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Life Cycle Assessment and Life Cycle Cost Analysis for Six Strategies for GHG Reduction in Caltrans Operations

Authors:

John T. Harvey, Ali A. Butt, Arash Saboori, Mark T. Lozano,
Changmo Kim, and Alissa Kendall

Partnered Pavement Research Center (PPRC) Project Number 4.72 (DRISI Task 3209):
LCA Alternate Strategies for GHG Reduction: Example Strategies

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation, and System Information
Office of Materials and Infrastructure

PREPARED BY:

University of California
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16. ABSTRACT
California state government has established a series of mandated targets for reducing the greenhouse gas (GHG) emissions that contribute to climate change. With a multiplicity of emissions sources and economic sectors, it is clear that no single change the state can make will enable it to achieve the ambitious goals set by executive orders and legislation. Instead, many actors within the state's economy—including state agencies such as the California Department of Transportation (Caltrans)—must make multiple changes to their own internal operations. The focus of this study and technical memorandum is to examine several strategic options that Caltrans could adopt to lower its GHG emissions in operating the California (CA) state highway network and other transportation assets so it can help meet the state's GHG reduction goals. Although many GHG reduction strategies appear to be attractive, simple, and effective, most also have limitations, trade-offs, and unintended consequences that cannot be identified without a preliminary identification and examination of the full system they operate in and their full life cycle. To achieve the most rapid and cost-effective changes possible, the costs, times to implement, and difficulty of implementation should also be considered when the alternative strategies are being prioritized. This project first developed an emissions reduction "supply curve" framework by using life cycle assessment (LCA) to evaluate full-system life cycle environmental impacts and life cycle cost analysis (LCCA) to prioritize the alternative GHG-reduction strategies based on benefit and cost. This framework was then applied to an example set of strategies and cases for Caltrans operations. This technical memorandum presents the results of the supply curve framework's development and its application to six strategies for changing several Caltrans operations identified by the research team. The six strategies were: (1) pavement roughness and maintenance prioritization, (2) energy harvesting using piezoelectric technology, (3) automation of bridge tolling systems, (4) increased use of reclaimed asphalt pavement, (5) alternative fuel technologies for the Caltrans vehicle fleet, and (6) solar and wind energy production on state right-of-ways. A summary of the methodology and the resulting supply curve that includes all the strategies considered and ranked is published in a separate white paper. This technical memorandum provides the details, assumptions, calculation methods, and results of the development of the GHG reduction supply curve for each strategy. Although this current study's scope is limited to development of a supply curve for GHG emissions only, there are plans to expand the study's scope to include other environmental impacts and to develop supply curves for them as well.

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Supply curve, life cycle assessment, life cycle cost analysis, decision support, California state level strategies, carbon reduction, greenhouse gas emissions

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The approach for evaluating strategies and policies for greenhouse reduction using environmental life cycle assessment (LCA) and life cycle cost analysis (LCCA) as well as identifying other benefits and disbenefits can be applied to other strategies and policies not covered in this technical memorandum, and should then be added to the supply curve for prioritization.

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

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

1.1 Background

California state government has established a series of mandated targets for reducing greenhouse gas (GHG) emissions contributing to global warming. Governor's Executive Order S-3-05 (2005) required the state to reduce its GHG emissions to 1990 levels by 2020, and to 80 percent below 1990 levels by 2050 *(1)*. California's 2006 Climate Change Solutions Act (Assembly Bill 32) made the 2020 reductions law and tasked many government entities, including local governments and government agencies, with helping to meet those goals *(2)*. In 2015, Governor's Executive Order B-30-15 required a reduction to 40 percent below 1990 levels by 2030, a mandate made into law by Senate Bill 32 in 2016 *(3)*. In 2018, another executive order, B-55-18, required the state to achieve carbon neutrality by 2045 *(4)*.

The California Climate Inventory found that in 2016 the state emitted 429.4 million metric tons (MMT) of carbon dioxide equivalent[1] (CO_2-e), achieving a 30 percent reduction from 2005 levels and meeting the 2020 goal of a reduction to 1990 levels four years ahead of time *(5, 6)*. The 2016 inventory also showed that the transportation, industrial, and electricity generation sectors were the economy's largest emissions sources—emitting 41, 23, and 16 percent of all GHGs, respectively. Most of the transportation sector's emissions came from combustion of gasoline and diesel. Most of the electricity sector's emissions resulted from combustion of natural gas at in-state power plants and from coal combustion at the out-of-state plants that provided the state's imported electricity during periods of peak electricity use. Industrial sector emissions included large contributions from oil and natural gas production and oil refining. Some of the contribution from refining can be attributed to production of the asphalt binder used in transportation infrastructure, while other contributions come from the production of cement and steel used in bridges, pavement, and other structures and hardscape.

With a multiplicity of emissions sources and economic sectors, it is clear that no single change the state can make will enable it to achieve the ambitious goals set by the executive orders and legislation. Instead, many actors within the state's economy—including state agencies such as the California Department of Transportation (Caltrans)—must make multiple changes to their internal operations. Proposed changes have come from many sources. These proposals have been based to varying degrees on science, the potential to grow markets or to shrink the markets of competitors, regulatory strategies, and on how easy it is to communicate the idea to policy makers and the general public.

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[1] Calculated by CARB using the global warming potential (GWP) factors published in 2007 by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report over a 100-year time horizon.

Further, the lack of a standard approach to compare the different proposals and strategies makes it even more difficult to identify, quantify, and select among the many possible strategies to achieve GHG reductions.

The focus of this study and technical memorandum is to examine several strategic options that Caltrans could adopt to lower its GHG emissions from operating the California (CA) state highway network and other transportation assets to help it meet the state's climate change goals. Although many GHG reduction strategies appear to be attractive, simple, and effective, the following limitations are also true for many of them:

- The net GHG reductions that result from implementing any of the strategies have often not been quantified;
- Few of the cases where GHG reductions have been quantified used a system-wide perspective for their estimates;
- In most cases the time it will take to implement a strategy and begin achieving GHG reductions has not been considered;
- The difficulties involved in implementing GHG reduction strategies have not been estimated; and
- Most importantly, the quantification of changes in environmental impacts and the initial and life cycle costs (LCCs) of implementing strategies have rarely been estimated in a way that prioritizes selecting the most cost-effective ones (that is, the strategies that will achieve maximal emissions reductions at minimal cost).

The last point above may be the most important one: government and industry will need to choose the GHG reduction strategies that prioritize getting the "greatest bang for the buck" to mobilize and maintain the state's political will and have the maximum benefit to the state's economy. Without a prioritizing process that takes cost-effectiveness constraints into consideration, government and industry may lose the long-term public support needed to implement the state's GHG reduction goals: taxpayers must be able to see that the efforts to meet the state's GHG targets are being conducted in the most cost-effective ways possible and that approaches that result in cost savings are being prioritized. Therefore, it is important that the calculations used to determine GHG emissions include life cycle cost considerations that show whether there are any taxpayer savings. The larger reform process that includes the calculations should also identify and include other short- and long-term benefits, and disbenefits, if any, even if they cannot be fully monetized. Doing so will help ensure that the reform process is a full system assessment, and that it maintains the transparency needed to keep the public's trust.

A full-system and life cycle view is necessary to fully understand changes in environmental impacts and to avoid unintended consequences of a strategy selection. A life cycle perspective is required for GHG accounting because benefits achieved during one stage of a strategy's life cycle may be reduced or reversed by carbon-intensive upstream or downstream stages. Similarly, if an incomplete system view is taken then benefits achieved in one part of the system may be reduced or reversed in another part of the system that was not considered. In some cases, two or more potential changes in operations may be incompatible in ways that will negate any benefits, and a full system view can help identify these conflicts as well. Life cycle assessment (LCA) is a methodology that provides a full system and life cycle quantification of environmental impacts.

The timeframe for change is also important because emissions reductions achieved sooner will have greater near-term climate benefits than reductions that occur later or are spread out over a longer period. However, current global warming potential (GWP) calculations—with GWP as the indicator frequently used to quantify and compare GHG emissions or reduction of these emissions—do not take timeframe considerations into account. This temporal dimension can be added by using an alternative indicator, *time-adjusted warming potential (7)*, in parallel with GWP to account for the timing of emission reductions.

As noted, LCA and related methods employ a system-wide full life cycle perspective to quantify environmental impacts and can be used to evaluate GHG reduction strategies and technologies, as well as other systems.[2] LCA is a structured evaluation methodology that quantifies environmental impacts over the full life cycle of a product or system, and includes impacts that occur throughout the system's supply chain. LCA provides a comprehensive approach to evaluating the total environmental burden of a product by examining all the inputs and outputs over its life cycle, from raw material production to the end of the product's life *(8)*. As LCA use has increased and broadened to answer increasingly complex questions in a number of fields, LCA limitations and problems have also been highlighted. As a result, LCA methods and data have continued to mature, often with a focus on producing more robust and trustworthy results. This stands in contrast to life cycle cost analysis (LCCA), where the methodology has already matured and remains in use within Caltrans for infrastructure decision-making support *(9)*.

1.2 Goals of the Study

The goal of this study—designated Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.72, "LCA Alternate Strategies for GHG Reduction: Example Strategies"—is to first develop an emissions reduction "supply curve" framework using LCA and LCCA for prioritizing alternative strategies for reducing GHG emissions based on benefit and cost, and then to apply the framework to a set of strategies and

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[2] When LCA is used only to examine GHG emissions and no other environmental impacts it is sometimes referred to as carbon footprinting, although this term has also been associated with determination of initial carbon emissions rather than life cycle emissions. In this study, life cycle assessment refers to a limited set of impact indicators, including global warming potential, which is quantified in terms of CO2-e, and several other indicators of importance in California. Despite the limited scope of these indicators, which are calculated using the principles and standards of LCA, the term LCA is used.

cases for Caltrans operations. This technical memorandum presents the results of the supply curve framework's development and its application to six strategies for changing several Caltrans operations identified by the research team. The six strategies were chosen as testbeds for the framework and intentionally reflect strategies with different underlying data and technology readiness levels. Depending on the chosen strategy, the underlying data for calculating the LCCA and LCA vary from the well-documented data to first-order estimations. The following six strategies are evaluated:

1. Pavement roughness and maintenance prioritization
2. Energy harvesting using piezoelectric technology
3. Automation of bridge tolling systems
4. Increased use of reclaimed asphalt pavement
5. Alternative fuel technologies for the Caltrans vehicle fleet
6. Solar and wind energy production on state right-of-ways

A summary of the methodology and the resulting supply curve that includes all the strategies considered and ranked is published in a separate white paper *(10)*. This technical memorandum provides the details, assumptions, calculation methods, and results of the development of the GHG reduction supply curve for each strategy. Although this current study's scope is limited to development of the supply curve for GHG emissions only, there are plans to expand the study's scope to include other environmental impacts and to develop supply curves for them as well.

1.3 Approach, Methodology, and Framework

The approach used in this study to support prioritization of strategies for reducing GHG emissions was to develop what are variously called "marginal abatement curves," "supply curves," or "McKinsey curves" (named after the company that has made extensive use of them) *(11)*. Supply curves illustrate the economics associated with changes and policies made for climate change mitigation. In particular, the work done by Lutsey and Sperling demonstrated how alternative strategies within the transportation sector can be quantified and compared using available information, and also compared with alternatives in other sectors of the economy *(12)*.

Using a supply curve approach provides a process for rank-ordering numerous GHG reduction options based on how cost-effective they are and provides additional information for decision-making, such as the magnitude of achievable reductions. Borrowing from economic theory, the supply curve approach shows graphically the supply of a given resource (on the x-axis) that is available at a given price (on the y-axis), as can be seen in Figure 1.1. Depending on the use and derivation of the costs and cumulative emissions reduction data, the curves can more aptly be labeled as *marginal abatement, incremental cost, cost of conserved carbon*, or *cost-effectiveness curves*. When the individual strategies used to create the curve are shown as blocks to illustrate the effects of their discrete changes, the curves can show incremental contributions toward a goal and the decreasing cost effectiveness as additional actions are taken *(13)*.

The example shown in Figure 1.1 is adapted from Lutsey's first-order assessment of alternative actions to reduce GHG emissions in the California transportation sector versus those in other sectors. The figure shows both the initial cost and life cycle cost (LCC). Although all the actions have a required initial cost to make the change, only some of those changes will result in LCC savings. And not only do those actions reduce GHG emissions, they also improve the efficiency of the overall economy.

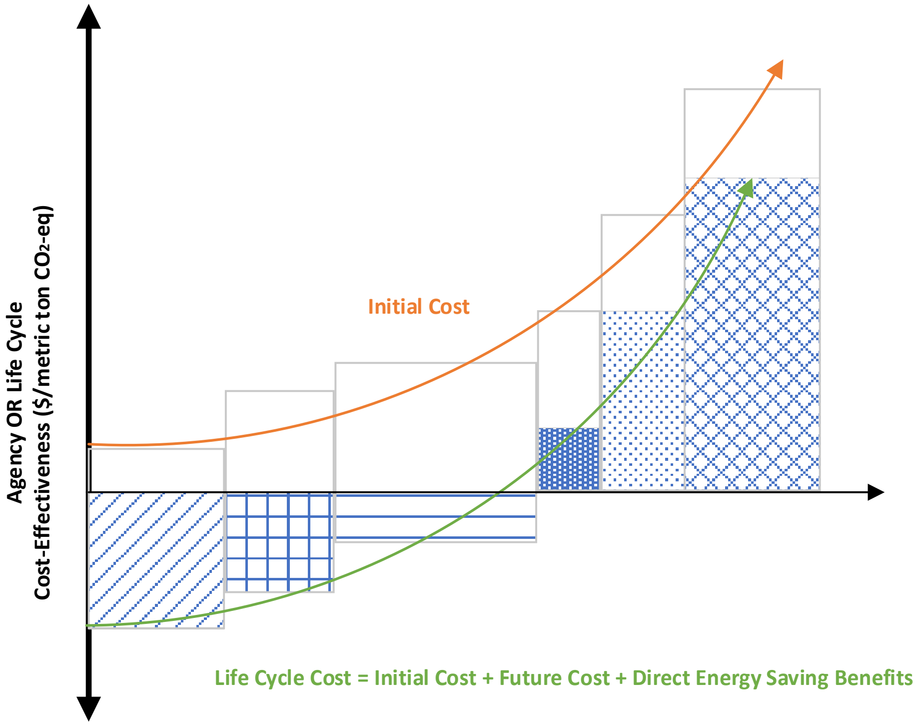

Figure 1.1: Example curve of cumulative GHG emission reduction versus cost effectiveness (adapted and recreated from *[13]*).

To help develop the LCA and LCCA analyses for this study, a list of information to be gathered was compiled to create the supply curve and to develop information regarding the potential for implementation, including a definition of the strategy, its technology and the system it would change, the strategy's state of readiness, the responsible stakeholders, and the factors that would drive the change. The information to be gathered is:

1. Definition of the change/technology
2. Definition of the state of readiness of the change of technology using ratings adapted from the Technology Readiness Level [TRL] approach adapted from a system developed by the National Aeronautics and Space Administration *(14)*
    a. TRL 1: basic principles observed
    b. TRL 2: technology concept formulated
    c. TRL 3 and 4: experimental proof of concept/technology validated in lab
    d. TRL 5 and 6: technology validated and demonstrated in relevant environment at less than full scale (industrially relevant environment in the case of key enabling technologies)
    e. TRL 7: system prototype demonstration in operational environment (full scale)
    f. TRL 8: actual system completed and determined to be operational through test and demonstration
    g. TRL 9: actual system proven in operational environment elsewhere or less-than-full-market penetration
3. Definition of the system in which the change occurs
4. Identification of whether the market will change or the change will result in same market with different market shares
5. Identification of who is responsible for the change
6. Definition of who is responsible for implementing the change
7. Identification of who pays for the change
    a. Government, level of government
    b. Producers without pass through to consumers
    c. Consumers
8. Identification of what will drive the change
    a. Market
    b. Market incentives (example, tax break)
    c. Regulation
    d. Legislation
    e. Public programs incentivizing change
    f. Education
    g. Identification of what the change will do to these other environmental indicators:

        i. Air pollution
        ii. Water pollution
        iii. Energy use
            - Renewable
            - Nonrenewable
            - Renewable energy source used as material
            - Nonrenewable energy source used as material
        iv. Water use
        v. Use of other natural resources
9. Definition of the performance metrics
10. Supply curve calculation data
    a. Calculation of the expected change in GHG output per unit of change in system
    b. Calculation of the expected maximum units of change in system
    c. Identification of the time to reach maximum units of change
    d. Estimation of the expected shape of change rate
        i. Linear
        ii. Increasing to maximum
        iii. Decreasing to maximum
        iv. S-shaped
    e. Identification of the total estimated initial cost (to be used with total change in GHG to calculate initial cost per unit of change)
    f. Identification of the estimated LCC per unit of change (to be used with total change in GHG to calculate initial cost per unit of change)
11. Documentation of the methodology used to gather, calculate, and estimate information
12. Documentation of the sources used to develop information
13. Completion of the data quality assessment
14. Completion of the outside critical review of results

The information used to develop the answers to all these questions needs to be fully documented, including:

- Citations
- Development of optimistic, best, and pessimistic estimates to the extent possible to permit sensitivity analysis
- Identification of the level of disagreement between different sources of information
- A ranking of the data and estimation quality such as *Excellent*, *Good*, *Fair*, *Poor*, or *Completely Unknown*

LCA can help with GHG emissions calculations and LCCA can help with cost estimations. Using these methodologies together can help decision makers prioritize the projects with the largest and most cost-effective benefits. Identification of answers to the questions listed above contributes to the speed of change estimates for each strategy considered and, along with supply curve development, forms the basis for this project's proposed framework.

In this study's approach, LCA is used to estimate the benefit by comparing the GHG emissions from the proposed change over the life cycle analysis period versus current practice. The LCA is performed using the best available information, which can range from very poor to very good and is based on ISO 14044:2006 *(15)* data quality parameters, discussed as they relate to pavements in the Federal Highway Administration Pavement LCA Framework *(16)*: time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, and reproducibility. The LCA documentation for the supply curve includes a data quality assessment, which must be taken into consideration when comparing alternative proposed changes on the supply curve.

This project's analysis period spans the years 2015 to 2050, the state's target year for achieving its GHG reduction goals at the time this study began. The Governor's Executive Order mandating carbon neutrality by 2045 was signed while the project was underway. The impact indicators were calculated using the TRACI impact assessment methodology, the most commonly used set of impact categories in the US. The TRACI methodology was developed by the US EPA, and the most recent version (TRACI 2.0) was released in 2012 *(17, 18)*.

Using the best available information, two costs were calculated for each proposed change to find the change per unit cost of the benefit values for the supply curve's y-axis: the initial implementation cost and the long-term or LCC. As with the LCA information, the economic analysis of the proposed changes for the supply curve is developed with the best available information, and documentation is required of the assumptions, calculations, and quality of the information used. Like the LCA, the LCCA requires that a data quality assessment be taken into consideration when comparing alternatives, although LCCA does not have as formal set of rules as does LCA.

The proposed strategies are put in rank order of cost effectiveness, with color coding to identify the uncertainty level of the information used for the analysis (not shown in the example in Figure 1.1).

All changes carry an implementation cost, but only a few changes will potentially result in LCC savings. Those changes to the left of the curve should be considered for implementation first because they provide the greatest improvement for the least cost. Changes that have negative LCCs are what Lutsey refers to as "no regrets" choices because they reduce costs over the life cycle. Moving to the right along the x-axis of the curve reveals the cumulative effect of changes toward the overall GHG reduction goal, and the increasing cost of achieving that goal. As with all economic analyses related to public policy, this economic analysis should consider not only the overall costs, but also determine who pays those costs or receives any savings, and whether those costs or savings are equitable.

In addition to GWP, this project used a measure called *time-adjusted warming potential* (TAWP) to capture the effects of the speed of change. Analogous to the use of a discount rate and the reporting of net present value (NPV) in LCCA calculations, the TAWP accounts for the timing of GHG fluxes (emissions [positive] or reductions [negative]) and reports the results in units of carbon dioxide equivalent (CO_2-e) for an equivalent reduction if the entire change were made at the time of this writing. The speed of change can be estimated in part by when an alternative strategy is likely to be implemented, what will drive the implementation (for example, policy, market, or regulation), how the change will be made (for example, technology adoption, change in practice, change in behavior, etc.), and the time horizon over which the change will remain in place.

The process for developing the supply curves included in this technical memorandum consisted of the following:

- Defining a functional unit and system boundaries for the technology
- Identifying available information about the strategy, specifically:
    - Technology of the strategy
        - Initial implementation
        - Life cycle, including maintenance, rehabilitation, replacement, or end-of-life
    - Costs of the strategy
    - Constraints on implementation relevant to implementation by Caltrans
- Creating information about the strategy:
    - By analogous estimating from existing sources about similar technologies, examining different scales of research, development or implementation, or its implementation in different contexts, and/or
    - By bottom-up estimation from existing sources about components of the technology
- Calculating:
    - Life cycle inventory and impacts
    - Initial costs
    - Life cycle costs
- Assessing data quality
- Including the strategy in the supply curve

The best available information that could be obtained was used for both the LCA and the LCCA. Data quality for both was assessed as part of the data analysis. The different strategies' data quality ranged widely, and appeared to be directly related both to the maturity of the strategy's research and development and to how widely the strategy has been implemented (which would influence how much real-world cost data could be gleaned from it.)

1.4 Comments on Use of Supply Curves

Developing supply curves to review alternatives provides a way to bring full system analysis, life cycle thinking, and, above all, quantification, to their development in a decision-making environment where they are often absent, and to support decision-making for prioritization that includes consideration of economics.

