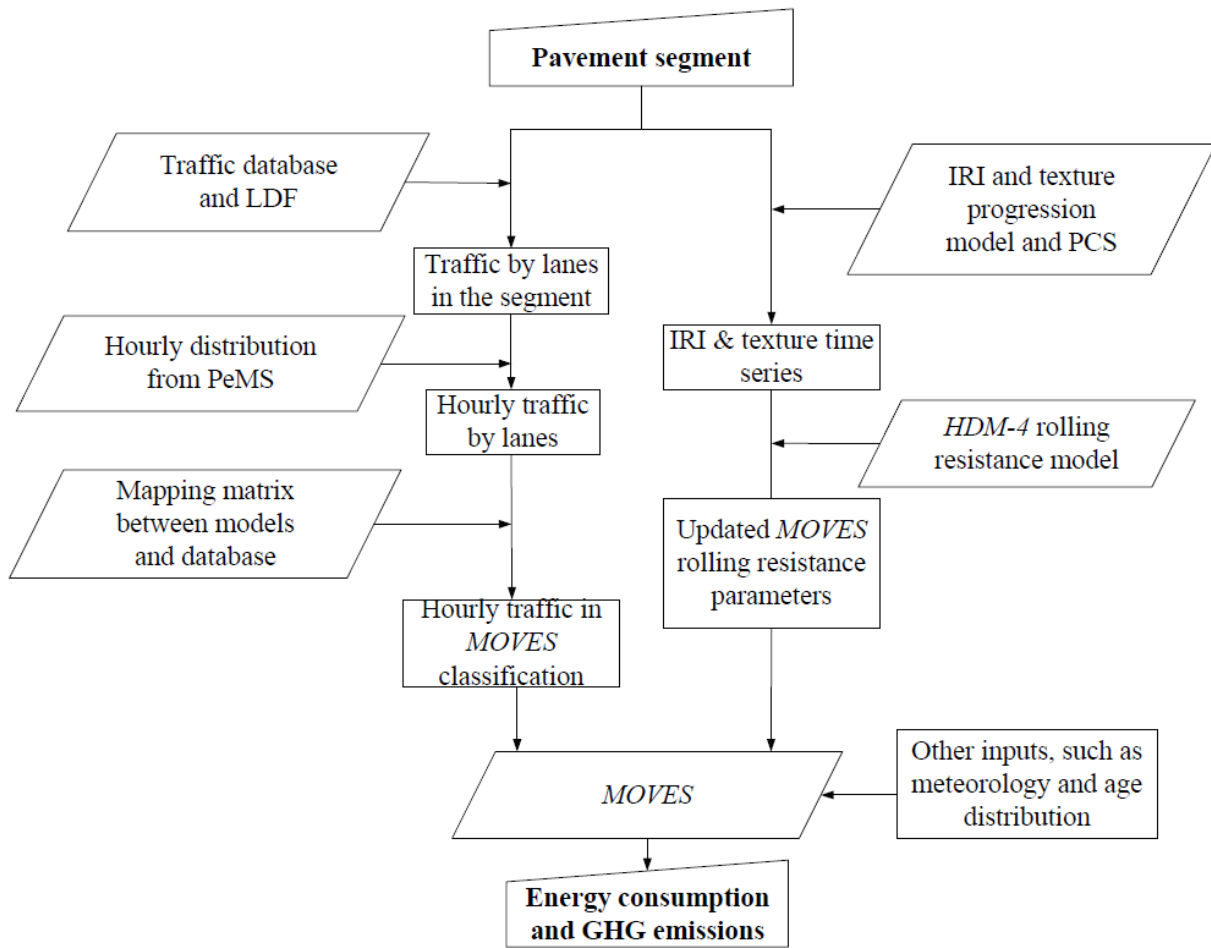
<sup>c</sup> Marceau, M., Nisbet, M.A., and VanGeem, M.G. 2007. *Life Cycle Inventory of Portland Cement Concrete* (PCA R&D Serial No. 3007). Skokie, IL: Portland Cement Association.

<sup>d</sup> Eurobitume. 2012. *Life Cycle Inventory: Bitumen*. Brussels, Belgium: European Bitumen Association. <https://www.eurobitume.eu/fileadmin/pdf-downloads/LCI%20Report-Website-2ndEdition-20120726.pdf>.

<sup>e</sup> Corti, A., and Lombardi, L. 2004. "End Life Tyres: Alternative Final Disposal Processes Compared by LCA." *Energy* 29, no. 12: 2,089–2,108.

## APPENDIX D: USE STAGE GREENHOUSE ROUGHNESS AND GAS EMISSIONS BACKGROUND

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*Note:* The approach shown in this figure was used to produce simplified equations for passenger vehicles and two-, three-, four-, and five-axle trucks operating at constant highway speeds.