However, supply curves are only one tool for GHG and other pollutant reduction decision-making, and they require cautious use because they have a number of limitations. Specifically, past use of supply curves has at times omitted any ancillary benefits from abating greenhouse gas emissions, done a poor job of considering data uncertainty, not considered dynamic interactions over time, and lacked transparency about their assumptions. Supply curves based on single assessments of abatement measures suffer from additional shortcomings: they do not consider interactions, non-economic costs, or behavioral changes; they count benefits incorrectly; and they have inconsistent baselines *(19)*. It has been suggested that supply curves be used more for comparing alternatives than for quantifying cumulative abatement progress *(20)*. Further, supply curves' inability to predict future abatement has been critiqued because they fail to consider longer-term market changes driven by consumer changes, the timing of policy actions, actions taken by other market actors, and changes in future technologies *(21)*. And even though most of these critiques have focused on national-level supply curves—rather than more granular and often less complex curves for agency- and local-level decision making—they must be kept in mind when using supply curves to support decision-making.

These critiques of past use of supply curves were addressed to the extent possible in the framework and initial case studies included in this technical memorandum. In particular, LCA and LCCA methodological approaches were used and LCA rules for documentation were intentionally followed to remedy many of the problems associated with past use of supply curves.

Before supply curves and their documentation are used for decision-making it is recommended that they be submitted to critical review by interested stakeholders, and that they be accompanied by documentation of the critiques and responses by the supply curve developers, following ISO LCA principles. This will be done for this technical memorandum.

1.5 Structure of This Technical Memorandum

Each chapter in this technical memorandum provides the details of each strategy following the order in which they are listed in Section 1.2. Each chapter includes an introduction to the technology and the system in which it operates; the scope of the proposed strategy; the methodology used to develop the information about the strategy for the supply curve, including assumptions, calculation methods, data sources, and quality assessment and limitations; and the results of the GHG abatement and cost calculations for both GWP and TAWP. An appendix in each chapter details the assumptions and calculations performed to obtain the results, and includes responses to the questionnaire about implementation for each strategy.

2 STRATEGY 1: FUEL USE REDUCTIONS THROUGH PAVEMENT NETWORK ROUGHNESS MANAGEMENT

2.1 Strategy Statement and Goal

The first alternative greenhouse gas (GHG) reduction strategy examined involved reducing fuel use by managing the roughness of the state highway pavement network operated by Caltrans. Implementing this strategy would first involve changing how the Caltrans pavement management system's (PMS) decision trees currently prioritize maintenance and rehabilitation (M&R) treatments. The decision trees' approach to pavement roughness would need to be altered to consider GHG reductions by using International Roughness Index (IRI) trigger levels "optimized" to reduce GHG emissions for different traffic levels rather than its current prioritization approach, which is focused primarily on pavement infrastructure preservation and avoiding excessively rough pavement. This network-level approach for reducing GHG emissions is based on the research documented in Wang et al. *(22, 23)*, which considers both the emissions from the material production, transportation, and construction stages during M&R activities that make the pavement smoother, and the emissions reductions attributable to vehicles' lessened fuel use when they operate on smoother pavements.

2.2 Introduction

2.2.1 Caltrans Plans and Documentation

Pavement roughness is defined worldwide in accordance with ASTM E867 as "[t]he deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality" *(24)*. Pavement roughness adversely affects driver safety, fuel efficiency, ride quality, vehicle maintenance costs, freight damage, and pavement durability *(25)*. Since 2015, Caltrans construction quality specifications for as-built roughness have been defined in terms of IRI *(26)*, .and it has been used in Caltrans pavement management system decision trees since the early 1990s, helping determine the timing for M&R projects. Before 2010, the Caltrans PMS used an M&R IRI trigger value of approximately 220 inches/mile (3.45 m/km) for the entire network regardless of the traffic volume on a given pavement segment—although it included a small difference for asphalt and concrete pavements. In 2010 that value was lowered to 170 inches/mile (2.68 m/km). These trigger values have been the same across the entire network regardless of the volume of traffic on a given pavement segment.

2.2.2 Abatement Strategy or Technology

Rolling resistance, the result of a moving vehicle's interaction with a pavement, affects that vehicle's fuel economy and GHG emissions levels. Specifically, rolling resistance is due to three pavement properties that combine to result in lost energy: pavement surface roughness, pavement surface macrotexture, and pavement structural response. The extent to which these affect fuel economy and GHG emissions depends on the pavement roughness and surface texture levels, on the structure of the pavement (its thickness, stiffness, and viscoelastic characteristics), their interaction with different vehicle type and traffic speeds, and the prevailing climate conditions—including temperature and rainfall *(27, 28, 29).* IRI and mean profile depth (MPD) or mean texture depth (MTD), as a measure of pavement macrotexture, are the two parameters commonly used to characterize the pavement surface characteristics that affect pavement-induced rolling resistance. Although the effects of structural response are a factor in vehicle fuel efficiency (a subject under investigation in another study for Caltrans by the UCPRC), the study discussed in this memorandum only considers the effect of roughness as measured by IRI.

Vehicles traveling on smooth pavement surfaces with lower macrotexture consume less fuel[3]. Evans et al. showed that a 10 percent decrease in tire rolling resistance can increase fuel economy by approximately 1.1 percent *(30)*. Another study provided a preliminary indication that roughness is the largest contributor to rolling resistance on the California state highway network *(31)*. However, to keep a pavement surface smooth requires M&R treatments, which demand additional resources and energy and thus produce GHG emissions.

A PMS helps determine appropriate network-wide strategies to achieve performance targets. First, the PMS identifies when a pavement segment needs treatment and what M&R treatments are appropriate for its particular pavement type and the condition each of its segment. Second, the PMS prioritizes treatments across the segments in a network in accordance with an agency’s allocated budget over a multiyear time horizon. Most PMSs use decision trees that trigger a treatment based on either the presence of cracking, which can lead to rapid loss of structural capacity and the need to perform a more extensive treatment, or the presence of rough pavement, which affects road users. A pavement can be rough because it was paved that way during construction or because exposure to traffic and the environment led to cracking and surface distortions that roughened it over time. Heavier truck axle loads and/or higher truck-traffic volumes can accelerate pavement deterioration, thus requiring frequent maintenance if the network is to remain smooth and uncracked, the conditions assumed in the performance models for IRI and cracking in the PMS.

Caltrans and most other state transportation departments currently use a single IRI value to trigger M&R treatment for all segments in their entire highway network. The hypothesis of this study was that maintaining roads in a smoother condition (that is, keeping roughness lower) would reduce both life cycle GHG emissions as well as LCCs since the fuel savings resulting from vehicles operating on smoother pavements would offset the emissions generated by more frequent treatments where there was sufficient traffic to generate the benefit. It was also hypothesized that LCCs using this approach would be same or lower because the cost of treatment to restore

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[3] Although low IRI poses no safety risk, some macrotexture is necessary to avoid hydroplaning on wet pavement at highway speeds.

smoothness to a cracked pavement is often less than the cost of treatment needed to restore a cracked pavement whose roughness is due to poor structural capacity. In this method, a hypothetical reduction in GHG emissions can be achieved by dividing the road network into lane-segments (the Caltrans PMS considers each lane separately, and a *lane-segment* is a length of one lane with a relatively homogenous pavement structure, climate region, and traffic) based on each segment's traffic volume, and then identifying an "optimized" IRI trigger value per lane-segment that minimizes the total GHG emissions resulting from the treatment process and the smoothness-induced fuel use improvement.

Note that the discussion above uses quotation marks with the term "optimized" because the optimization included in this study was derived empirically from simulations rather than from a formal closed-form optimization process, and because the optimization exercise had limited scope. The optimization performed by Wang and which is used in this study results in different IRI trigger values for different traffic levels. Lower IRI trigger values for segments with more traffic result in reduced emissions because the emissions resulting from doing the treatment are the same regardless of the traffic level compared to the current network-wide trigger value; however, the benefits of improved fuel use are a function of the number of vehicles using that pavement segment. The current IRI trigger values are kept for segments with lower traffic to maintain ride quality and acceptable vehicle operating costs for all segments on the network.

2.3 Scope of the Study

2.3.1 Scope for Implementation across the Network

This case study's objective was to evaluate the GHG emissions related to improvements in ride quality (mainly improvements to pavement roughness) by performing M&R activities on California's highway network. To accomplish this, data from the Caltrans pavement management system *PaveM* and the benefit/cost treatment prioritization tool *Pavement Analyst*™ (PA) were used. PA prioritizes maintenance treatments for road segments based on a benefit/cost analysis of pavement repair activities and timing. The study assumed that an unconstrained budget was available. For this analysis, the *benefit* was defined as the reduction in GHG emissions for the entire California highway network, and it was calculated by finding the difference between the GHG emissions that resulted over the analysis period after the treatment was performed—a quantity that included both the emissions due to construction and resulting from the improved surface condition—and the GHG emissions that would result by *doing nothing* (that is, by letting the road continue to deteriorate and become rougher). Two cases are evaluated:

- Case 1: Unlimited Budget Current IRI—This case assumes there are no budget constraints on M&R activities and triggers them based on an IRI of 170 inches/mile (2.68 m/km) each time a network lane-segment reaches that roughness value *(32).*

- Case 2: Unlimited Budget Optimized IRI—This case assumes there are no budget constraints on M&R activities and triggers them based on the optimized IRI trigger values below based on the traffic level on the lane-segment:
  - A network lane-segment with passenger car equivalent (PCE) less than 2,517: no IRI trigger value (no maintenance needed)
  - 2,517<PCE≤11,704: IRI trigger value of 177 inches/mile (2.8 m/km)
  - 11,704<PCE≤33,908: IRI trigger value of 127 inches/mile (2.0 m/km)
  - 33,908<PCE: IRI trigger value of 101 inches/mile (1.6 m/km)

Traffic levels are calculated in terms of PCE, where each truck is considered to be equal to 1.5 equivalent passenger cars *(33)*. The percentiles of PCE for the state highway network as of 2013 are shown in Reference *(34)*.

Table 2.1: Traffic Groups, Lane-Miles, and PCE Range

Traffic Group Number	Percentile (P) Range of Lane-Miles in the Cumulative Density Plot	Total Lane-Miles	Total Daily PCE Range
1	0<P≤25	12,068	0<PCE≤2,517
2	25<P≤50	12,068	2,517<PCE≤11,704
3	50<P≤60	4,827	11,704<PCE≤19,108
4	60<P≤70	4,827	19,108<PCE≤33,908
5	70<P≤80	4,827	33,908<PCE≤64,656
6	80<P≤90	4,827	64,656<PCE≤95,184
7	90<P≤100	4,827	95,184<PCE

The optimization of IRI triggering values is detailed in a UCPRC report *(23)*. The relationship between M&R spending (agency cost only) and pavement GHG emissions (from construction and vehicles) is explained in Appendix A.

2.3.2 Functional Unit and Graphical Representation of System Boundary

The functional unit for this study is defined as the M&R program of the California state highway network maintained at a target condition as defined in Cases 1 and 2, for an analysis period of 35 years where 2015 is Year 0 and 2049 is Year 35. The state highway network managed by Caltrans includes approximately 47,954 lane-miles (77,685 lane-km) of pavement, managed using the Caltrans PMS. These lane-miles are composed of 37,233 lane-miles of asphalt pavements and 10,721 lane-miles of concrete pavements *(16, 35)*. The concrete pavement consists primarily of jointed plain concrete, much of which was not built with dowels (construction prior to 2000), and some newer continuously reinforced concrete. The asphalt-surfaced pavements types include flexible (asphalt on granular base or subgrade), composite (asphalt on concrete), and semi-rigid (asphalt on cemented base), and some segments that have had full-depth reclamation (FDR) and cold in-place recycling (CIR).

Materials and construction during the M&R stage are included in the system boundary as shown in Figure 2.1. Treatments for concrete pavements include slab replacement, grinding, slab replacement with grinding dowel bar retrofit, concrete lane replacement, concrete overlays, and asphalt overlays. Treatments for asphalt-surfaced pavements include seal coats, thin to thick asphalt overlays, FDR, and CIR.

For Case 1, the current Caltrans decision tree IRI trigger value is used. For Case 2, the optimized IRI trigger values are used. Both cases considered GHG emissions due to maintenance activities during the M&R stage and from vehicles during the use stage. Full agency costs, per lane-mile, are taken from the Caltrans PMS database. User costs are not considered. The system diagram shown in Figure 2.1 also summarizes a list of data needs to run the analysis.

2.4 Calculation Methods

2.4.1 Major Assumptions

This study's results are based on Caltrans Automated Pavement Condition Survey (APCS) data reflecting the state of the network in 2017 as the starting point for the analysis. Because the purpose of the analysis is to evaluate a change in policy for triggering contracted maintenance and rehabilitation treatments in the PMS decision trees over an analysis period that is longer than the design lives of nearly all treatments, the results of the analysis should be valid for at least 10 years into the future.

The current PMS setup assumes zero traffic growth across the network over the analysis period. This is clearly not what should be expected over the analysis period but the assumption was made because the current PMS (Caltrans Performance Measurement System, PeMS) version cannot determine where demand is less than current lane capacity or where new lanes to increase capacity will be added.

The current analysis now also assumes there will be no changes in vehicle technology, such as a transition from fossil fuel vehicles to electric ones or to other alternative power technologies. This too is an unlikely scenario, but the assumption was made because the literature search found no studies about the effects of pavement roughness on electric vehicles, no good readily available information regarding likely vehicle transition paths, or information on adapting pavement management systems to consider vehicle type changes. Further, there were also no available studies on the pavement-damaging effects of electric vehicles and natural gas vehicles, which are heavier than gasoline and diesel vehicles.

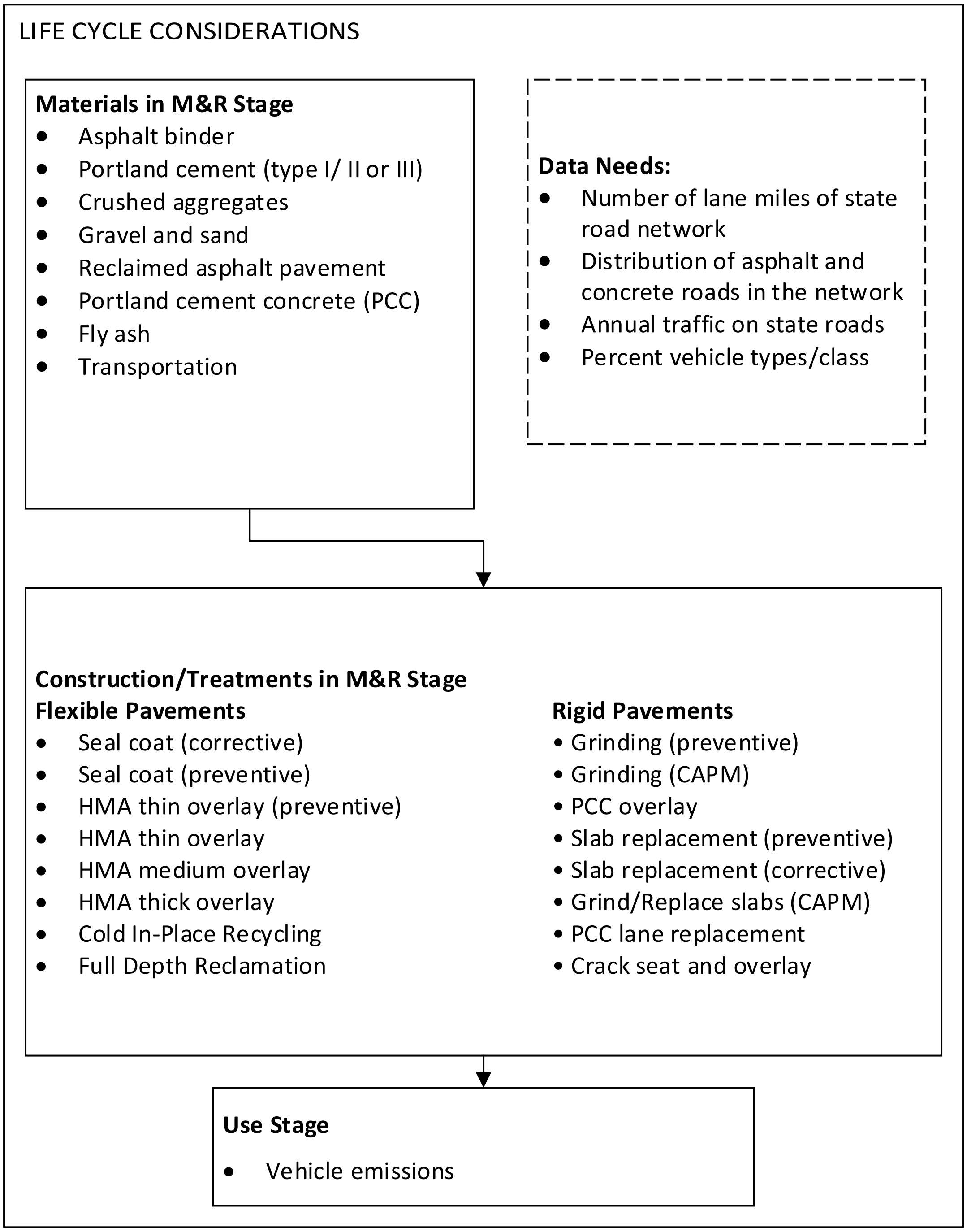

Figure 2.1: Scoping system diagram for life cycle (environmental impacts and cost) considerations.

For this analysis, the initial condition of the network based on the 2017 condition survey was used. "Fine" segmentation of the network was used, dividing the network up, lane-by-lane, into segments with similar traffic, climate, pavement structure, condition, and past construction history. Segment lengths are mostly less than one 1 mile (1.6 km).

The major assumption made for both Cases 1 and 2 is that state funding is unconstrained (that is, it was assumed that Caltrans can spend any dollar amount to maintain the California state highway network following the decision trees in the PMS). The major difference between the two cases is the selected IRI trigger value approach: For Case 1, a constant IRI trigger value for the entire network was defined, and for Case 2, the IRI trigger values were allowed change based on segments' traffic levels.

The optimized IRI trigger values for reducing GHG emissions were developed using data from the years 2010 to 2013, a time when Caltrans lacked sufficient funds to do many rehabilitation projects. Also, only the M&R treatments discussed above were considered because UCPRC had not yet developed a model for calculating the emissions from construction work zone (CWZ) traffic congestion (one has been completed since, as documented in Reference *[36]*) and CAPM treatments are primarily constructed at night to minimize traffic impacts. Currently, the PMS assumes that M&R activities are performed during nighttime, and this assumption of no CWZ traffic delay occurring was included in this study.

The models for calculating the effect of speed on fuel use employed in this strategic analysis assumed free-flow driving conditions, and that roughness has similar effects at different speeds and for different drive cycles. No information about the effects of roughness on fuel use—and therefore on GHG emissions—under any drive cycle other than free-flow conditions were found in the literature.

Drivers tend to drive faster on smoother pavements under free-flow conditions (*28*). This may result in increased vehicle fuel use, negating the purpose for which the pavements are made smoother. In this study, it was assumed that there are no changes in vehicle speeds on smoother pavement under free-flow conditions.

It was assumed that all pavement materials are recycled into some form of new pavement materials. The processing at end of life is part of the LCA analysis. The costs of removal and processing are included in the construction costs that are in the Caltrans pavement management system. They are not broken out because they are part of the bid cost of the contractor.

2.4.2 Calculation Methods

Caltrans' PA was used to run the two cases using the Caltrans PaveM database. The Caltrans PaveM database includes each treatments' estimated unit agency cost as shown in Table 2.2. The emissions factors data available in the PMS for the materials production, materials transportation, and construction stages for each treatment on a per lane-mile basis were used as the unit life cycle inventory (LCI) for each treatment. These unit LCIs and unit costs were then multiplied by the actual lane-miles of each lane-segment to calculate the total material production and construction LCI and cost whenever an M&R activity was performed. The factorial of CO_2 emission factors for each treatment is described in Appendix A, and details can be found in References *(23)* and *(24)*.

Caltrans uses a 4 percent discount rate in life cycle cost analysis (LCCA) calculations and that value was also used here *(37)*. Since the cost results that PA generates have not been programmed to include discount rates, a 4 percent discount rate was applied to the results after PA was run. Only agency costs, including those for management, are calculated in this study. Although road user cost savings from smoother pavements have not been calculated, they could be considerable due to reduced fuel use, less vehicle maintenance, and longer vehicle lives.

PA was run in the PMS for a 30-year analysis period (common Caltrans practice). The average of the results (costs and GHG emissions) of the last five years (Year 25 to Year 30) were carried forward for the analysis period's next five year (Years 30 to 35). The PMS is currently set up to only run 30-year analyses.

Table 2.2: Unit Cost for Each Treatment

Treatment	Cost per Unit
Slab Replacement – Preventive	$1,955,000 per lane-mile (multiply by percent of slabs replaced)
Slab Replacement – Corrective	$1,955,000 per lane-mile (multiply by percent of slabs replaced)
Seal Coat – Preventive	$50,000 per lane-mile
Seal Coat – Corrective	$65,000 per lane-mile
Grinding – Preventive	$85,000 per lane-mile
HMA Thin Overlay	$120,000 per lane-mile
HMA Thin Overlay – Preventive	$120,000 per lane-mile
HMA Medium Overlay	$260,000 per lane-mile
HMA Thick Overlay	$600,000 per lane-mile
Cold In-Place Recycling	$345,000 per lane-mile
Cold In-Place Recycling – Class 3	$312,500 per lane-mile
Full-depth Reclamation	$726,154 per lane-mile
Grinding – CAPM	$131,250 per lane-mile
Grind/Replace Slabs – CAPM	$265,000 Replace and grind slabs
PCC Lane Replacement	$1,769,231 per lane-mile
PCC Overlay	$1,400,000 per lane-mile
Crack Seat and Overlay	$1,000,000 per lane-mile

Note: HMA =hot mix asphalt; PCC = portland cement concrete; CAPM = capital preventive maintenance

2.4.3 Data Sources and Data Quality

The major data life cycle inventory sources for pavements include the pavement LCI produced by Stripple et al. *(38)* in Sweden, the asphalt inventory produced by the Athena Institute in Canada *(39)*, EcoInvent *(40)*, the US Life Cycle Inventory produced by the National Renewable Energy Laboratory *(41)*, and the cement LCI study by the Portland Cement Association (PCA; *42*). These data sources for materials are more than five years old, and are currently being updated for inclusion in the Caltrans PMS in late 2019.

A data quality check is necessary for interpreting the analysis results with an appropriate level of certainty. Table 2.3 shows the data assessment used for the analysis. The scoring in the table is based on the recommendations of the FHWA pavement LCA framework document and on ISO standards *(15, 35, 43)*.

2.4.4 Limitations or Gaps

Following are details about the study's data gaps and limitations. Because of these gaps and limitations, the results from this study should be considered as preliminary only.

A major assumption for both of the cases considered is that there are no constraints on state funding for the M&R activities determined by the decision trees. Historically, this is far from the reality, but passage of California State Senate Bill 1 *(44)* in 2017, which increased the state motor vehicle fuel tax, and rejection of the law's repeal in a 2018 election, have provided approximately $1.5 billion for the State Highway Operations and Protection Program. These funds are to be used for M&R on the state highway network, and have been considered here as an unlimited budget to help identify how much funding would be needed to perform all the treatments called for by the decision trees for the two cases.

Another limitation is that the original scope for the development of the optimized IRI trigger values used in Case 2 was applicable to 2010 to 2013, a time when Caltrans lacked sufficient funds to undertake many rehabilitation projects and only considered a restricted set of its most common treatments when determining optimization. For asphalt-surfaced pavements, these treatments included the use of thin- and medium-thickness asphalt overlays, and for concrete pavements they included either slab replacement using rapid strength concrete followed by diamond grinding, or a few concrete lane replacements using typical Caltrans paving concrete for badly damaged segments. The emissions factors used for both cases' models were calculated considering Caltrans use of significant amounts of both rubberized asphalt mix for its asphalt overlays and supplementary cementitious materials in its ordinary paving concrete.

Other important factors not considered in the study include these: the effects of change in vehicle speeds on fuel economy, and therefore on GHG emissions, the effects that construction work zones (CWZ) have on congestion, and any effects due to the interaction of roughness and drive cycle (instead of the free-flow conditions assumed in the fuel economy models' development).

Table 2.3: Data Quality Assessment

Categories	Data Sources	Data Quality							
		Reliability	Geography	Time	Technology	Completeness	Reproducibility	Representativeness	Uncertainty
Data Type									
Lane-miles of state network	Caltrans/ PaveM	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Pavement Types	Caltrans/ PaveM	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Average pavement thicknesses	Caltrans/ PaveM	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Annual traffic	Caltrans/ PaveM	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Percent vehicle types/class	Caltrans/ PaveM	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Pavement condition	Caltrans APCS data	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
LCA-Related									
Asphalt	Athena Institute *(39)*	Good	CDN/US	Poor	Very Good	Poor	Yes	Yes	High
Cement	Marceau *(42)*	Good	US	Poor	Very Good	Poor	Yes	Yes	High
Other materials	Stripple *(38)*/ Wang 2013 *(34)*	Good	SE/US	Poor	Very Good	Fair	Yes	Yes	High
Other materials	EcoInvent *(40)*	Good	SW	Poor	Very Good	Fair	Yes	Yes	High
Other materials	USLCI *(41)*	Good	US	Poor	Very Good	Fair	Yes	Yes	High
Material and treatment factors	Wang 2013 *(34)*/ PaveM	Good	US	Fair	Very Good	Fair	Yes	Yes	Low
Cost-Related									
Agency costs	PaveM	Very Good	US	Good	Very Good	Good	Yes	Yes	Low
Discount Rate	Caltrans	Good	US	Good	Very Good	Good	Yes	Yes	Low

This analysis did not consider the traffic flow changes through CWZs during treatment construction, even though these can impact GHG emissions, and it assumed that Caltrans performs work at night so no CWZ traffic delays occur.

Although Caltrans performs the majority of its construction work using nighttime closures, this is not always the case. And it has been found that the presence of a CWZ on a given segment can either increase or decrease the emissions levels prevailing when there is no CWZ. For example, when congestion forces traffic to operate with stop-start drive cycles, this often increases GHG emissions, although the amount of the increase depends on vehicle speeds when there is no CWZ. However, when a CWZ slows traffic from higher speeds to a steady one of about 45 mph (75 km/hr), then GHG emissions are reduced.

The study also assumed that vehicle speeds remained the same before and after a pavement treatment reduced roughness. The literature found regarding driver behavior up until the year 2013 was primarily based on statistical analysis that did not consider before- and after-treatment measurements at the same location; this literature showed that drivers traveled at higher speeds on the smoother pavement. However, in two earlier UCPRC reports *(27, 28)*, the results of vehicle speed analyses at the same locations on California freeways before and after treatment showed driver behavior to be less sensitive to pavement smoothness (0.2 to 0.6 mph [0.3 to 1.0 km/hr] change for typical changes in IRI) than previous studies had. In general, it was found that increases in free-flow speed higher than 46.6 mph (75 km/hr) result in greater fuel use and GHG emissions. The effects of speed on fuel use—and therefore on GHG emissions—differ from vehicle to vehicle; vary under different air temperatures, which affects the aerodynamic drag effects of speed; and change under different congestion conditions. A rough estimation from the literature *(45)* is that a 1 mph (1.6 km/hr) speed increase will raise CO_2-e emissions from automobiles by about 2.4 percent at high free-flow speeds and that truck fuel use can be even more sensitive *(46)*. The earlier UCPRC traffic speed study did not separate the results from trucks and automobiles, but it did show that vehicles in the outer truck lanes were less sensitive to speed changes than vehicles were in the inner automobile lanes, with a range of values for these effects as low as a 0.3 percent change in automobile fuel use for each 1 mph (1.6 km/hr) speed increase *(47)*.

No studies on the effects of roughness on fuel use under conditions other than free flow were found in the literature. Consequently, the models used in this strategy analysis were developed under free-flow driving conditions, and it was assumed that roughness would have the same effects under different drive cycles.

Although small, these changes in speed are of an order of magnitude similar to the changes in fuel economy from changes in IRI, and therefore they should be included in updates of the optimized IRI trigger values and GHG calculations in the Caltrans PMS. Much of the traffic in California occurs in non-free-flow conditions, and the effects of changes in roughness on speed changes under those conditions should also be explored.

This study considered only one environmental impact: GWP. The study's scope could be broadened to include other environmental impacts such as noise, particulate matter ($PM_{2.5}$), water, and others, and several other social and cost indicators could also be included in such an analysis. In its analysis of costs, the study only used agency cost although user costs could give a better picture of how total LCCs are affected (other costs such as insurance, vehicle damage, and risk costs were not considered). Some of the social and environmental issues and other cost considerations not included in the system boundary are safety, vehicle depreciation/damage considerations, job creation, noise, accidents, freight damage, applicability (available funds, practicality), effects on vehicle life (less damage/longer life), cost of risk (causality/loss cost), and effects on the market (more vehicles on road).

2.5 Results and Discussion

2.5.1 Numerical Results from Case Study

Caltrans' annual cost to perform M&R activities based on its current IRI triggering value and the optimized IRI triggering value results are plotted in Figure 2.2. Initial costs in the first two years are high because they include the costs required to eliminate the backlog of triggered segments that built up earlier under highly constrained budgets, but during the next several years (that is, after the backlogged segments have been treated) costs are much lower. Over the remainder of the 30 years, costs for triggered projects rise and fall as they develop cracking and become rough. As noted earlier, the cases' final five years were taken from average values from years 25 through 30.

Figure 2.3 shows the annual GHG emissions over the 35-year analysis period for Cases 1 and 2 resulting from materials and construction during the M&R stage, and Figure 2.4 shows annual GHG emissions from the use stage (vehicle operation). Case 2 (optimized IRI) shows higher GHG emissions peaks in several years (Figure 2.3) because lower IRI trigger values have resulted in more frequent M&R activities occurring; however, over the 35-year analysis period, there are fewer treatment-related emissions for the optimized IRI trigger values than for the current value. The GHG-reduction benefit from use stage emissions reductions due to the better fuel economy on smoother pavements can be seen in Figure 2.4. Table 2.4 presents a summary of agency cost, GHG emissions, and the cost-effectiveness of GHG reductions for a 30-year analysis period, a 35-year analysis period with the Year 25 to 30 averages projected over the last five years, and a 35-year analysis period including the 30-year average projections projected over the last five years.

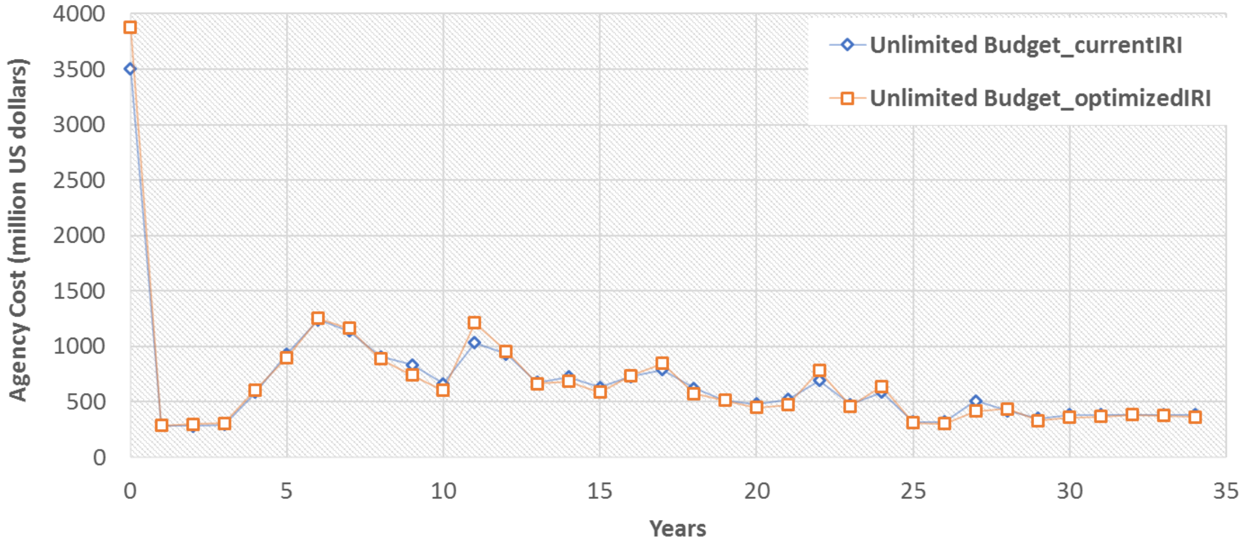

Figure 2.2: Agency cost (million $) versus analysis time for the two cases (4 percent discount rate included).

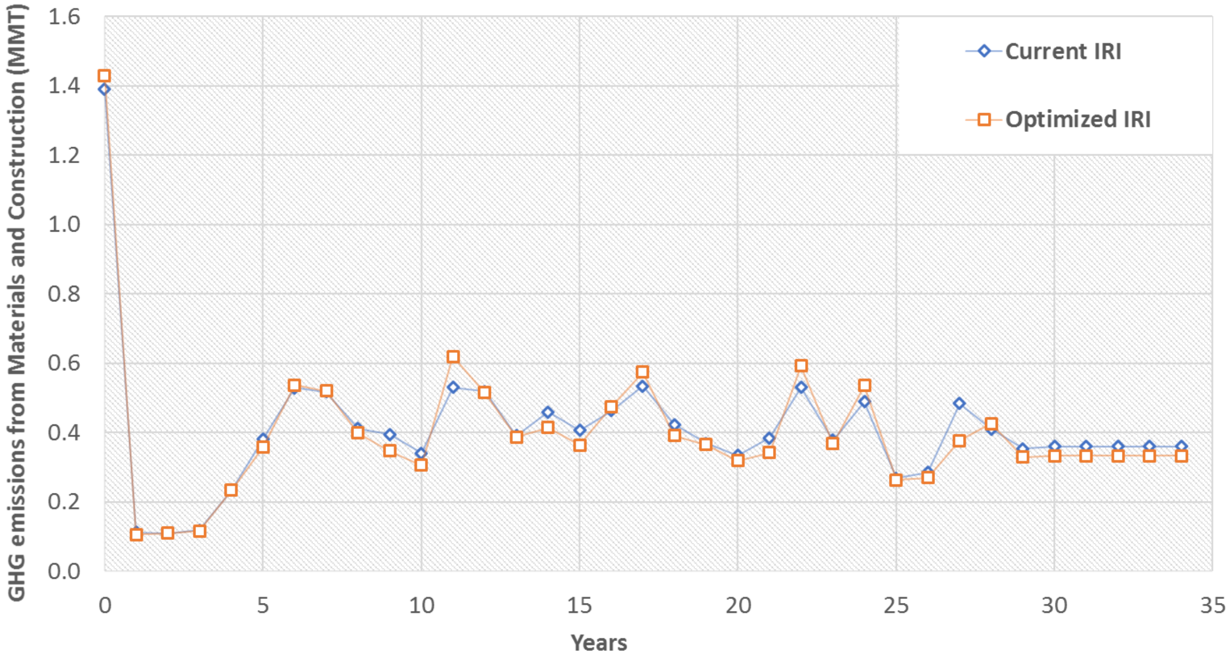

Figure 2.3: Annual GHG emissions due to material and construction in M&R stage for Cases 1 and 2.

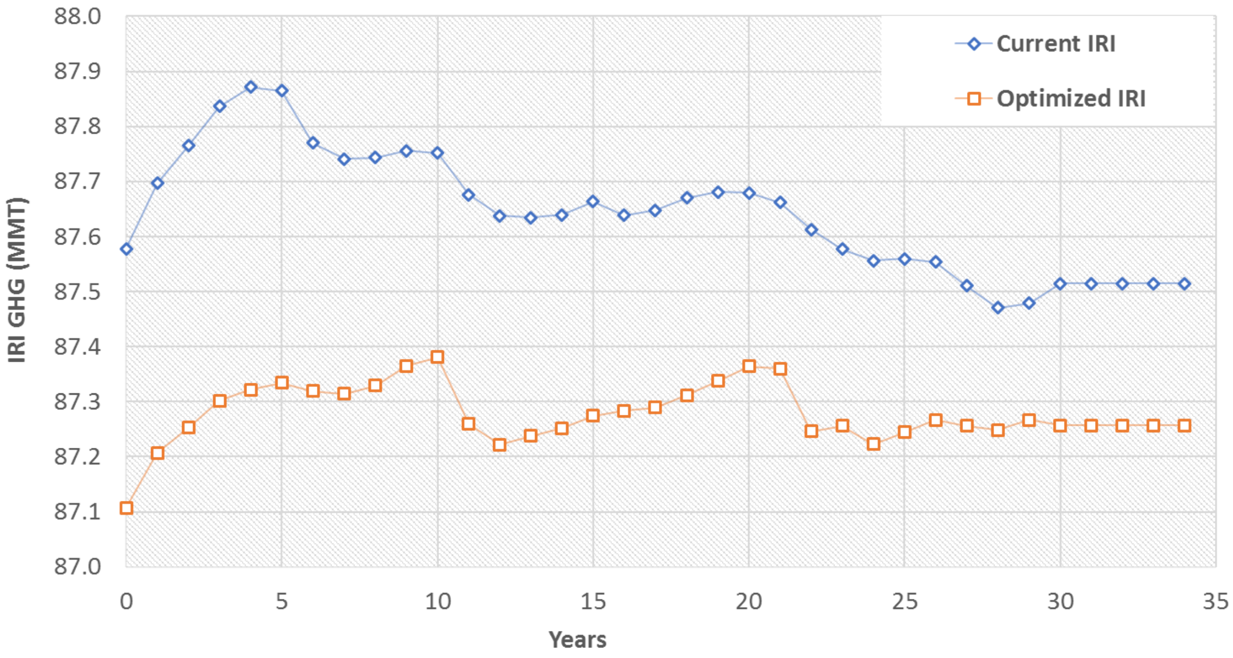

Figure 2.4: Annual GHG emissions during the use stage (vehicle emissions) for Cases 1 and 2.

Table 2.4: Agency Cost, GHG Emissions, and Cost-Effectiveness Summary

	Analysis Period (years)	**Case 1: Current IRI Agency Cost (million $)**	**Case 1: Current IRI GHG (million tonnes)**	**Case 2: Optimized IRI Agency Cost (million $)**	**Case 2: Optimized IRI GHG (MMT)**	**Costs Case 2 – Case 1 (million $)**	**GHG Change Case 2 – Case 1 (million tonnes)**	**Agency Cost Effectiveness ($/tonne of GHG emissions)**
PaveM results	30	21,994	2,642	22,277	2,631	283	-11.65	24.3
PaveM results + last 5 years average carried forward up to 35 years	35	23,907	3,082	24,125	3,069	216	-13.07	16.5
PaveM results + 30 years average carried forward up to 35 years	35	25,660	3,083	25,990	3,069	330	-13.59	24.3

Note: 4 percent discount rate applied to the costs

Table 2.4 shows that implementing the Case 2 optimized IRI triggering values would result in extra Caltrans spending of $216 million over the 35-year analysis period (using the averages of the last five years in the 30-year analysis period projected over the last five years of the 35 years). The total agency cost for Case 1 (current IRI triggers) was calculated to be $23.9 billion whereas that for Case 2 (optimized IRI triggers) was $24.1 billion. When the last five years' projections are not considered, it will cost Caltrans $283 million extra to implement Case 2. When the 30-year agency cost averages are projected to the last five years of the 35-year analysis period, the results show that the Case 2 implementation will cost Caltrans an additional $330 million.

The total GHG emissions due to rough pavement for Case 1 are 3,082 MMT and for Case 2 they are 3,069 MMT over the 35-year analysis period (with the last five-year averages of the 30-year analysis period projected over the last five years of 35 years). The GHG emission reductions from implementing Case 2 over the 35 years are 0.3 MMT and 12.7 MMT for materials and construction, and the use stage, respectively. Both, the 30-year and 35-year (with 30-year average projections over the last five years) analysis periods show that it will cost Caltrans $24.3 per tonne of GHG reduction as shown in Table 2.4.

2.5.2 Implications for Total Abatement Potential

According to the results shown in Figure 2.5, by switching to the Case 2 approach (optimized IRI triggers) from the Case 1 approach (current IRI trigger), Caltrans would reduce its total GHG emissions (GHG from materials, construction, and vehicles) in the range of 0.2 to 0.55 MMT annually over the 35-year analysis period. Cumulative GHG emission reductions of 13 MMT and 11.65 MMT can be achieved for the 35- and 30-year analysis periods, respectively. The agency cost-effectiveness of reducing GHG emissions by 1 tonne was calculated to be $16.5 if Case 2 were implemented. However, it should be noted that the effects of vehicle speed on fuel economy and user costs have not been considered in this analysis. It is expected that vehicle speed changes from smoother pavement would result in smaller use stage GHG emissions reductions than are shown here, and this would increase the cost per ton of GHG reduced. Taking construction work zones into account might either increase or decrease use stage GHG emissions, depending on whether the work zones reduce traffic speeds to about 45 mph, or cause congestion.

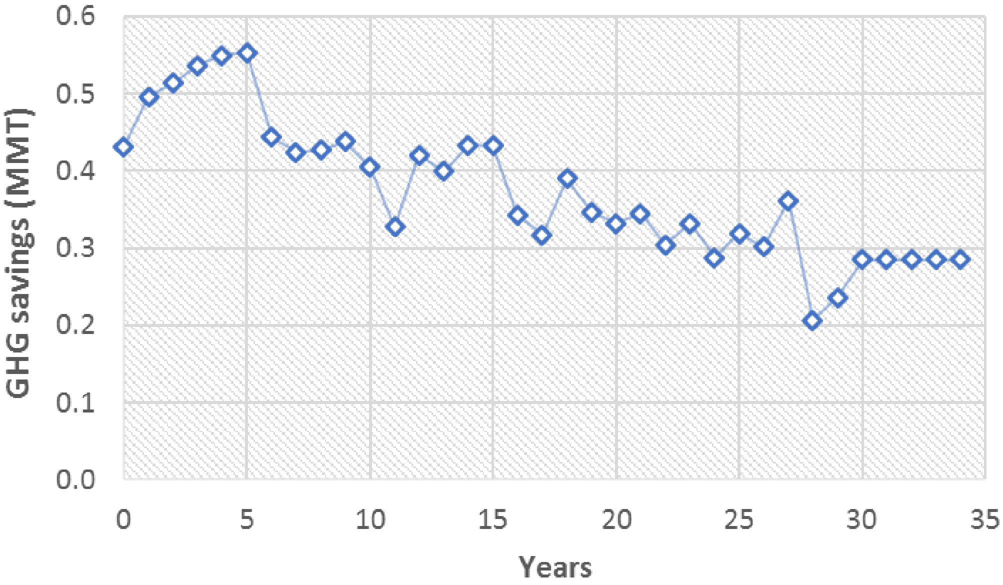

Figure 2.5: Annual GHG savings over the 35-year analysis period if Case 2 is implemented.