**Figure D.1: Procedure to calculate the effect of rolling resistance on vehicle fuel consumption and emissions.**

**Table D.1: IRI Coefficient Equations per Pavement Type per Treatment  
for Different ESAL and Climate Conditions**

				<b>IRI</b> $(IRI_L + IRI_R) / 2 = a + b * Age^c$ $Age = ((Average\_IRI - a) / b)^{1/c}$ (in./mi.)			
Pavement Type	Treatment	ESAL/yr <sup>a</sup>	Climate <sup>b</sup>	Node ID	a	b	c
Flexible Pavement	1. Full-Depth Reclamation	A	Severe	1	157.3	3.4	1.0
			Mild	2	88.8	2.0	1.0
		B	Severe	3	143.0	5.1	1.0
			Mild	4	88.3	2.2	1.0
		C	Severe	5	139.6	5.4	1.0
			Mild	6	87.8	2.5	1.0
	2. Thick Overlay or Reconstruct	A	Severe	7	157.3	3.7	1.0
			Mild	8	88.8	2.3	1.0
		B	Severe	9	143.0	5.4	1.0
			Mild	10	88.3	2.5	1.0
		C	Severe	11	139.6	5.7	1.0
			Mild	12	87.8	2.8	1.0
	3. Very Thin Overlay	A	Severe	13	89.5	3.8	1.0
			Mild	14	90.8	2.4	1.0
		B	Severe	15	77.3	5.5	1.0
			Mild	16	92.5	2.6	1.0
		C	Severe	17	76.4	5.8	1.0
			Mild	18	94.3	2.9	1.0
	4. Medium Overlay	A	Severe	19	118.5	3.8	1.0
			Mild	20	90.0	2.3	1.0
		B	Severe	21	105.5	5.5	1.0
			Mild	22	90.7	2.6	1.0
		C	Severe	23	103.5	5.7	1.0
			Mild	24	91.5	2.8	1.0
	5. Thin Overlay	A	Severe	25	95.3	3.8	1.0
			Mild	26	90.7	2.4	1.0
		B	Severe	27	82.9	5.5	1.0
			Mild	28	92.1	2.6	1.0
		C	Severe	29	81.8	5.8	1.0
			Mild	30	93.8	2.9	1.0
	6. Seal Coat	A	Severe	31	119.4	3.3	1.0
			Mild	32	118.3	3.2	1.0
		B	Severe	33	123.2	2.8	1.0
			Mild	34	120.8	2.7	1.0
		C	Severe	35	123.6	2.1	1.0
			Mild	36	123.6	2.2	1.0

				<b>IRI</b> $(IRI_L + IRI_R)/2 = a + b * Age^c$ $Age = ((Average\_IRI - a)/b)^{(1/c)}$ (in./mi.)			
Pavement Type	Treatment	ESAL/yr <sup>a</sup>	Climate <sup>b</sup>	Node ID	a	b	c
	7. Cold In-place	A	Severe	37	90.0	2.3	1.8
			Mild	38	90.0	2.0	1.7
		B	Severe	39	90.0	2.4	1.8
			Mild	40	90.0	2.1	1.7
		C	Severe	41	90.0	2.5	1.8
			Mild	42	90.0	2.2	1.7
	8. Seal Cracks	A	Severe	43	119.4	3.3	1.3
			Mild	44	118.3	3.2	1.3
		B	Severe	45	123.2	2.8	1.3
			Mild	46	120.8	2.7	1.3
		C	Severe	47	123.6	2.1	1.3
			Mild	48	123.6	2.2	1.3
	9. Unknown	A	Severe	49	111.8	3.6	1.0
			Mild	50	99.4	2.6	1.0
		B	Severe	51	104.4	4.6	1.0
			Mild	52	100.9	2.6	1.0
		C	Severe	53	103.5	4.6	1.0
			Mild	54	102.6	2.6	1.0
JPC	1. Crack, Seat and Overlay (CSOL)	A	Severe	55	137.9	3.8	1.0
			Mild	56	89.4	2.3	1.0
		B	Severe	57	124.2	5.4	1.0
			Mild	58	89.5	2.6	1.0
		C	Severe	59	121.5	5.7	1.0
			Mild	60	89.6	2.8	1.0
	2. PCC Lane Replacement	A	Severe	61	60.0	0.5	1.1
			Mild	62	60.0	0.5	1.1
		B	Severe	63	60.0	0.7	1.2
			Mild	64	60.0	0.7	1.2
		C	Severe	65	60.0	1.0	1.5
			Mild	66	60.0	1.0	1.5
	3. Grind	A	Severe	67	60.0	1.1	1.1
			Mild	68	60.0	1.1	1.1
		B	Severe	69	60.0	1.2	1.2
			Mild	70	60.0	0.9	1.2
		C	Severe	71	60.0	2.0	1.5
			Mild	72	60.0	1.4	1.5
	A	Severe	73	60.0	0.8	1.1	

				<b>IRI</b> $(IRI_L + IRI_R) / 2 = a + b * Age^c$ $Age = ((Average\_IRI - a) / b)^{(1/c)}$ (in./mi.)				
Pavement Type	Treatment	ESAL/yr <sup>a</sup>	Climate <sup>b</sup>	Node ID	a	b	c	
	4. Grind with Slab Replacement		Mild	74	60.0	0.8	1.1	
			B	Severe	75	60.0	1.0	1.2
				Mild	76	60.0	0.8	1.2
			C	Severe	77	60.0	1.5	1.5
				Mild	78	60.0	1.2	1.5
	5. Slab Replacement	A	Severe	79	60.0	1.0	1.1	
			Mild	80	60.0	1.0	1.1	
		B	Severe	81	60.0	1.1	1.2	
			Mild	82	60.0	0.9	1.2	
		C	Severe	83	60.0	1.8	1.5	
			Mild	84	60.0	1.3	1.5	
	6. Unknown	A	Severe	85	60.0	0.9	1.1	
			Mild	86	60.0	0.9	1.1	
		B	Severe	87	60.0	1.0	1.2	
			Mild	88	60.0	0.8	1.2	
C		Severe	89	60.0	1.7	1.5		
Mild	90	60.0	1.3	1.5				

<sup>a</sup> ESAL/yr: A = <100,000; B = >100,000 and <500,000; C = >500,000

<sup>b</sup> Climate: North Coast: Severe; High Desert: Mild; Inland Valley: Mild; Central Coast: Mild; Desert: Mild; South Coast: Mild; High Mountain: Mild; South Mountain: Severe; Low Mountain: Severe