2.5.3 Time-Adjusted GHG Emissions

Adopting optimized IRI triggering values (Case 2) would result in approximately 3,069 MMT of GHG emissions over the 35-year analysis period. However, using TAWP instead of GWP, the result for the 100-year analytical time horizon is calculated to be 2,650 MMT. The total GHG emissions reduction due to implementation of Case 2 versus Case 1 can result in around 11.5 MMT when the time adjusted GHG emissions methodology for the 100 years analytical time horizon is used. The difference between the TAWP and GWP results for this strategy reflects the fact that the GHG emissions reductions are achieved in small annual increments over the entire analysis period.

2.5.4 Summary of Abatement Potential Information

The information regarding the abatement potential calculations presented in this chapter is summarized in Table 2.5 for a 35-year analysis period.

Table 2.5: Summary of Abatement Potential for Fuel Use Reductions through Pavement Network Roughness Management

	35-Year Analysis Period				Average Annual over 35-Year Analysis Period		
	CO_2-e Change (MMT)	**Time-Adjusted CO_2-e Change (MMT)**	**Life Cycle Cost Change ($ million)**	**Cost/Benefit ($/tonne CO_2-e reduced)**	**CO_2-e Change (MMT)**	**Time-Adjusted CO_2-e Change (MMT)**	**Life Cycle Cost Change ($ million)**
Five-year (years 25 to 30) average projected to last five years of 35-year analysis period	-13.1	-11.5	216	16.7	-0.37	-0.33	6.2
30-year average projected to last five years of 35-year analysis period	-13.6	-11.9	330	24.6	-0.40	-0.34	9.4

3 STRATEGY 2: ENERGY HARVESTING USING PIEZOELECTRIC TECHNOLOGY PER 100 LANE-MILES OF INSTALLATION

3.1 Strategy Statement and Goal

Over the last ten years, energy harvesting from pavement has attracted increased attention from the media, from government agencies and policy-makers, and from researchers and engineers. The various proposed energy-harvesting technologies can broadly be grouped into those that capture photovoltaic energy hitting the pavement, those that capture thermal energy from the pavement, and those that capture mechanical energy from vehicles operating on the pavement *(48)*.

After extensive publicity in the media regarding several companies proposing to implement technologies using piezoelectric devices embedded in the pavement to capture energy from passing vehicles, Assembly Bill 306 (2011), titled "B-306 Energy: piezoelectric transducers: study," was introduced and passed by the legislature but was then vetoed by the governor *(49)*. Following the veto of the bill, in 2014 the California Energy Commission subjected the technology to a readiness evaluation based on available information in the literature *(50)*. The CEC evaluation concluded that "Until the power output per module is transparently quantified, cost-of-energy estimates will contain inherent uncertainty. With the information currently available, it appears that power densities of 300 W/ft^2 or more are needed to approach the economic viability claimed by vendors. The results of this research indicate a demonstration and further evaluation of the technology should attempt to quantify the power output, durability, and lifetime of the system in addition to its performance as a function of traffic volume is warranted." Based on that conclusion, the CEC funded a pilot project with UC Merced that started in May 2017 and is expected to be completed in December 2020 *(51)*.

In this case study, one of the pavement energy harvesting technologies is examined: placement of piezoelectric devices in a pavement to capture the mechanical energy from passing vehicles and converting that energy into electrical energy to offset other electricity produced by methods presumed to be more carbon intensive. The information used to evaluate this strategy comes from a number of previous studies that have examined piezoelectric energy-harvesting technologies.

3.2 Introduction

3.2.1 Background and Policy Context

Increased renewable energy production is required to wean California from fossil fuel. The state has set electricity generation mix goals of 25 percent renewable energy by 2025 and 50 percent by 2030, yet the current percentage of renewables in the grid mix is about 18 percent. Therefore, it is imperative to explore additional forms of renewable-energy generation. One opportunity for renewable-energy generation from roadway infrastructure is the use of piezoceramics for in-pavement energy harvesting. This relatively new technology has seen limited application around the world. Piezoelectric energy harvesting from installation of devices in the pavement is currently a topic of research at the University of California, Merced funded by the California Energy Commission *(52)*. Results from this research are not yet published.

As of this writing, piezoelectric energy-harvesting is not being used anywhere in California, although piezoelectric technology is currently being used to weigh truck axles at one site out of 106 weigh-in-motion (WIM) systems installed in its highway network *(53, 54)*. WIM measure axle loads at highway speeds, unlike California Highway Patrol load stations which use static or low-speed scales.

3.2.2 Abatement Strategy or Technology

Compression-based piezoelectric generation has been explored as an in-pavement energy generation approach for at least the past decade. The technology consists of a piezoceramic sensor composed of lead zirconate titanate (hence, PZT) that generates a voltage when compressed. Individual PZT sensors can be housed together to create a larger piezoelectric transducer. By embedding a row of PZT transducers in a highway pavement, the traffic passing over the transducers generates a voltage difference that can be harvested for various functions as illustrated in Figure 3.1.

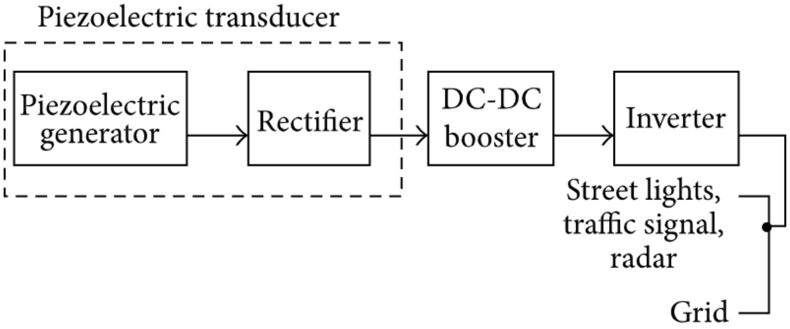

Figure 3.1: Piezoelectric generator and system components *(55)*.

Earlier research has compared the effectiveness of different piezoceramics *(56)*, designed ceramic caps to optimize output and stiffness consistency between the sensor and roadway materials *(57)*, and quantified output under varying loads *(58)*. Other studies have looked at the feasibility of this technology for powering small roadside loads like street lights and traffic signals *(59, 60)*. These studies have concluded that the ideal sensor installation depth below the pavement surface is two inches. Roashani et al. found that installing the sensors two inches (50 mm) deep rather than on the pavement surface is beneficial because embedding them protects them from damage by direct contact with tires but still allows them to achieve 90 percent of maximum energy generation *(61)*. Roshani et al. also conducted a laboratory study to investigate the effect of temperature (40 to 104°F) on the sensors' power output and found it to be insignificant.

A 2014 study examined the large-scale energy production capabilities of in-pavement piezoelectric technologies, concluded more research was needed on this technology, and provided no clear conclusions on the effectiveness or readiness of the technology *(62)*. However, a more recent study attempted to model the output of one lane-kilometer of a road embedded with piezoelectric transducers *(55)*. The study developed a Matlab model that included specifications for the PZT sensors used, efficiencies of the various output adjusters seen in Figure 3.1, vehicle weights, and traffic rates. A sample of their results (which were referenced in the current study) can be seen in Table 3.1.

Table 3.1: Hourly Energy Generation of PZT Technologies According to the Hourly Traffic Rate and Average Speed of Travel as Determined by the Model Developed in Reference *(55)*

Duration	Traffic Rate/hr	Speed of Travel (km/hr)	Energy Generated (KWhr)
Peak time	500	60	74
		80	137
		100	254
		120	469
	300	60	61
		80	106
		100	183
		120	281

This current study combines the outputs of Najini's model *(55)* with a life cycle approach to determine the life cycle emissions and costs of a piezoelectric road.

3.3 Scope of the Study

This study examines the net life cycle GHG reduction potential and LCCs of deploying piezoelectric technology in California's roadway network. The GHG-reduction potential is a function of site conditions where the technology is deployed.

3.3.1 Scope for Implementation across the Network

In-pavement piezoelectric energy generation is a function of traffic load and speed. Electricity generation from these sensors depends on the vehicle weights, vehicle speeds, and the number of passes. When intended for integration with the grid, these systems are ideally located in areas of high traffic volumes, low congestion, and proximity to utility power lines. Further, it is recommended that the sensors be placed in the outer lane (truck lane) to ease installation and to minimize installation-related delays. This study assumes that in-pavement piezoelectric technology can be installed at several locations across California's state highway network, over a total of 100 lane-miles.

3.3.2 Functional Unit and Graphical Representation of System Boundary

The functional unit for this study is the implementation and operation of in-pavement piezoelectric energy generation infrastructure for 100 lane-miles over 35 years, from 2015 through 2050. This is compared to a business-as-usual (BAU) case of not installing piezoelectric technology and proceeding with regularly-scheduled pavement maintenance without the additional capacity for energy production. The environmental impacts of GHGs are reported in metric tons (tonnes) of carbon dioxide equivalent (CO_2-e). The life cycle stages considered in this study are the material production stage, the use (operation) stage, and the end-of-life stage, as shown in the system boundary diagram (Figure 3.2).

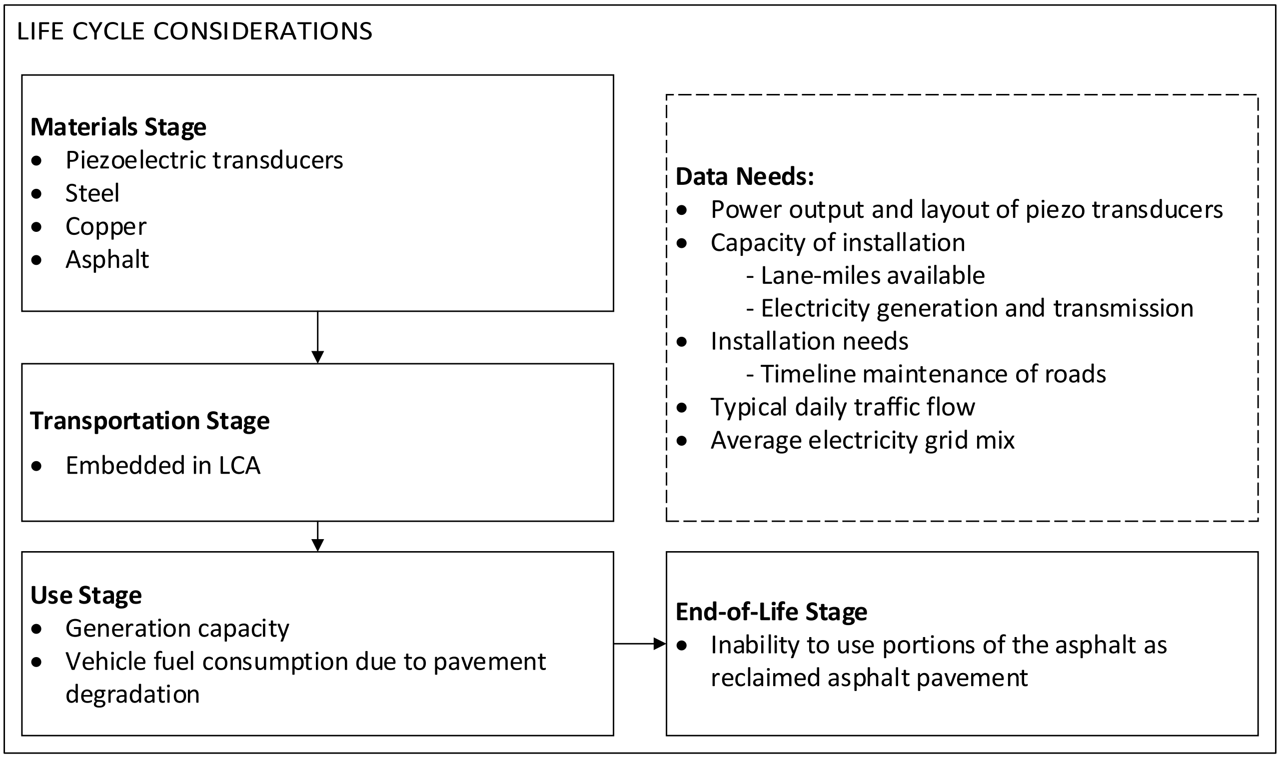

Figure 3.2: Scoping system diagram for life cycle (environmental impacts and cost) considerations.

3.4 Calculation Methods

3.4.1 Major Assumptions

The first major assumption is that the model for the power output of the technology developed by Najini et al. *(55)* is reliable; very few studies have explored the potential for large-scale piezoelectric energy production, and fewer have published unbiased results. While that study was not necessarily robust, it was better than most other studies found. Therefore, while uncertain, it was assumed that the numbers published by the study were at least somewhat reliable.

The following three assumptions made were also made for the current study:

- That installation of the transducers and the required wiring coincides with planned pavement repair, thus no additional planning or demolition is assumed to be needed except when connecting to the grid. It is also assumed that the PZT sensors last the duration between large pavement repair projects (20 years) with negligible performance degradation; a study by Sherrit et al. *(63)* showed that PZTs can still perform well after being compressed 10 billion times, which is at least two orders of magnitude higher than the amount of compressions in-pavement PZTs would experience in 10 years; a follow up study by the same author *(64)* tested PZT stacks through up to 100 billion cycles and found a performance reduction of 3 to 4 percent.
- It is assumed that the material extraction production impacts of the DC-DC booster and the inverter are negligible.
- It is assumed that that use of Gauge 2 copper wire is appropriate for collecting the power output from each piezoelectric transducer per lane-mile.

The published energy outputs of the model reference for a specific set of traffic rates and velocities ranged from 50 to 500 vehicles per hour and 37.5 to 75 miles per hour, respectively. The case study completed for this project was for a section of Interstate 580 in Berkeley, California. The I-580 traffic was assumed for all 100 miles of installation on nearby highways as well, although I-580 is shorter than 100 miles. The traffic velocity acquired from the Caltrans Performance Measurement System (PeMS) was approximated to match the specific intervals used in the reference model, and the output for a given traffic rate was interpolated from the outputs at that given speed. In cases where the traffic rate exceeded 500 vehicles, the energy generation was capped. This was justified because (1) these high traffic rates occurred at congested (not free-flow) speeds, and (2) the references study indicated that at high traffic loads with low speeds, not every vehicle can affect a PZT transducer—with 500 vehicles per hour traveling at 75 miles per hour, the traffic load rate is 444 instead of 500. Therefore, especially at high traffic rates and low speeds, the traffic load rate was assumed to be constant.

3.4.2 Calculation Methods

Materials and Installation

The referenced model by Najini et al. *(55)* provides dimensions for each piezoelectric transducer that was used to estimate the quantity of PZT ceramic and steel required per transducer. Each transducer has two, 1 cm-thick steel caps with sixteen, 2 cm-long PZT "piles" (cylinders) between them. Each pile has a radius of 1.5 cm, and the steel caps are squares of 20 cm length. There was presumed to be an unspecified amount of plastic used to encase the structure, but since there was not enough information this was not included in this study's calculations. As mentioned previously, Gauge 2 copper wire was used as connection wiring within the pavement, and between the transducers and the rest of the system. Thus, the amount of copper needed was also quantified. Because the installed materials displace asphalt, the resulting reduction in asphalt-related life cycle impacts was considered.

Each installation also requires a connection to the grid. Some utilities offer free grid connection if the source is less than 150 feet from the closest hookup point. However, it is likely that these hookup points will be further away from the piezoelectric installations. Therefore, a new half-mile underground power line installation was considered for every mile installed. One source suggests that a new 69 kilovolt underground line costs $1.5 million *(65),* and this additional cost was included as part of the initial installation cost. This study also accounted for the GHG emissions produced to provide the copper used in the power lines; a specification sheet was referenced to estimate the total amount of copper required *(66)*.

The installation rate was assumed to be 20 miles per year, such that 100 miles are installed by the fifth year. This analysis considered data for one mile and multiplied those results accordingly to assess what deployment would look like. Installation was assumed to overlap with scheduled major road maintenance, which occurs every 20 years. This means that 20 years after the first installation, the road would be fully milled, which would result in the removal of the in-pavement devices, so they would then need to be installed again. Note that the costs for the second round of installations do not include the cost of connecting to the grid, as that was completed during the first round of installations. A 4 percent annual discount rate is included in LCC calculations.

It was assumed that most metal parts of the devices would be recycled on replacement. The costs and environmental impacts of landfill of parts not recycled were assumed to be minimal and were not included. No data were available to provide an alternative assumption. Because the grid connections are expected to remain well beyond the end of the analysis period, no environmental or cost impacts for removal and disposal were included.

Operation, Energy Generation, and Maintenance

To estimate energy generation, the traffic rate and average speed were acquired through PeMS for a section of Interstate 580 in Berkeley, California; hourly traffic data with different rates and speeds for average weekday and average weekend were used. Average daily traffic was assumed to be 20,000 vehicles per lane, with an average flow rate of 416 vehicles per hour per lane. As noted, the recommended transducer installation depth is 2 inches below the pavement surface. However installing the transducer at this depth will affect certain pavement surface rehabilitation methods, such as partial mill and fill. Therefore, this study considered installation at 4 inches below the pavement surface, a depth that has been shown to decrease piezoelectric output by about 25 percent *(67)*.

In a normal maintenance setup, a pavement's top 4 inches (100 mm) are milled and sent for inclusion in reclaimed asphalt pavement (RAP) projects. However, for this study it was assumed that the 2 inches of pavement that include the piezoelectric installation would be sent to a landfill instead because current technology mills the entire lane. This study accounts for the reduced benefits attributable to the lost asphalt pavement surrounding the piezoelectrics that cannot be used for RAP. Because the amount of RAP is finite, the analysis considers that the pavement that cannot be included in RAP must instead be replaced by new crushed aggregate and bitumen, the two primary components of hot mix asphalt. The resulting increase in GHG emissions is accounted for.

Electricity on the Grid

The grid's carbon intensity was determined using the expected grid mix over time developed as part of the US Energy Information Administration's (EIA) *Annual Energy Outlook (68)*, combined with the emissions values per fuel source outlined in the GREET 1.0 model *(69)*; the emissions values per kWh of electricity were calculated through the year 2050. Since the price of generated electricity is uncertain, two prices were used. Under a high-price case, utilities would provide net-metering benefits, an arrangement in which the energy generated by the piezoelectric installations is used to offset electricity charges that Caltrans incurs elsewhere across the state, including the electricity used by buildings, for illuminating highways, and more. A price of $0.152 per kWh was used for this case, which is the average electricity price across all California sectors, according to a report released by the EIA *(70)*. Under a low-price case, utilities would purchase the electricity at the significantly lower rate, specifically between $0.03 and $0.04 per kWh, set by the California Public Utilities Commissions *(71)*. A value of $0.035 per kWh was used for this case. However, since the state has many utilities and they charge differently for electricity, and since each can decide to use one of these approaches or to combine them, the results provide a cost range bounded by what the strategies would achieve if they were deployed.

That is, in the high electricity price case, all the generated electricity would sell for $0.152 per kWh, and the installation would achieve a maximum economic benefit. In the low electricity price case, all the electricity would sell for $0.035 per kWh, and the installation would achieve the smallest economic benefit. In both cases, all other costs remain constant.

3.4.3 Data Sources and Data Quality

Data were acquired for various key materials' life cycle impacts in terms of the GHGs produced in different life cycle stages; these stages include raw material acquisition, material refining and processing, transportation, and end-of-life. The life cycle impact per kilogram of PZT ceramic was acquired from a study by Ibn-Mohammed et al. *(72)*. The life cycle impacts for one kilogram of steel (region: Global) and copper (region: North America) were taken from the EcoInvent database *(73)*. The life cycle impacts of HMA overlay were acquired from a study by Saboori et al. *(74)*. Prices for the PZT material were acquired from APC International, a major supplier of piezo products. The cost for the "772 Disk" PZT ceramic was $18.00. The ceramic is of the proper dimensions but there is no wiring or other processing of the material to make it suitable for this study's purposes, nor is there a bulk price; therefore, there is uncertainty about what its true cost would be. The GHG impacts and costs for each material are summarized in Table 3.2. The data quality assessment is presented in Table 3.3.

Table 3.2: A Summary of the Life Cycle Environmental Impacts and Cost of Key Materials

Material	**GHG Impact (kg CO_2-e)**	**Cost (2018 USD)**
PZT Ceramic	25.34 per lb (55.74 per kg)	$41.8 per in^3 ($2.55 per cm^3)
Steel	1.15 per lb (2.54 per kg)	$0.40 per lb ($0.89 per kg)
Copper	2.53 per lb (5.57 per kg)	$2.02 per lb ($4.44 per kg)
Hot mix asphalt	0.103 per ft^3 (3.62 per m^3)	$72.72 per ton ($80.00 per tonne)
California Electricity (Avg.)	$240.36 per MWh	$152.30 per MWh

Table 3.3: Data Quality Assessment

Categories	Data Sources	Data Quality							
		Reliability	**Geography**	**Time**	**Technology**	**Completeness**	**Reproduc--ibility**	**Represen-tativeness**	**Uncertainty**
Data Type									
Energy generation model	Najini et al. *(55)*	Poor	Middle East	Good	Fair	Fair	Yes	No	High
Piezoelectric Transducer materials	Najini et al. *(55)*	Poor	Middle East	Good	Fair	Fair	Yes	Yes	High
Traffic Speeds and Vehicle Passes	PeMS	Very Good	I-580 Berkeley	Very Good	Very Good	Very Good	Yes	Yes	Low
LCA-Related									
PZT Ceramic	Ibn-Mohammed *(72)*	Good	EU	Good	Very Good	Very Good	Yes	Yes	Low
Steel	EcoInvent *(73)*	Good	Global	Fair	Very Good	Fair	Yes	Yes	High
Copper	EcoInvent *(73)*	Good	US	Fair	Very Good	Fair	Yes	Yes	High
Hot mix asphalt	Saboori et al. *(74)*	Very Good	US	Very Good	Very Good	Very Good	Yes	Yes	Low
Electricity	US EIA *(70)*	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Cost Related									
PZT Ceramic	APC International	Very Good	US	Very Good	Very Good	Good	Yes	Yes	High
Steel and Copper	Focus Economics *(75)*	Good	US	Very Good	Very Good	Good	Yes	Yes	Low
Hot mix asphalt, RAP	Saboori et al. *(74)*	Very Good	US	Very Good	Very Good	Very Good	Yes	Yes	Low
Electricity	US EIA *(70)*, CPUC *(71)*	Very Good	US	Good	Very Good	Good	Yes	Yes	Low
Grid connection	Alonso and Greenwell *(65)*	Fair	US	Fair	Fair	Fair	No	No	High

3.4.4 Limitations or Gaps

Several limitations were not considered in this study. They include the following:

- **Assumed compression event independence:** The energy produced by a transducer is assumed to be generated from a stable rest position to one of maximum displacement under load conditions. Once the load is released, there will be residual vibration that will dampen over time. If the next compression occurs before the vibration is fully dampened, the true power output will differ from the expected output.
- **Capture of traffic due to swerving and varying vehicles widths:** It is assumed that the vehicles in the road lane always travel on the wheelpath, which may not be true due to road users' range of driving behaviors. Additionally, vehicle widths can differ substantially, with values ranging between 67 and 102 inches (1,700 and 2,600 mm). The transducers can be manufactured with increased sensor surface area to enable them to capture all the vehicles that pass, however this will result in increased life cycle GHG emissions and cost.
- **Feasibility of connecting to the grid:** In densely populated areas, it may be difficult to acquire permission to add energy to the grid. For example, an area encompassing San Francisco and Oakland does not allow customers to add energy to the grid through Net Energy Metering in order to preserve grid stability. Therefore, confirmation is required from the local electricity provider to ensure that a potentially transient technology like PZT energy production could safely and stably add energy to the grid.
- **Effect of technology on pavement degradation and subsequent increase in fuel consumption:** Most studies assume that the pavement and the PZT transducer have identical resistance to compression, but this may not be entirely true; if the pavement and transducer have different deformations under loading, the pavement can degrade faster. Increased pavement degradation can lead to higher roughness, which results in increased fuel consumption and higher GHG emissions. Pavement degradation would also make more frequent repairs and replacement necessary, and this will add to the costs and GHG emissions from materials and construction. The effects of PZT transducers on long-term pavement degradation have not been studied. The technology is too immature to be implemented at this point and has not been investigated enough.
- **Changes in efficiency over time:** While it was assumed that PZT transducers have negligible efficiency losses over time since they can undergo many compression cycles without degradation, even a 1 percent loss would have significant consequences on the system's power output. However, the decrease in efficiency over time, especially for this use, has not been documented.
- **Change in price of electricity over time:** The rate at which electricity prices will presumably increase over time was not accounted for, but with an increasing number of renewables and a better levelized cost of electricity (LCOE) it is uncertain exactly how electricity prices will shift. This uncertainty therefore affects the return on investment calculation for this energy generation method.

3.4.5 Sensitivity/Uncertainty Methods

Uncertainty exists regarding this technology's effects on vehicle fuel consumption, and therefore a sensitivity analysis was conducted to determine how much of an effect a small increase in fuel consumption would have on the project's environmental and cost impacts. An average fuel economy of 22 miles per gallon was assumed for gasoline vehicles, the same as the average for light-duty vehicle fuel efficiency in the US in 2015 *(76)*. An LCA of gasoline found its impacts to be 100.58 g CO_2-e/MJ gasoline, where gasoline has an energy content of 131.76 MJ/gallon *(77)*. The price of gasoline was assumed to be $3.75 per gallon, the average statewide California price on July 11, 2019 *(78)*. A 1 percent increase in fuel use was tested and resulted in a fuel economy value of 21.8 miles per gallon. Because the fleet's future is uncertain, it was assumed that there would be no change in fuel use, fuel carbon intensity, fleet economy, or fuel cost.

3.5 Results and Discussion

3.5.1 Numerical Results from Case Studies

The energy generation output of the referenced model is plotted in Figure 3.3. The legend shows the different traffic rates that were considered for the analysis cases.

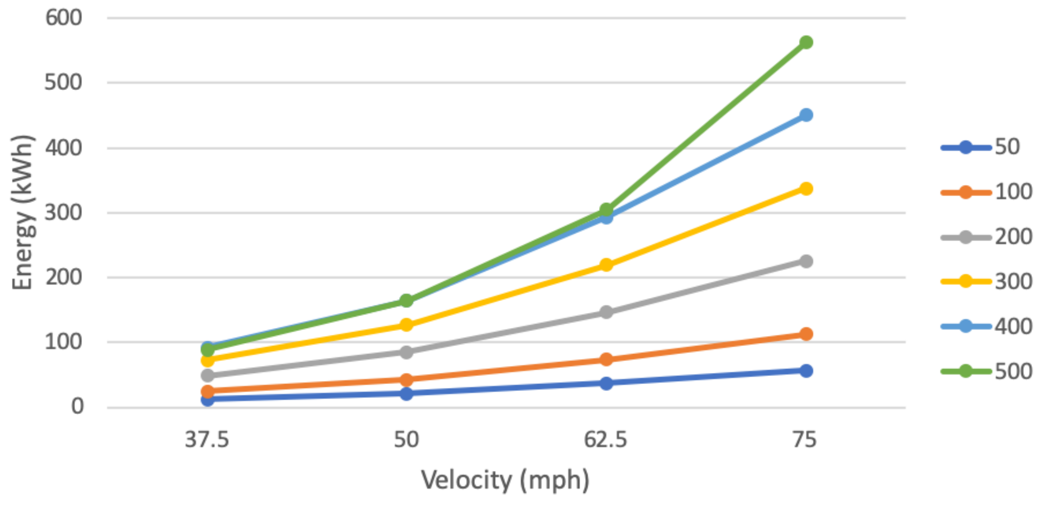

Figure 3.3: For a constant vehicle load, energy generation increases with velocity and traffic rate.

These data were combined with the information acquired from PeMS for I-580 to model energy generation for a typical weekday and weekend, which are presented respectively in Figure 3.4 and Figure 3.5.

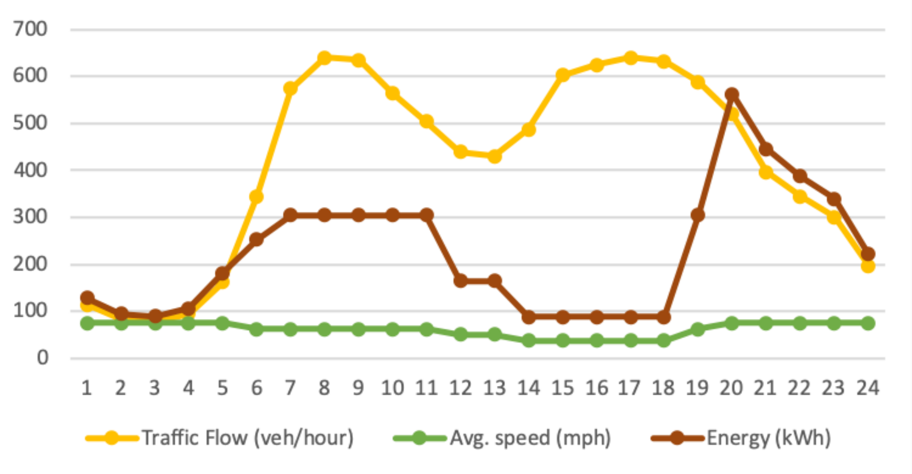

Figure 3.4: Energy generation over the modeled one lane-mile of highway over one weekday.

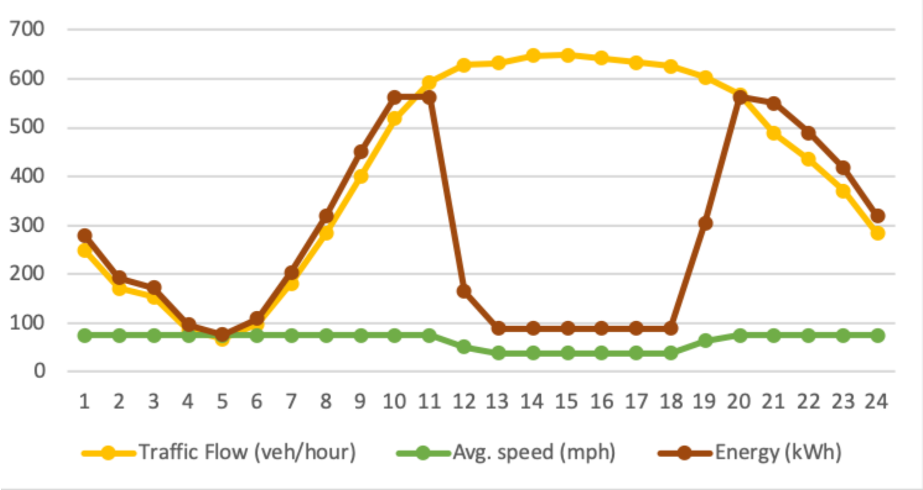

Figure 3.5: Energy generation over the modeled one lane-mile of highway over one day on the weekend.

Note that energy generation is largely dependent on traffic flow, the exceptions in both cases being when average speed decreases. These data were used to model the energy generation of one mile of highway in one year, which was then scaled to correspond to how many miles were installed in a given year. The expected annual energy generation per lane-mile is approximately 2,067 MWh.

3.5.2 Implications for Total Abatement Potential

Based on the assumption that 100 miles of piezoelectric technology would be installed, this results in the production of 206.7 GWh annually. The installation costs have a net present value (NPV) of $486 million and generate 126,000 tonnes of CO_2-e in GHG emissions. Accounting for the emissions reductions benefits achieved by selling the generated electricity to local utilities, this strategy achieves a cumulative net emissions reduction of 798,000 tonnes of CO_2-e over the 35-year analysis period. When the high electricity price achieved by getting rebates on purchased electricity is assumed, the NPV is -$133 million (net reduction in LCC). When the low electricity price where generated electricity is treated as excess energy was assumed, the NPV is $343 million (net increase in LCC). These cases are shown in Figure 3.6.

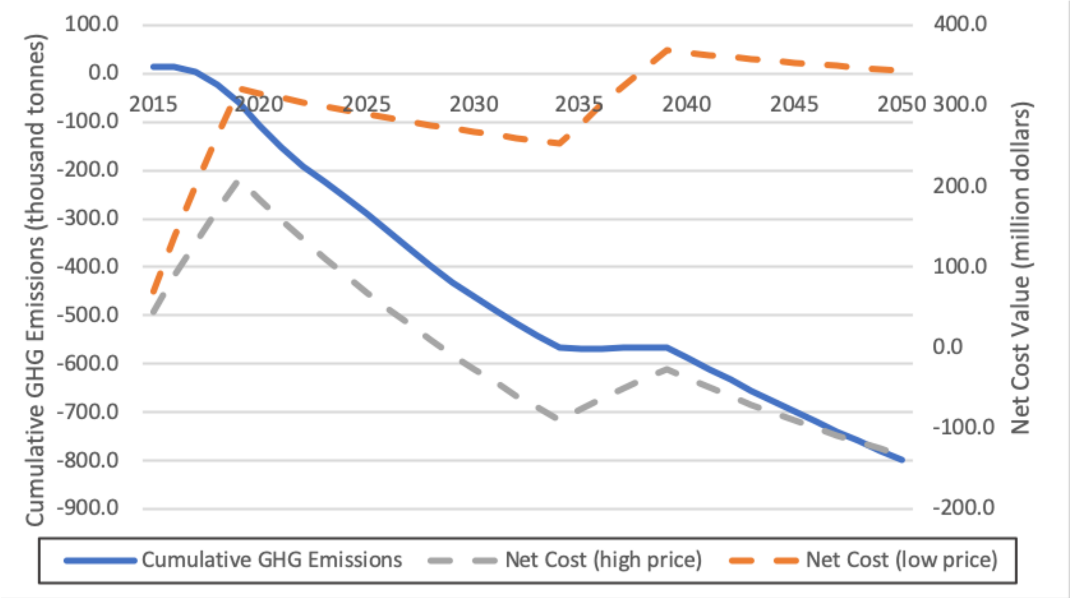

Figure 3.6: Cumulative net emissions and net costs for both the high and low prices for the electricity generated by the system.

The cost-effectiveness of the piezoelectric installation considering only agency cost is a $608.35 per tonne reduction of CO_2-e. The LCC effectiveness, which would include income from electricity net metering, is a -$167.12 cost per tonne reduction of CO_2-e (a net savings) in the high-price case and a $430.14 cost per tonne reduction of CO_2-e in the low-price case.

3.5.3 Time-Adjusted GHG Emissions

The initial analysis of the piezoelectric installation estimated the net reduction in GHG emissions to be 798,000 tonnes of CO_2-e. The TAWP 100-year net reduction in emissions is calculated to be 688,000 tonnes of CO_2-e.

3.5.4 Discussion

One concern not fully addressed in this initial assessment of piezoelectric transducers is the risk of pavement degradation and its effects on vehicle fuel efficiency, and the resulting increase in GHG emissions (see Chapter 1 for the mechanism behind this phenomenon). For example, if a one percent increase in annual vehicle fuel consumption over the installed 100 miles were to occur due to rougher pavement over the transducers, vehicle gasoline use would increase by 275,000 gallons. This would increase the GHG emissions from vehicles by 3,640 tonnes of CO_2-e per year, and cost motorists $960,000 per year.

Over the 35-year analysis period, the new GHG emissions reduction for the system considering pavement degradation and the effect on vehicle fuel use is 646,000 tonnes of CO_2-e, an increase in GHG of 152,000 tonnes compared to the case that assumes no increase in pavement roughness due to the energy harvesting. The pavement degradation also increases costs for vehicle fuel by $41 million, which drastically reduces the piezoelectric system's cost-effectiveness. Note that the fuel efficiency used is the average of light-duty vehicles, but taking into account heavy-duty vehicles as well would further increase the impact that increased fuel use would have on emissions.

Another unaddressed concern is the accuracy of the technology's actual energy generation potential when used in a real-world environment because the technology has not yet been deployed at the scale and conditions described earlier in "Gaps and Limitations." Consequently, the following numbers consider the base case, and not the additional fuel use scenario. Analysis of the findings from this study shows that even in the higher-revenue case where electricity was valued at $0.15 per kWh, if energy generation were to be 21.6 percent less than expected, the net revenue by 2050 would be zero. If energy generation were 76.8 percent less than expected, the net impact on GHG emissions would be zero, meaning there is no GHG emissions benefit to installing this technology.

3.5.5 Summary of Abatement Potential Information

The information regarding the abatement potential calculations presented in this chapter is summarized in Table 3.4 for the 35-year analysis period.

Table 3.4: Summary of Abatement Potential for Energy Harvesting Using Piezoelectric Technology

	35-Year Analysis Period				Average Annual over 35-Year Analysis Period		
	CO_2-e Change (MMT)	**Time-Adjusted CO_2-e Change (MMT)**	**Life Cycle Cost Change ($ million)**	**Cost/ Benefit ($/tonne CO_2-e reduced)**	**CO_2-e Change (MMT)**	**Time-Adjusted CO_2-e Change (MMT)**	**Life Cycle Cost Change ($ million)**
High Electricity Price	-0.798	-0.688	-133	-167.12	-0.0228	-0.0196	-3.8
Low Electricity Price	-0.798	-0.688	343	430.14	-0.0228	-0.0196	9.8
Increased Fuel Use from Pavement Roughness (high elec. price)	-0.646	-0.565	-91	-125.66	-0.0185	-0.0161	-2.6
Increased Fuel Use from Pavement Roughness (low elec. price)	-0.646	-0.565	386	531.90	-0.0185	-0.0161	15.20

4 STRATEGY 3: AUTOMATION OF BRIDGE TOLLING SYSTEMS

4.1 Strategy Statement and Goal

Congested traffic conditions and traffic queuing, as well as stop-and-start and slow-and-accelerate vehicle operations, consume more fuel and produce more GHG emissions per distance traveled than do operations at free-flow speeds, if drivers do not travel at excessively high speeds under free-flow conditions. The scenario presented in this part of the study compares the costs and GHG emissions resulting from changing the approach to how tolls are collected on seven state-owned Caltrans bridges. Two approaches are examined: the current FasTrack automated toll collection system—which collects both electronic tolls and cash, allowing some vehicles to maintain free-flow speeds while requiring others to stop at a tollbooth—and an alternative approach that uses an all-electronic system that does not require vehicles to stop or slow down.

4.2 Introduction to Abatement Strategy or Technology

Caltrans operates seven state-owned toll bridges in California. These bridges are located in District 4, the San Francisco Bay Area. In 2007, Caltrans installed the electronic toll collection system FasTrak at all these bridges, and they all currently have at least one FasTrak-only lane in operation. In the current FasTrak lane set up where both cash and electronic payment are accepted, a vehicle must either slow down or stop to pay and pass: cash-paying drivers decelerate their vehicles to a stop at a tollbooth and then accelerate back to traffic flow speeds, while drivers paying electronically decelerate without stopping near the booth as a gantry-mounted FasTrak receiver completes the toll transaction.

Other all-electronic tolling (AET) technologies that differ from the FasTrak toll booth arrangement are also available. In general, AET technology replaces cash collecting tollbooths with electronic tolling lanes that use a transponder device or license plate recognition system mounted on overhead gantries to collect tolls while preventing traffic flow interruptions. Of the seven Caltrans bridges, only 9 of the 18 tolled lanes (northbound direction) have the equivalent of AET, which is also called *open-road tolling* (ORT).

In an AET system, drivers choose one payment option: FasTrak, Pay-by-Plate, toll invoice, or a one-time payment. The system requires a reliable electronic infrastructure and real-time management, but it improves traffic flow and reduces fuel consumption by eliminating stops at the cash tollbooths. Studies by the UCPRC and others *(36, 79, 80, 81)* have shown that in accelerating from a stop to free-flow speed vehicles consume more fuel and emit more air pollutant emissions than when they travel at constant free-flow speed, and that the size of these increases depends on vehicle type, traffic conditions, and driving patterns. As the benefits of AET use include mobility improvement (congestion reduction), it is hypothesized that implementation will also result in GHG reductions, improved road user safety, and agency cost savings. AET implementation is also expected to reduce vehicle exhaust emissions by reducing unnecessary vehicle decelerations and accelerations at the toll plaza and by eliminating weekend toll-plaza traffic backups. By reducing or eliminating abrupt vehicle stoppages, speed changes, and toll-plaza lane changes, it is also expected that AET will improve road user safety. AETs' reduced toll-plaza waiting times are also expected to reduce travel times. Finally, eliminating cash toll collection is also expected to reduce labor costs.

4.3 Scope of the Study

4.3.1 Scope for Implementation across the Network

A decision was made to test the hypothesis that implementing AET might improve traffic flow and reduce GHG emissions by using a cradle-to-grave LCA approach, which includes the materials, installation, maintenance, transportation, and use stages. The scope of this work is to determine what potential cost-effectiveness improvements and GHG emissions reductions an AET system might bring by comparing LCA and LCCA results from that system with results obtained from a similar analysis of the current FasTrak system (which includes some cash collection) for the seven Caltrans toll bridges *(82)*. The bridges included in this study are described in Table 4.1. The scope of the study includes changing half the tolled lanes on the Benicia-Martinez Bridge, although that change has already occurred.

Table 4.1: List of State-Owned Toll Bridges (year 2017)

Bridge	**Route**	**Location**	**Toll Direction**	**Number of Lanes (Two-way)**	**AADT (Two-way)**
Antioch	SR 160	Between Contra Cost and Sacramento Counties	NB	2	13,600
Benicia-Martinez	I-680	Between Marin and Contra Costa Counties	NB	9 (4 SB, 5 NB)	122,000
Carquinez	I-80	Between Solano and Contra Costa Counties	EB	8	118,000
Dumbarton	SR 84	Between San Mateo and Alameda Counties	WB	6	81,000
Richmond-San Rafael	I-580	Between Marin and Contra Costa Counties	WB	5 (2 WB, 3 EB)	80,000
San Francisco-Oakland Bay	I-80	Between San Francisco and Alameda Counties	WB	10	265,000
San Mateo-Hayward	SR 92	Between San Mateo and Alameda Counties	WB	6	93,000
Total					**772,600**

Note: AADT = Annual Average Daily Traffic

4.3.2 Functional Unit and Graphical Representation of System Boundary

The scope of this study, life cycle considerations, and data requirements are illustrated in Figure 4.1, and for the analysis the functional unit is a toll lane. The seven Caltrans-owned toll bridges operate with twenty-four toll lanes in total, and in this study's analysis the results for one lane were extrapolated to all twenty-four. The study looked at five life cycle stages—(1) materials, (2) transportation, (3) installation, (4) maintenance, and (5) use—for the 35 years of service life from 2015 to 2050.

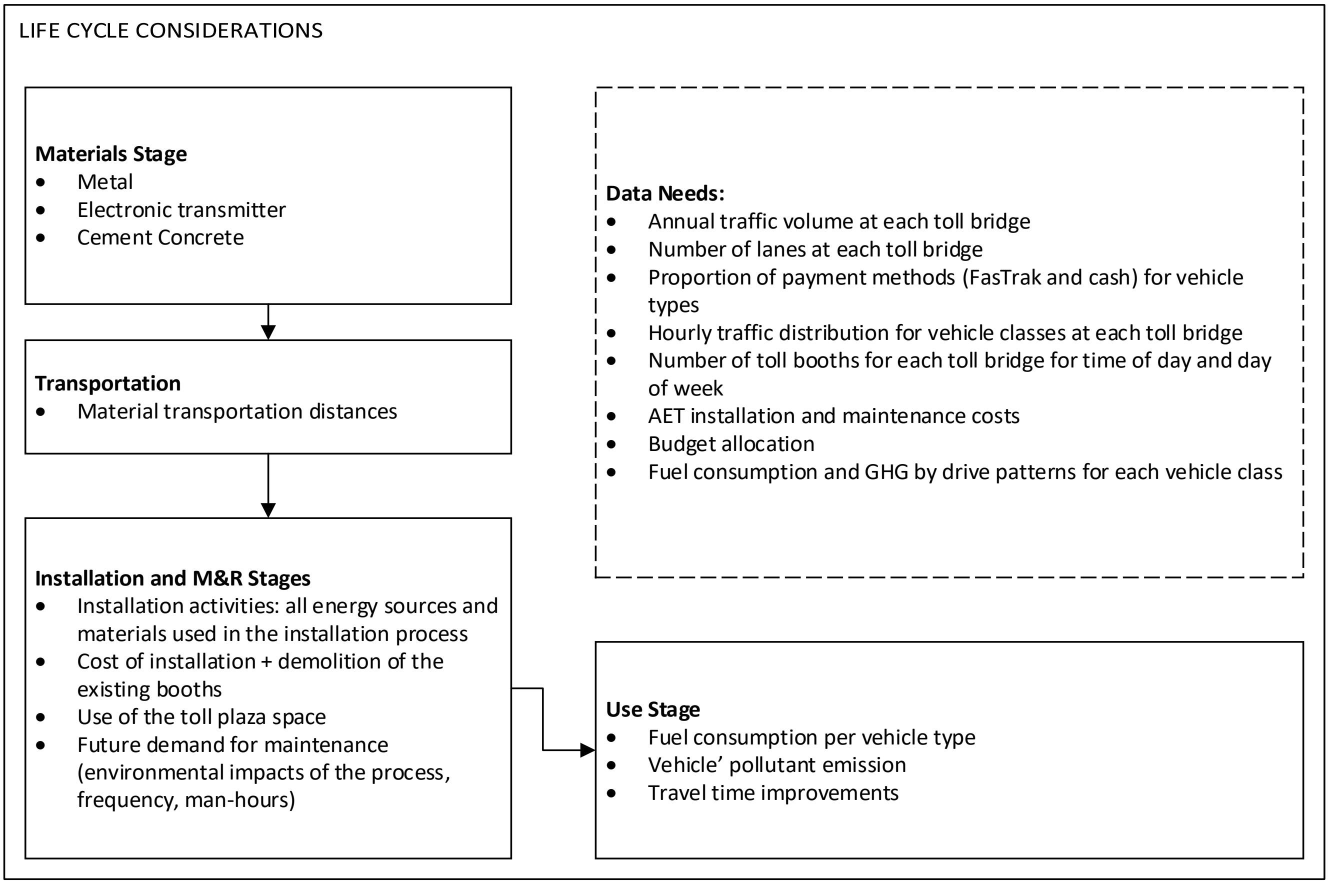

Figure 4.1: Scoping system diagram for life cycle (environmental impacts and cost) considerations.

4.4 Calculation Methods

4.4.1 Major Assumptions

Major assumptions made in this study for all seven state-owned bridges and the AET system include the following:

- a constant traffic growth rate (1 percent/year);
- consistent AET implementation cost per lane;
- four vehicle types (passenger cars [gasoline], sport utility vehicles (SUVs) [gasoline], light-duty truck [diesel], heavy-duty trucks [diesel]);

- that demolition of the existing structure followed by the waste management of the demolition materials is insignificant and contributes far less than 5 percent of the emissions, so it was therefore not considered in this study. A minimal impact was also assumed for disposal cost and these costs were not included; and
- that the environmental impacts from the construction and maintenance of the tolling equipment is assumed to be negligible. The construction and maintenance of the tollbooth includes the toll gantry, toll gantry erection, wiring, cameras, and other electronic equipment installation.

Vehicle GHG emissions and energy consumption for a specific hour in January and in August 2018 were estimated using the US Energy Protection Agency (EPA) program *MOtor Vehicle Emission Simulator* (MOVES). These two months were selected to represent a year's two extreme seasons, winter and summer, respectively. MOVES was used instead of the California-specific program EMFAC because MOVES has the capability to simulate different drive cycles with a project-level simulation of individual vehicles at different analysis levels, such as by vehicle type or traffic congestion level *(83)*. *EMFAC* does not provide an option that allows a user to modify the drive cycle of an individual vehicle in a specific traffic condition *(84)*.

Using MOVES, the daily GHG emissions and energy consumption for each vehicle type were estimated for a bridge tollbooth lane by aggregating a single vehicle's GHG emissions and energy consumption with the hourly number of vehicles per vehicle type.

4.4.2 Calculation Methods

The study used the MOVES model to estimate a vehicle's fuel consumption and pollutant emissions based on the drive cycle scenarios for the toll collection alternatives. A *drive cycle* is a series of data points that represent a vehicle speed versus time. This research used a project-level simulation approach (simulation of individual vehicles), allowing *MOVES* to perform estimates at different analysis levels, such as vehicle types and traffic congestion levels *(83)*.

To investigate how the electronic tolling system can affect GHG emissions, this study compared the CO_2-e generated and the fuel consumed within a one-mile stretch by different vehicle types using two toll payment methods—AET and FasTrak—with two FasTrak payment methods considered—cash and electronic. For this study, two different situations were evaluated for each vehicle type, and the annual GHG emissions and fuel consumption were calculated:

1. AET system (FasTrak only): vehicles travel at traffic free-flow speed (at a constant speed of 65 miles per hour).
2. Cash and FasTrak mixed: hourly queue lengths are calculated based on hourly traffic and tollbooth operation schedules by simulation of vehicles' travel patterns at tollbooth using vehicles' drive cycles.

Vehicles using FasTrak's electronic system travel at a constant 65 mph (free-flow speed). Vehicles using the traditional cash payment situation (that is, paying by stopping at a tollbooth) must come to a full stop from a constant speed of 65 mph, pay a toll, and then re-accelerate to 65 mph. Since heavy vehicles require more time to accelerate and decelerate than lighter vehicles, it was necessary to determine the drive cycles for each vehicle type separately. Estimates for these vehicle type drive cycles were determined from field experiments conducted in a UCPRC study of deflection energy *(85)*.

4.4.3 Data Sources and Data Quality

MOVES uses traffic volume, road section length and gradient, and user-specified drive cycles to estimate pollutant emissions for a specific time period. Data for the hourly toll schedules, annual traffic, and revenue for all seven bridges in California were supplied by the Metropolitan Transportation Commission (MTC), the transportation planning, financing and coordinating agency for the nine-county San Francisco Bay Area. Caltrans provided data for annual average daily traffic (AADT) and hourly traffic distribution for state-owned toll bridges. Table 4.2 shows the list of state-owned bridges and their location and traffic volumes.

Overall for the seven bridges in 2018 (Table 4.2), 31 percent of vehicles paid cash at the tollbooth, and the hourly average queue length was determined to be 40 vehicles. For vehicles using cash, the hourly average per vehicle travel time required to pass a tollbooth was almost 5 minutes.

Table 4.2: Average Daily Traffic for Cash and FasTrak at State-Owned Toll Bridges (One-Way, 2018)

Toll Payment Option	SF-Oak Bay	San Mateo-Hayward	Dumbarton	Carquinez	Benicia-Martinez	Antioch	Richmond-San Rafael	Total
Cash	33,974	15,470	10,093	22,899	20,393	3,347	11,496	117,673
FasTrak	91,997	37,691	22,146	36,049	37,257	3,926	28,092	257,159
Total	125,970	53,162	32,239	58,948	57,651	7,273	39,588	374,832

Table 4.3 presents the data quality assessment for this study. The table includes two data categories: quantitative data and cost-related data.

Table 4.3: Data Quality Assessment

Categories	**Data Sources**	**Data Quality**							
		Reliability	**Geography**	**Time**	**Technology**	**Completeness**	**Reproduc- -ibility**	**Represen- tativeness**	**Uncertainty**
Data Type									
Traffic	Caltrans	Very Good	California	Very Good	Very Good	Very Good	Yes	Yes	Low
Percent vehicle types/class	Caltrans	Very Good	US	Very Good	Very Good	Very Good	Yes	Yes	Low
Drive cycles	Field	Good	California	Very Good	Very Good	Very Good	Yes	Yes	Low
Temperature	US EPA/MOVES *(83)*	Good	California	Fair	Very Good	Very Good	Yes	Yes	Low
Humidity	US EPA/MOVES (83)	Good	California	Fair	Very Good	Very Good	Yes	Yes	Low
Number of state-owned bridges	Caltrans	Very Good	California	Very Good	Very Good	Very Good	Yes	Yes	Low
Number of tollbooths	MTC	Very Good	California	Very Good	Very Good	Very Good	Yes	Yes	Low
Tollbooth operation schedule	MTC	Very Good	California	Very Good	Very Good	Very Good	Yes	Yes	Low
Cost-Related									
Time value	Caltrans	Very Good	California	Very Good	Very Good	Good	Yes	Yes	Low
Discount rate	Caltrans	Good	California	Fair	Very Good	Good	Yes	Yes	Low
AET cost	Golden Gate District	Good	California	Very Good	Very Good	Good	Yes	Yes	Medium
Labor cost	Golden Gate District	Good	California	Very Good	Very Good	Good	Yes	Yes	Low

4.4.4 Limitations or Gaps

Several potential limitations and gaps were not considered in this analysis. They include the following:

- Future changes in traffic growth rates and vehicle classifications
- Future changes in material costs and maintenance frequency cycles
- Future changes in fuel consumption and engine efficiencies
- Traffic congestion downstream of AET locations
- Applicability (available funds or practicality)
- Installation/construction period and traffic handling
- Traffic safety

4.5 Results and Discussion

4.5.1 Numerical Results from Case Studies

Assuming the AET system's life cycle is 20 years, it will need replacement in 2035. The AET installation cost was determined to be about $1.2 million per lane *(86),* and the total installation cost for 24 lanes at the seven toll bridges was $28.8 million. The installation costs were assumed to occur in the years 2015 and 2035, and the total cost was estimated to be $57.6 million. The operation cost per cash pay toll lane was calculated to be $0.2 million. The current tolling system requires $4.8 million/year to operate the 24 lanes at the seven toll bridges. The annual agency costs are illustrated in Figure 4.2. Table 4.4 shows the total agency cost analysis results for the current tolling system and the AET system. The total toll collector cost for 35 years was calculated to be $168.0 million. The total cost savings of implementing the AET alternative was estimated to be $110.4 million for the life cycle analysis period. These calculations do not include inflation adjustments to the installation and operation costs *(87)*.

Table 4.4: Life Cycle Agency Cost Analysis Result for the Current Tolling System and the Alternative (AET) System

Agency Cost	Current Tolling System	Alternative (AET) System
Total Agency Cost	$168.0 million	$57.6 million
Savings	$110.4 million	

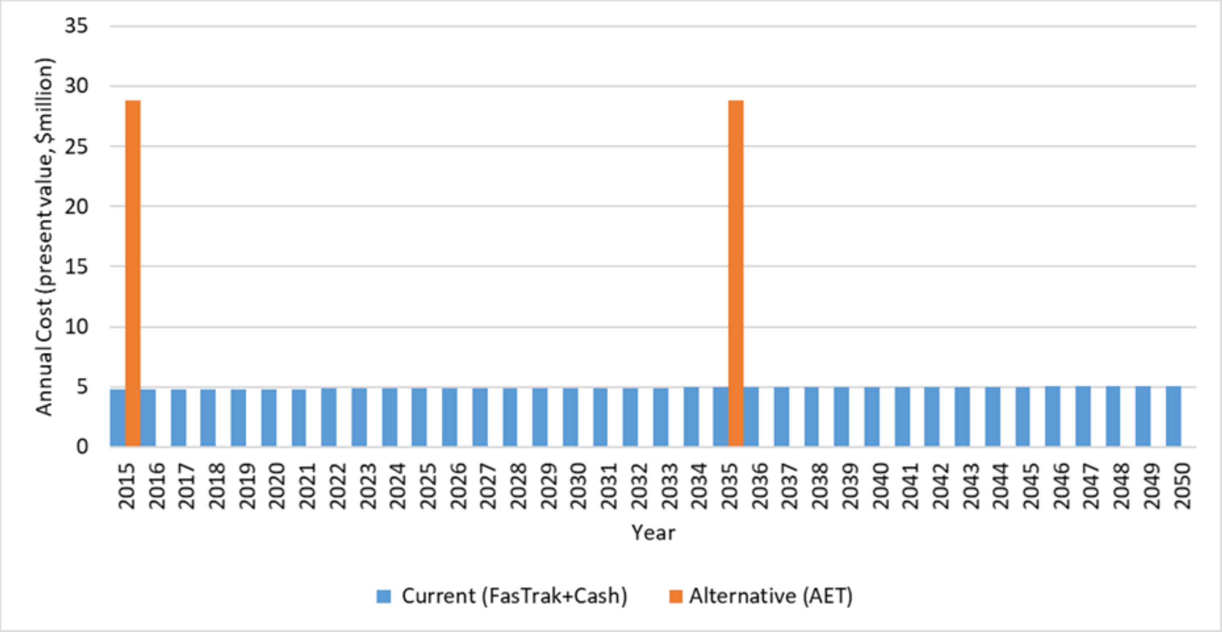

Figure 4.2: Agency costs for state-owned toll bridges with the current tolling system and the alternative (AET) over 35 years.

<u>Travel Times and User Costs</u>

Each bridge user's average hourly waiting time in queue was calculated using probabilistic queuing models for the two alternative systems. Bridge users' daily average travel times for each bridge were aggregated from each vehicle's average hourly in-queue waiting time for weekdays and weekends. The annual average travel times for all seven bridges were aggregated from the average daily travel times on each bridge. The probabilistic queuing models used in this study are described in Appendix C *(88)*.

Based on Caltrans vehicle operation cost parameters *(89)*, the time value for passenger cars and SUVs was $13.65/hr and the time value for light-duty trucks and heavy-duty trucks was $31.40/hr. Total travel times for the current tolling system and the AET system were 398.5 and 321.4 million hours, respectively, for the 35-year life cycle analysis period. Total user costs for the current tolling system and the AET system were $6,147 million and $4,957 million, respectively, for the life cycle analysis period (Table 4.5).

Annual present value user costs with one percent average annual traffic growth rate, and the cumulative user travel time and costs for the current tolling system and the AET system from 2015 to 2050 are shown in Figure 4.3 and Table 4.5, respectively. The potential user cost savings from the AET over 35 years for all seven state-owned bridges was $841 million.

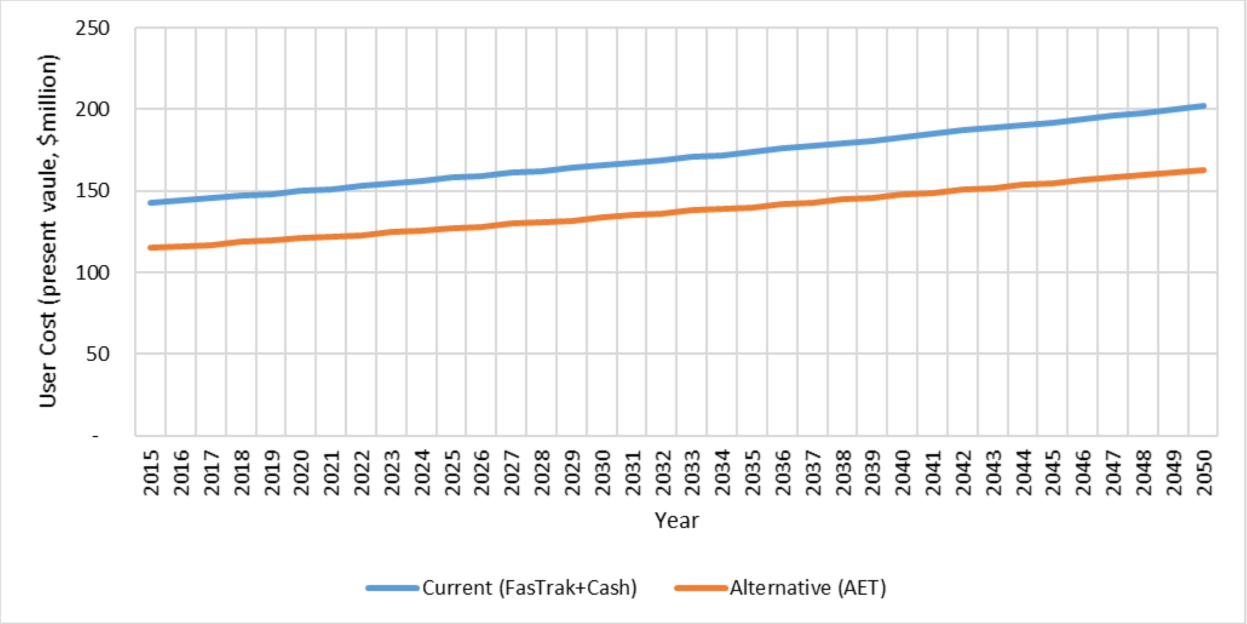

Figure 4.3: Annual user costs (in present value) for the current tolling system and the AET system from 2015 to 2050 applying a one percent average annual traffic growth rate.

Table 4.5: Cumulative User Travel Time and User Cost Savings for the Seven Toll Bridges for 35 Years

Indicator	**Current Tolling System**	**Alternative (AET) System**	**Savings**
Total User Travel Time	398.5 million hours	321.4 million hours	77.1 million hours
Total User Cost (present value)	$4,346 million	$3,505 million	$841 million

Total Life Cycle Costs (Agency and User Costs)

For the life cycle analysis period, total LCCs (agency and user costs) for the current tolling system and the AET system were $6,324.4 million and $5,014.6 million, respectively. The total savings realized over the course of the life cycle analysis period due to the implementation of the AET system at all seven state-owned toll bridges were estimated to be close to $1,310 million.

Greenhouse Gas (GHG) Emissions

The GHG emission simulation results were generated for the scenarios of the current system and the AET system, starting with traffic information from 2017 and projected from 2015 to 2050, with an average annual traffic growth rate of one percent. At the seven toll bridges, the difference between current tolling system's 2015 annual GHG emissions (0.032 MMT) and the alternative (AET) system's emissions for that same year (0.022 MMT) was estimated to be a reduction of 0.010 MMT. The difference between the current tolling system's 2050 (the last year of the analysis period) annual GHG emissions (0.046 MMT) and the alternative (AET) system's emissions for that same year (0.032 MMT) was estimated to be a reduction of 0.011 MMT. The cumulative GHG emissions from the traffic drive cycles over 35 years were 1.41 MMT for the current tolling system and 0.97 MMT for the alternative (AET) system.

4.5.2 Implications for Total Abatement Potential

The total agency cost (installation and operation costs) savings for the seven state-owned toll bridges was $110 million over 35 years and the total user cost saving was $ 1,190 million over that period. Therefore, implementing AET on those bridges resulted in a total LCC savings of $1,300 million for the 35-year analysis period.

Over that 35-year period, a total savings of approximately 0.44 MMT in GHG emissions was calculated for the seven state-owned toll bridges (Figure 4.4).

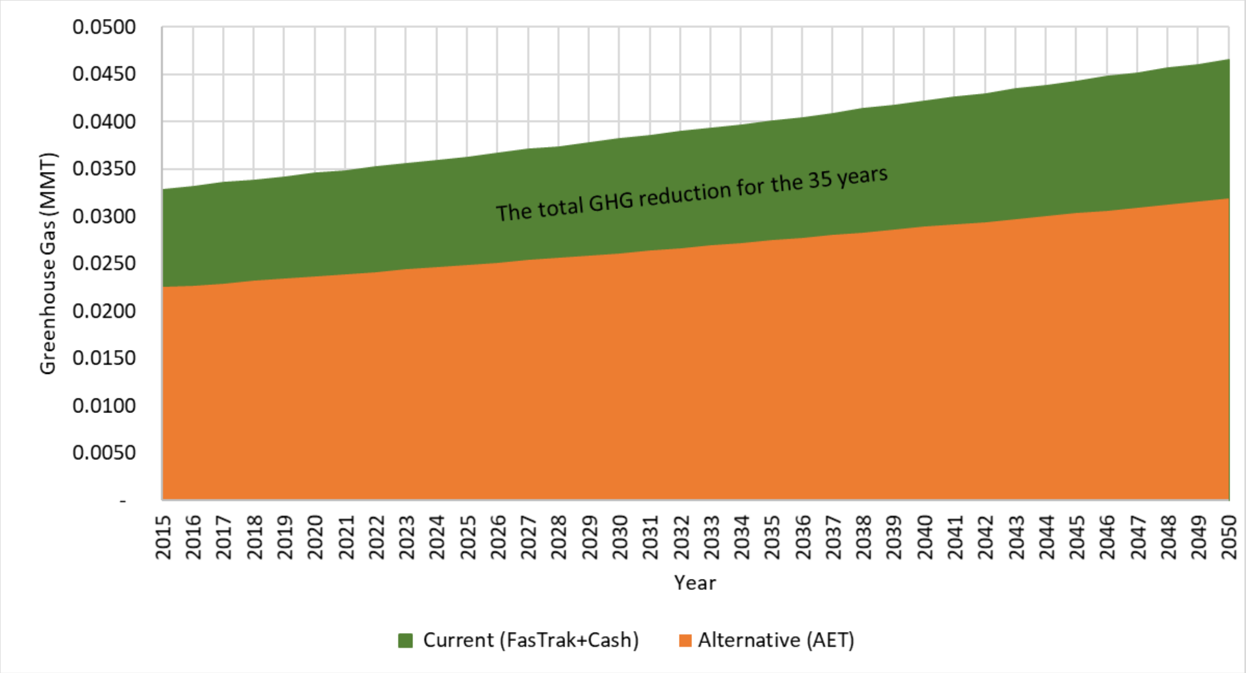

Figure 4.4: Annual GHG emissions for state-owned toll bridges with the current tolling system and the alternative (AET) for 35 years.

4.5.3 Time-Adjusted GHG Emissions

Using the time-adjusted GHG emission methodology *(7)*, the results for 30-year and 100-year analytical time horizons were calculated to be 0.59 MMT and 1.20 MMT of GHG emissions for the current system and 0.41 MMT and 0.83 MMT for the AET system, respectively. The time-adjusted GHG emissions methodology with a 100-year analytical time horizon produced a result that showed a total GHG emissions reduction of approximately 0.37 MMT can result by replacing the current system with the alternative one.

4.5.4 Sensitivity/Uncertainty Analysis

GHG Changes by Electric Vehicle Use

GHG generation changes attributable to increased electric vehicle (EV) use were estimated for the scenarios, continuing with the current FasTrak mixed payment methods and the use of AET. If EVs replace 10 percent of passenger cars, the total GHG amounts for the current and the alternative (AET) tolling systems will decrease by 3.7 percent (a difference of 0.052 MMT, from 1.41 to 1.36 MMT) and 3.5 percent (a difference of 0.034 MMT, from 0.97 to 0.935 MMT), respectively.

If EVs replace 20 percent of passenger cars, then the total GHG amounts for the current tolling system and for the alternative (AET) will decrease by 7.3 percent and 7.0 percent, respectively. As the amounts of GHG for both scenarios decrease due to increased EV use, the amount of the GHG reduction from the current tolling system to the alternative (AET) system decreased (4 percent decrease per 10 percent of EV increase) (Figure 4.5).

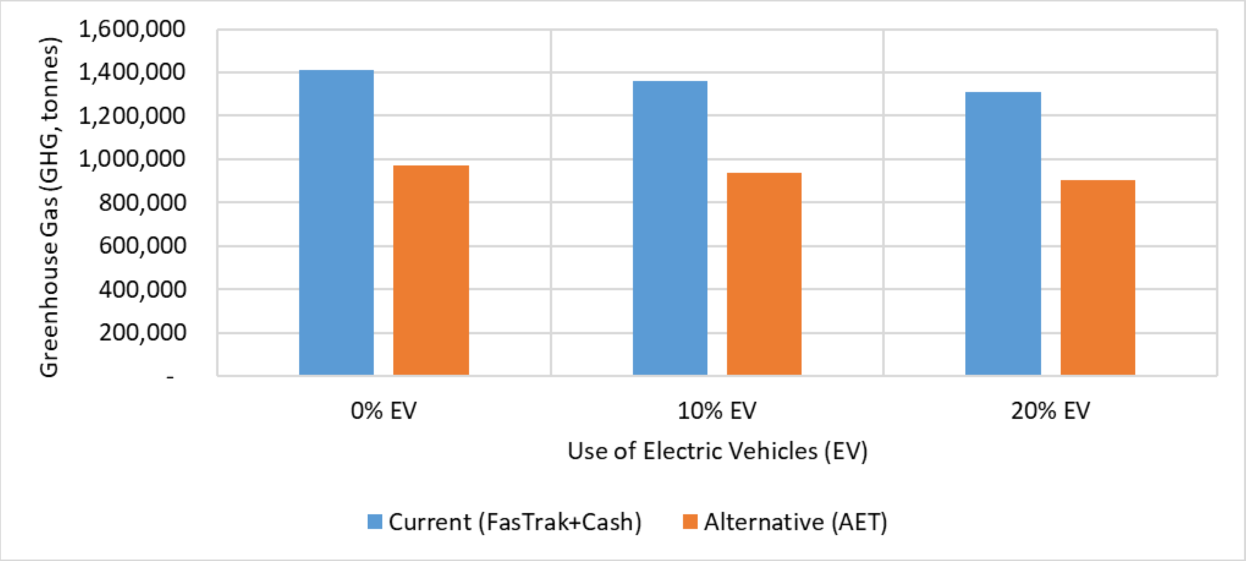

Figure 4.5: GHG changes by increasing use of electric vehicles (EV).

4.5.5 *Summary of Abatement Potential Information*

Information regarding the abatement potential calculations presented in this chapter is summarized in Table 4.6 for the 35-year analysis period.

Table 4.6: Summary of Abatement Potential for Automation of Bridge Tolling Systems in California

Cases	35-Year Analysis Period				Average Annual over 35-Year Analysis Period		
	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Agency Life Cycle Cost Change ($ million)	Agency Cost/ Benefit ($/tonne CO_2-e reduced)	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Agency Life Cycle Cost Change ($ million)
0% EV	-0.444	-0.379	-110.4	-249	-0.0126	-0.0108	-3.15
10% EV	-0.427	-0.364	-110.4	-259	-0.0123	-0.0104	-3.15
20% EV	-0.409	-0.348-	-110.4	-270	-0.0117	-0.0099	-3.15

5 STRATEGY 4: INCREASED USE OF RECLAIMED ASPHALT PAVEMENT

5.1 Strategy Statement and Goal

Hot mix asphalt (HMA) is the surface material on approximately 75 percent of the California state highway network and is a widely used structural material in a number of different pavement applications. Reclaimed asphalt pavement (RAP) is an old HMA that has been milled off an existing HMA pavement surface, and it can be used in new HMA as a partial substitute for virgin asphalt binder and aggregate. This study compares and evaluates the GHG impacts of increased amounts of RAP use in HMA with those from typical recent practice.

5.2 Introduction

5.2.1 Caltrans Plans and Documentation

For a number of years *(90),* Caltrans has allowed contractors to use up to 15 percent RAP (by weight) in HMA without any additional engineering; this percentage serves as the baseline for the strategy discussed in this chapter. More recently, Caltrans began to allow up to 25 percent RAP, but the specifications for this increased percentage called for both a very conservative approach to the engineering of the blended RAP/virgin binder and the use of expensive, time-consuming testing requiring highly regulated solvents. These strict requirements, which industry considered onerous, essentially eliminated the use of more than 15 percent RAP for several years. Then, in 2018, Caltrans changed its specifications to allow up to 25 percent RAP in HMA without the need for that testing (a change in the virgin binder grade is required) and is now working to develop approaches that will allow inclusion of up to approximately 40 percent.

It must be noted that Caltrans is mandated to use rubberized hot mix asphalt (RHMA)—which includes recycled used tires in the binder—as the surface layer material for a significant portion of the state's asphalt pavements, but the department does not currently allow RAP to be used with RHMA because the recycled material reduces the rubberized mix's cracking resistance, a key characteristic in its selection as a surface material. To address these incompatible needs, Caltrans is concurrently evaluating technical approaches and specifications to increase the RAP percentages in HMA and examining ways to also allow some in RHMA without diminishing this material's performance. Since coarse RAP consists of the larger-sized particles in the material and has low binder content, in this strategy for RHMA the RAP would replace virgin aggregate but not virgin and rubberized binder and would therefore not reduce recycled tire use. This approach would allow the use of up to 10 percent coarse RAP in RHMA. It should be noted that this study did not consider the use of RAP in RHMA. The impact on GHG emissions of this approach is likely very small because no virgin binder replacement is allowed.

5.2.2 Abatement Strategy or Technology

Each year Caltrans works with contractors to maintain its nearly 50,000 lane-miles of state highway pavement infrastructure. Included among these projects are construction and maintenance of additional pavement infrastructure, such as ramps, parking lots, turnouts, shoulders, rest areas, gore areas, drainage facilities, dikes, and curbs. Taken together, these project types contribute a large part of the environmental impacts attributable to the department. The purpose of this case study was to assess how much Caltrans might reduce the environmental impacts attributable to the HMA materials used in these infrastructure projects, specifically by increasing the amount of RAP replacing virgin materials.

Pavement projects use many different types of materials, but as a starting point this case only focuses on the increased use of RAP in flexible pavements. Similar evaluations should also be conducted for other transportation infrastructure materials, such as portland cement concrete, metals, plastic polymers, and additives.

As stated earlier, HMA and RHMA are used as surface materials on the majority pavements in California *(91)*. Use of up to 15 percent RAP in asphalt mixtures is a mature and common practice across the US. At the end of the asphalt surface layers' service life, they can be milled and used as RAP in new construction or for M&R activities. This RAP can be blended with virgin asphalt binder and aggregates to reduce the use of virgin materials (aggregate and binder) in a new HMA mix. Since virgin binders are expensive, as to a lesser extent are virgin aggregates, and since RAP contains a less expensive binder, RAP use provides cost savings to material producers. The binder in RAP is aged, stiff, and brittle, but if it is properly blended with virgin binder softer than is normally used, and if complete blending occurs, then the new blended mix can perform the same as the mix with only the normally used virgin binder and no RAP.

RAP collected from one location often includes layers placed at different times and from different sources. In addition, RAP collected from different locations is frequently stockpiled together at asphalt plants for use in new mixes, which means that a RAP stockpile at a plant often contains a mix of multiple asphalt layers that have been placed there over several years. Therefore, before it can be used in new mixes, RAP should be processed for better uniformity. This makes measuring and engineering the resultant properties of the blended binder, and determining the degree of blending that occurs during mixing, technological challenges that must be dealt with when using high RAP percentages. As noted above, the use of high RAP percentages often requires the use of a softer virgin binder in addition to the use of softening additives, called rejuvenators, to facilitate blending of the aged and the virgin binders. Importantly, the mix containing the RAP should have similar performance to a mix with virgin binder with respect to fatigue and low-temperature cracking and rutting. If the RAP mix lacks these similarities, any potential cost and/or environmental benefits may be jeopardized because the mix will need to be replaced more frequently with a commensurate increase in the environmental impacts.

5.3 Scope of the Study

5.3.1 Scope for Implementation across the Network

The goal of this study was to calculate how much GHG emissions can be reduced if the maximum allowed RAP content in HMA mixes rises from 15 percent binder replacement to 25, 40, or 50 percent, and to scale the use of HMA on the state network in California.

This study is an example of an LCA with *cradle-to-gate* scope, as it considers all the impacts attributable to the material extraction and transportation (to plant) LCA stages, and the impacts due to all the in-plant processes that prepare the final mix. For the project it was assumed that the construction process and field performance of the higher-RAP-content mixes matched those of the base scenario, and therefore the construction, use, and end-of-life stages were excluded from the scope. However, this assumption is not true in all cases and depends on an asphalt technology's ability to adjust to the different RAP properties considered in this study, but the assumption was sufficiently valid for this first-order analysis. Figure 5.1 shows the system diagram considered for this case study.

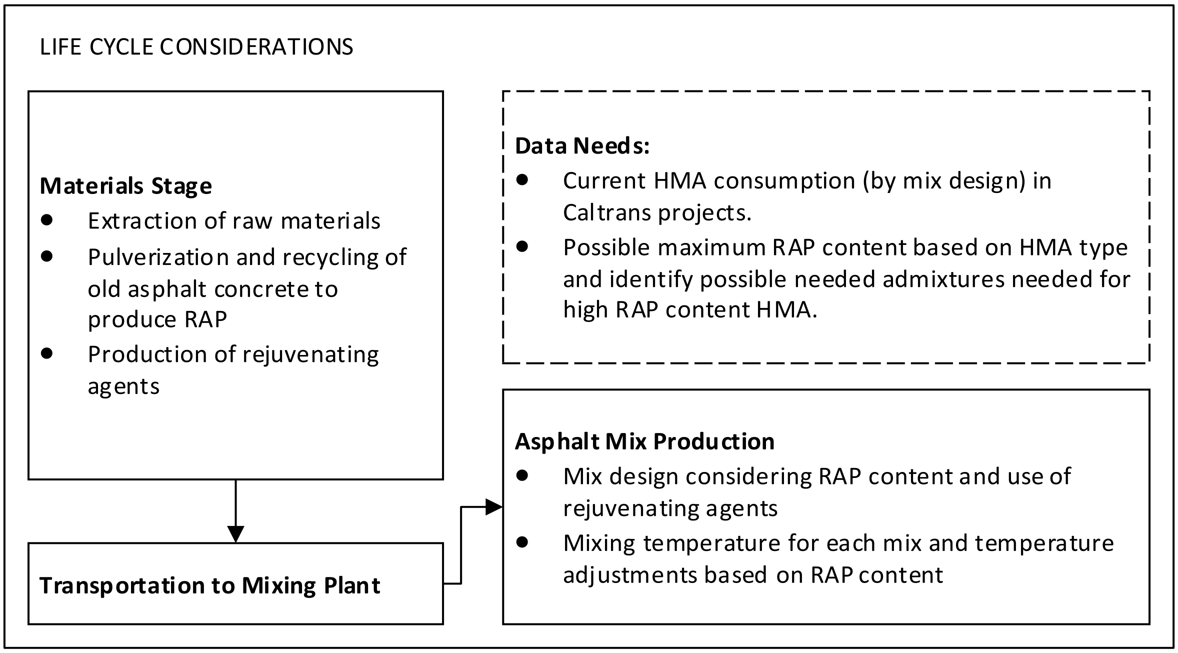

Figure 5.1: Scoping system diagram for increased use of RAP.

5.3.2 Functional Unit and Graphical Representation of System Boundary

This study's defined functional unit is the California highway network, and its analysis period spans the 33 years from 2018 to 2050. The cost implications of these scenario changes were of interest to enable comparisons with other reduction strategies.

5.4 Calculation Methods

5.4.1 Major Assumptions

The framework used for conducting this analysis is shown in Figure 5.2. A major effort was made in part of in this study to estimate the amounts of materials used on the state highway network each year over the analysis period. These estimates were based on two sources of information:

- Programmed work in the Caltrans pavement management system (PaveM)
- Historical construction project data published annually in the Construction Cost Data Book (CCDB) projected into the future.

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

Taking the PaveM approach would involve using the program's output for either a recommended type of repair treatment for each network segment or a *do-nothing* instruction for each year over the analysis period, within the defined budget limits. PaveM also calculates the cost of each treatment applied. The asphalt concrete overlay treatments recommended by PaveM are defined as *thin, medium,* and *thick*, and these thickness categories provide a basis for calculating the required volume of material for a project: the volume quantity can be calculated by multiplying a value corresponding to one of the thicknesses by a segment's length and lane widths. Using a typical density value, this volume calculation can then be converted to the mass units typically used for asphalt materials. It is important to note that PaveM estimates tend to be lower than the actual total asphalt concrete amounts used by Caltrans because the program only considers treatments in the traveled way; it does not consider any paving on shoulders, ramps, parking lots, gore areas, or other places where Caltrans uses this material.

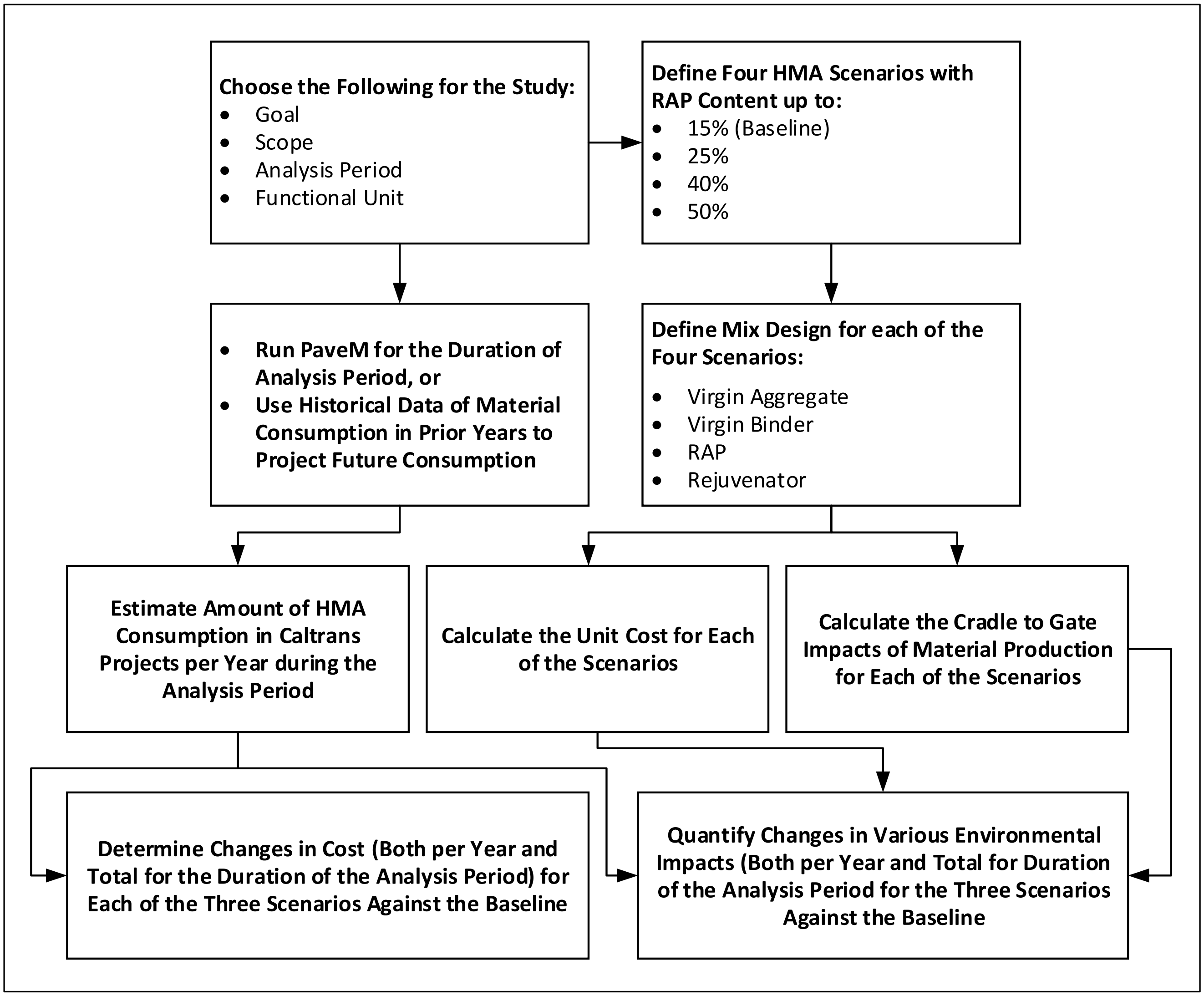

Figure 5.2: Flowchart of model development used for this study.

An alternative to the PaveM approach would be to use the Contract Cost Data Book (CCDB), which Caltrans publishes annually. The CCDB lists the costs for all the items used for Caltrans projects undertaken in the previous fiscal year, with the unit cost and the quantity of each item purchased over that year regardless of where it was used. The CCDB can be used to estimate the amount of each material type used in Caltrans projects in prior years. and that result can then be used with historical data to project future materials consumption. The CCDB includes materials purchased by Caltrans used for all applications, whether on the traveled way or not.

Discrepancies can result in estimates prepared using the two approaches. For example, a PaveM run conducted under the current default budgeting scenario projected an expenditure of 267 million dollars for asphalt paving materials in 2018. However, the data in the 2018 Construction Cost Data Book (items 390132, 390135, 390136, 390137, 390401, 390402, 395020, and 395040)[4] showed an expenditure of 545 million dollars for the same items in that same year. To address this discrepancy and to calculate material consumption in each year during the analysis period, the tonnages of materials from the 2018 CCDB were multiplied in every year after 2018 by the ratio of 2018 CCDB purchases to the PaveM projections for 2018 purchases. The study assumed this process would account for the additional materials used outside the traveled way lanes.

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

It should also be noted that local agencies in Northern California counties often follow Caltrans specifications, and so any effects from changed a Caltrans specification would be amplified when those localities implement those specifications. Changes in environmental impacts from local government practices following changes in Caltrans specifications were not considered in this study.

5.4.2 Calculation Methods

5.4.2.1 Material Consumption per Year

Figure 5.3 shows the HMA and RHMA amounts needed each year between 2018 and 2050 in Caltrans projects, based on from PaveM results. This run provides data up to the year 2046. Because of the lack of a better alternative for estimating the amount of materials needed in the years 2046 to 2050, it was assumed that the average tonnage of HMA and RHMA used over the 10 prior years (years 2036 to 2046) would be applied during that time period. Table D.1 in Appendix D includes the details of the amount of HMA and RHMA needed per year per treatment type.

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[4] *ppmoe.dot.ca.gov/hq/esc/oe/awards/2018CCDB/2018ccdb.pdf*

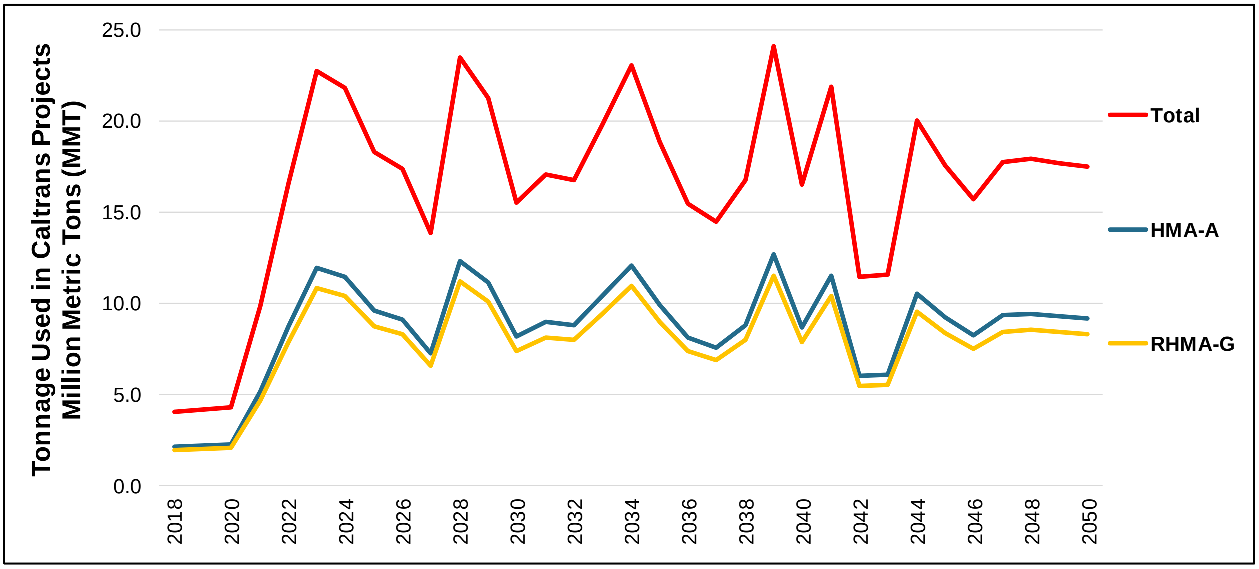

Figure 5.3: The total amount of materials needed per year between 2018 and 2050 based on PaveM outputs.

5.4.2.2 Mix Designs

The use of RAP in RHMA is not currently allowed in Caltrans projects. Therefore, four HMA mixes with increasing maximum RAP content were considered, as shown in Table 5.1. To avoid heating RAP to high temperatures, which can damage any of its residual binder, the heating temperature for RAP was limited to 350°F (177°C), while the virgin aggregates were heated to 500°F (260°C) to compensate and reach the required mixing temperature required for blending the materials. These temperature differences have no implications for the life cycle inventory of energy use for each mix because the final mix temperature set for all the mixes would require the same amount of heat for a 1 lb (0.45 kg) mix of blended RAP or one of virgin materials, independent of the mass ratios of the two components. Increasing the RAP content will only result in higher temperatures needed for virgin aggregate materials to achieve the same mixing temperature for the blend.

Ensuring that a mix with higher than 25 percent RAP content performs reliably requires adding a rejuvenating agent (RA). The RA must be added to counter the effect of the higher percentage of aged binder in the blend from the RAP. Three common rejuvenating agent types are aromatic extracts made from petroleum, bio-based RAs made from soy oil, and bio-based RAs made from the tall oil that comes from trees. Use of softer virgin binder in the blend can also handle higher aged-binder contents, and eliminate the need for rejuvenators, but this method is only generally applicable for mixes with RAP contents up to about 25 percent. For RAP contents above 25 percent, it is usually difficult to obtain full blending of the RAP and virgin binders without a rejuvenating agent.

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

In practice, the actual amount of virgin binder replaced in mixes by RAP binder is usually somewhat less than the specified upper limit, as contractors work to meet a long list of other binder and mix specification requirements. Also, since high RAP mixes replace some of the virgin binder with rejuvenator, future specifications may also consider rejuvenator as part of the RAP binder, and not as part of the virgin binder, when determining maximum RAP content. Therefore, as shown in Figure 5.2 the assumed binder replacements for each maximum allowed RAP content were somewhat less than the maximum allowed. The assumed amounts for each specified maximum replacement category were selected based on a review of available mix designs.

Table 5.1: The Five Scenarios Considered for HMA for Caltrans Projects across the Entire Network

Mix Title	Max RAP Content	Actual Binder Replacement	Virgin Binder Replaced by RAP	Virgin Binder Replaced by Rejuvenator
HMA (Max 15% RAP)	15%	11.5%	11%	0%
HMA (Max 25% RAP)	25%	20%	15%	5%
HMA (Max 25% RAP)	25%	20%	20%	0%
HMA (Max 40% RAP)	40%	35%	28%	7%
HMA (Max 50% RAP)	50%	42%	32%	10%

This study's baseline mix designs for HMA and RHMA were taken from the UCPRC Case Studies report *(92)* and are presented in Table D.2 in Appendix D. Further, it was assumed that the RAP materials had a binder content of 5 percent by mass with a 90 percent binder recovery ratio, resulting in an effective RAP binder content of 4.5 percent. Therefore, the total binder content for the HMA baseline was 4.7 percent (0.04 + 0.15 * 0.045 = 0.047). The RHMA total binder content was 7.5 percent. These data, combined with the information in Table D.2, were used to develop the mix designs for the new HMA scenarios shown in Table 5.2.

Table 5.2: Mix Design Component Quantities by Mass of Mix for HMA Scenarios and RHMA Used in This Study

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

5.4.2.3 LCA Calculations

The mix designs were then used to calculate each mix's cradle-to-gate environmental impacts using the LCA methodology. The LCI database created by the UCPRC *(74)* was used as the data source. All the details of model development, data sources, and the assumptions made can be found in that reference.

Table 5.3 shows the LCI results for the main construction materials used in this study; these data were taken from the UCPRC LCI database. The electricity grid mix used for modeling the material production stage was based on the 2012 California grid mix *(93)*. Only the following impact categories and inventory items are reported in this study: Global Warming Potential (GWP); Smog Formation Potential; Particulate Matter 2.5 (PM 2.5); and Primary Energy Demand (PED), which is reported as Total, Nonrenewable (NR), and Renewable (R).

Table 5.3: LCI of the Materials and Energy Items Used in This Study

Item	Unit	GWP [kg CO_2-e]	Smog [kg O_3-e]	PM 2.5 [kg]	PED-Total [MJ]	PED-NR [MJ]	PED-R [MJ]
Electricity	1 MJ	1.32E-01	4.28E-03	2.54E-05	3.09E+00	2.92E+00	1.70E-01
Natural Gas (Combusted)	1 m3	2.41E+00	5.30E-02	1.31E-03	3.84E+01	3.84E+01	0.00E+00
Aggregate (Crushed, Virgin)	1 kg	3.43E-03	6.53E-04	1.59E-06	6.05E-02	5.24E-02	8.03E-03
Binder (Virgin)	1 kg	4.75E-01	8.09E-02	4.10E-04	4.97E+01	4.93E+01	3.40E-01
Crumb Rubber Modifier	1 kg	2.13E-01	6.90E-03	1.05E-04	4.70E+00	3.60E+00	1.10E+00
Reclaimed Asphalt Pavement	1 kg	7.16E-03	1.39E-03	2.70E-06	1.02E-01	1.02E-01	0.00E+00
Rejuvenator	1 kg	6.44E-01	1.57E-04	3.20E-02	4.78E+01	4.76E+01	2.18E-01
Rejuvenator, Bio-based (Soy Oil)	1 kg	3.00E-1	2.60E-2	1.73E-4	3.48E+0	3.48E+0	0.00E+0
Rejuvenator, Aromatic BTX	1 kg	6.44E-1	1.57E-4	3.20E-2	4.78E+1	4.76E+1	2.18E-1

Table 5.4 shows the material production impacts for 2.2 lb (1 kg) of each of the mixes in this study. The GWP for the mixes, expressed in kg CO_2-e, are compared in a bar chart in Figure 5.4.

Table 5.4: Environmental Impacts of Material Production Stage for 2.2 lb (1 kg) of Each of the Mixes

Mix Title	Rejuvenator Type	Unit	GWP [kg CO_{2}-e]	Smog [kg O_{3}-e]	PM 2.5 [kg]	PED-Total [MJ]	PED-NR [MJ]	PED-R [MJ]
HMA (Max 15% RAP)	N/A	1 kg	4.95E-02	4.68E-03	3.25E-05	2.56E+00	2.54E+00	2.23E-02
HMA (Max 25% RAP)	Aromatic BTX	1 kg	4.91E-02	4.37E-03	1.06E-04	2.46E+00	2.44E+00	2.10E-02
HMA (Max 25% RAP)	Bio-Based (Soy Oil)	1 kg	4.83E-02	4.43E-03	3.12E-05	2.36E+00	2.34E+00	2.05E-02
HMA (Max 25% RAP)	No Rejuvenator	1 kg	4.78E-02	4.41E-03	3.09E-05	2.35E+00	2.33E+00	2.01E-02
HMA (Max 40% RAP)	Aromatic BTX	1 kg	4.69E-02	3.90E-03	1.33E-04	2.16E+00	2.15E+00	1.78E-02
HMA (Max 40% RAP)	Bio-Based (Soy Oil)	1 kg	4.58E-02	3.99E-03	2.87E-05	2.02E+00	2.00E+00	1.71E-02
HMA (Max 50% RAP)	Aromatic BTX	1 kg	4.64E-02	3.67E-03	1.77E-04	2.07E+00	2.05E+00	1.67E-02
HMA (Max 50% RAP)	Bio-Based (Soy Oil)	1 kg	4.48E-02	3.79E-03	2.76E-05	1.86E+00	1.85E+00	1.57E-02
RHMA-G	N/A	1 kg	6.00E-02	5.97E-03	1.00E-04	3.50E+00	3.46E+00	4.53E-02

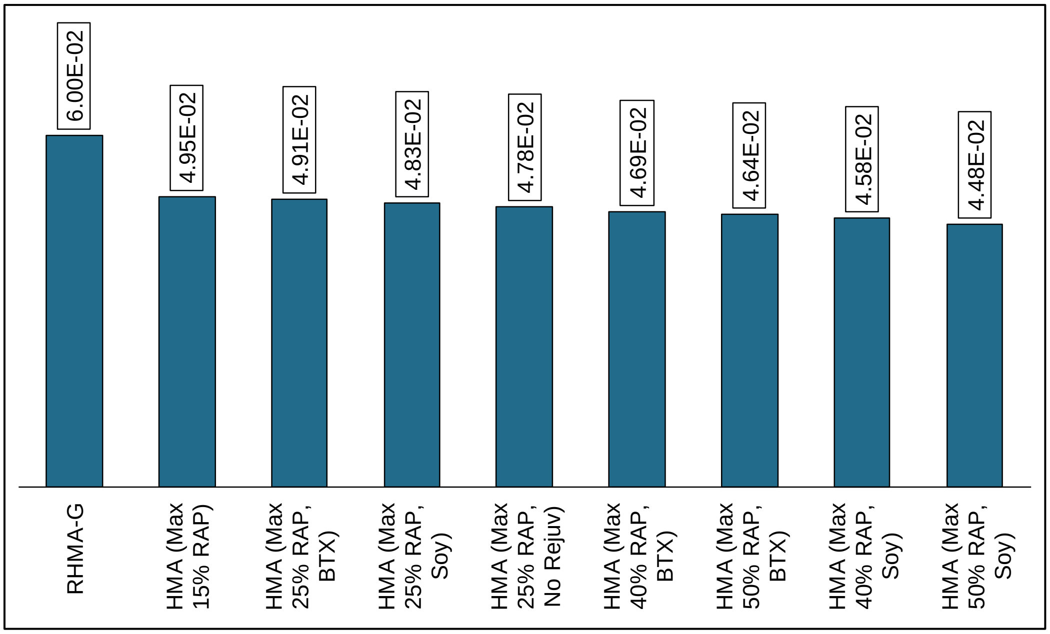

Figure 5.4: Materials stage GHG emissions (kg CO_{2}-e) for 1 kg of each mix.

5.4.3 Data Sources and Data Quality

Table 5.5 summarizes the sources of all the data used in this study and presents further details about the data's quality.

Table 5.5: Data Sources and Data Quality Assessment

Categories	**Data Source**	**Data Quality**							
		Reliability	**Geography**	**Time**	**Technology**	**Complete-ness**	**Reprodu-cibility**	**Represen-tativeness**	**Uncertainty**
Data Type									
HMA Usage per Year	PaveM	Excellent	Excellent	Excellent	Excellent	Very Good	Y	Excellent	Low
LCA-Related									
Electricity	GaBi/	Very Good	Good	Excellent	Excellent	Good	Y	Good	Low
Natural Gas (Combusted)	GaBi	Good	Fair	Excellent	Good	Good	Y	Good	Low
Aggregate (Crushed)	GaBi/Lit.	Good	Good	Good	Good	Good	Y	Good	Low
Bitumen	GaBi/Lit.	Good	Good	Very Good	Good	Good	Y	Good	Low
Crumb Rubber Modifier	GaBi/Lit.	Good	Good	Good	Good	Good	Y	Good	High
Extender Oil	GaBi	Fair	Fair	Good	Poor	Fair	N	Fair	High
RAP	GaBi/Lit	Very Good	Fair	Excellent	Good	Good	Y	Good	Low
Rejuvenator Aromatic BTX	GaBi	Good	Fair	Good	Good	Good	N	Good	High
Rejuvenator Bio-Based (Soy Oil)	GaBi	Good	Fair	Good	Good	Good	N	Good	High
Wax	GaBi	Good	Fair	Very Good	Good	Good	N	Good	Low
Cost-Related									
Material Costs	Caltrans	Excellent	Excellent	Excellent	Excellent	Very Good	Y	Excellent	Low

5.4.4 Limitations or Gaps

Following are the few limitations identified for this study:

- This study was conducted under the assumption that the performance of mixes with higher RAP content is similar to that of mixes currently in use in Caltrans projects. This assumption is currently being investigated and verified through research experiments, field studies, and pilot projects. An investigation is required because all the possible savings in the materials stage due to use of a higher percentage of RAP can be offset by potential performance reductions during the use stage because increased RAP content often results in more frequent maintenance and rehabilitation. All possible savings in the material production stage due to higher percentage of RAP use can be offset by possible reduced performance during the use stage as it results in more frequent maintenance and rehabilitation in the future.
- The quality of materials recycled again at the end of life of HMA with high RAP content is another issue not included in this study's scope. Possible reductions in quality after multiple rounds of recycling is an issue to be considered in a more detailed study once research results in this area are available.

5.5 Results and Discussion

5.5.1 Numerical Results from Case Study

5.5.1.1 GHG Emissions per Year

The total GHG emissions due to the materials stage of HMA and RHMA mixes used in Caltrans projects were quantified by combining the amount of materials used each year and the data in Table 5.3 (LCA results for unit mass of each mix). The full results of the analysis are available in Table D.3 in Appendix D. The material production impacts of HMA over the entire 33-year analysis period (2018 to 2050) resulted in close to 14.1 MMT of CO_2-e for the baseline scenario. RHMA production impacts over the same time period were about 15.5 MMT CO_2-e. RHMA was responsible for about 52 percent of the combined HMA and RHMA GHG emissions. As noted previously, RAP use is currently not permitted in RHMA mixes. The impact of using RAP in RHMA will depend on the benefits resulting from use of a virgin aggregate replacement since binder replacement is not being considered (it is not being considered because it would reduce the number of tires that are recycled).

Increasing the RAP binder replacement of virgin binder from the original 11.5 percent (for the maximum 15 percent RAP baseline) to 20, 35, and 42 percent (for maximum allowable percentages of 25, 40, and 50 percent), as shown in Table 5.2, can result in approximately 96 thousand, 729 thousand, and 870 thousand tonnes of CO_2-e savings compared to the baseline, respectively, during the 33-year analysis period, when using aromatic BTX RAs. These reductions are equivalent to 0.7, 5.2, and 6.2 percent reductions in GHG emissions compared to the baseline over the analysis period, as can be seen in Table 5.6.

When a bio-based RA is used the CO_2-e reductions for the maximum 25, 40, and 50 percent RAP mixes were 326 thousand, 1,052 thousand, and 1,331 thousand tonnes respectively, resulting in 2.3, 7.4, and 9.4 percent reductions compared to the baseline. The case with a 25 percent RAP maximum and use of a softer virgin binder alone with no rejuvenator resulted in a 470 thousand tonne CO_2-e savings compared to the base case, a 3.3 percent reduction. The softer virgin binder has the same environmental impacts as a stiffer virgin binder.

Table 5.6: Total Changes in GHG Emissions Compared to the Baseline for the Analysis Period (2018 to 2050)

Metric	**Unit**	**Max 15%, No Rejuvenator**	**Max 25% RAP, BTX**	**Max 25% RAP, Soy Oil**	**Max 25% RAP, No Rejuvenator**	**Max 40% RAP, BTX**	**Max 40% RAP, Soy Oil**	**Max 50% RAP, BTX**	**Max 50% RAP, Soy Oil**
Total GHGs	MMT CO_2-e	14.1	14.0	13.8	13.7	13.4	13.1	13.3	12.8
CO2-e Changes	MMT CO_2-e	0	-0.096	-0.33	-0.47	-0.73	-1.05	-0.87	-1.33
Percent Changes in GHG Emissions vs. Base Case	%	0.0%	-0.7%	-2.3%	-3.3%	-5.2%	-7.4%	-6.2%	-9.4%

5.5.1.2 Cost Considerations

Table 5.7 shows each treatment's cost per year for each year over the study's analysis period, and assumes that RA is used for all cases and that it costs the same as an asphalt binder. The information in this table is taken from PaveM and the values are corrected as previously described in Section 5.4.1, Major Assumptions.

5.5.1.3 Cost Savings due to RAP Use

Using RAP lowers the amount of virgin aggregate and binder in a mix, which results in cost savings. The cost calculations were done using data extracted from Caltrans Construction Procedure Directive (CPD) 16-8, Attachment 7 *(94).* Table 5.8 shows the prices of virgin aggregate and binder (per short ton, which was later converted into metric tons [tonnes], 1 tonne = 1.10231 short ton).

Table 5.7: Annual Tonnage of Material and Costs

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

Note: NPV =net present value

Table 5.8: Cost ($/ton) of Virgin Binder and Aggregate

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

As noted (in Section 5.5.1.2), the cost of rejuvenator was assumed to be similar to the cost of virgin binder and, therefore, to calculate the cost savings due to increased RAP use, the amount of virgin binder and virgin aggregate replaced only by RAP materials were calculated and multiplied by the estimates shown in Table 5.9, per the instructions of CPD16-8. Table 5.9 shows the cost-saving results per tonne of HMA for the three scenarios with higher RAP content than the baseline.

Table 5.9: Cost Savings for Each Mix ($ per tonne of HMA)

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

Table D.4 in Appendix D shows the cost savings per year across the whole network for each of the scenarios versus the baseline of HMA with up to 15 percent RAP, which can be compared alongside the GHG emission savings shown in Table D.3. Applying the assumed discount rate to the costs shown in Table D.4 results in between 237 and 1,245 million dollars in savings (NPV) from using higher percentages of RAP over the 33-year analysis period. These cost savings correspond to a 95.6 thousand to 1.33 MMT CO_2-e reductions calculated from the values shown in Table D.3, which are 0.7 to 9.4 percent reductions from the baseline. Figure 5.5 shows the amount of savings in total GHG emissions between 2018 and 2050 compared to the baseline for the HMAs with higher RAP content, and Figure 5.6 shows the percent change in emissions for each scenario versus the baseline.

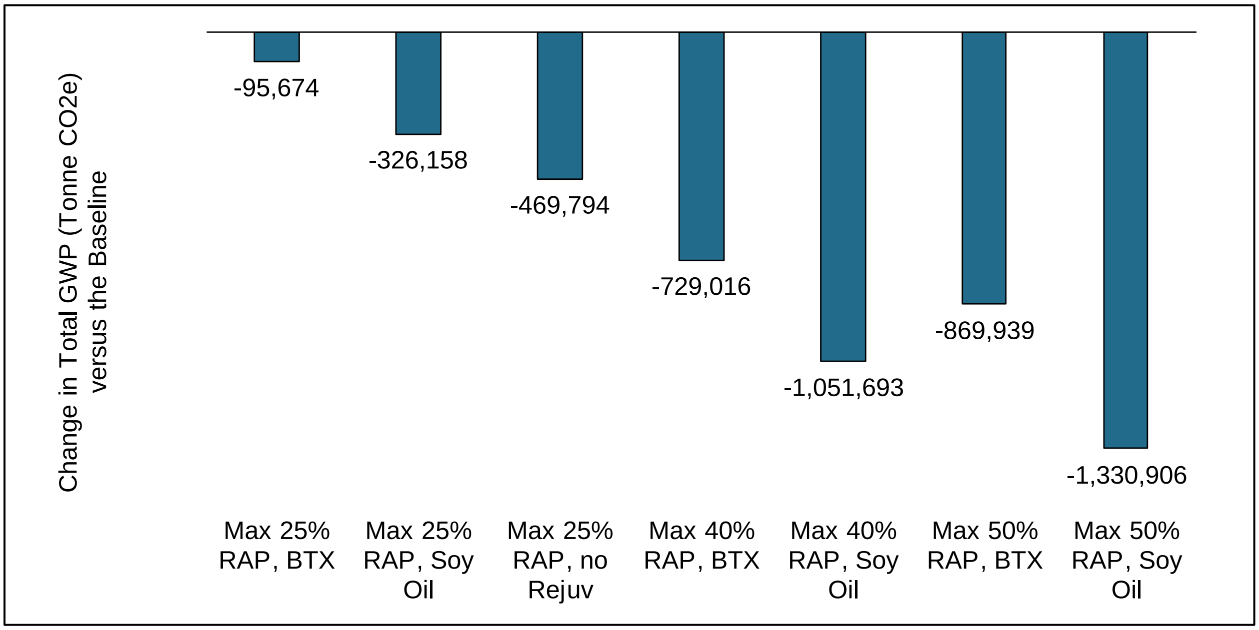

Figure 5.5: Change in total GHG emissions between 2018 and 2050 compared to the baseline for the three scenarios with higher RAP content.

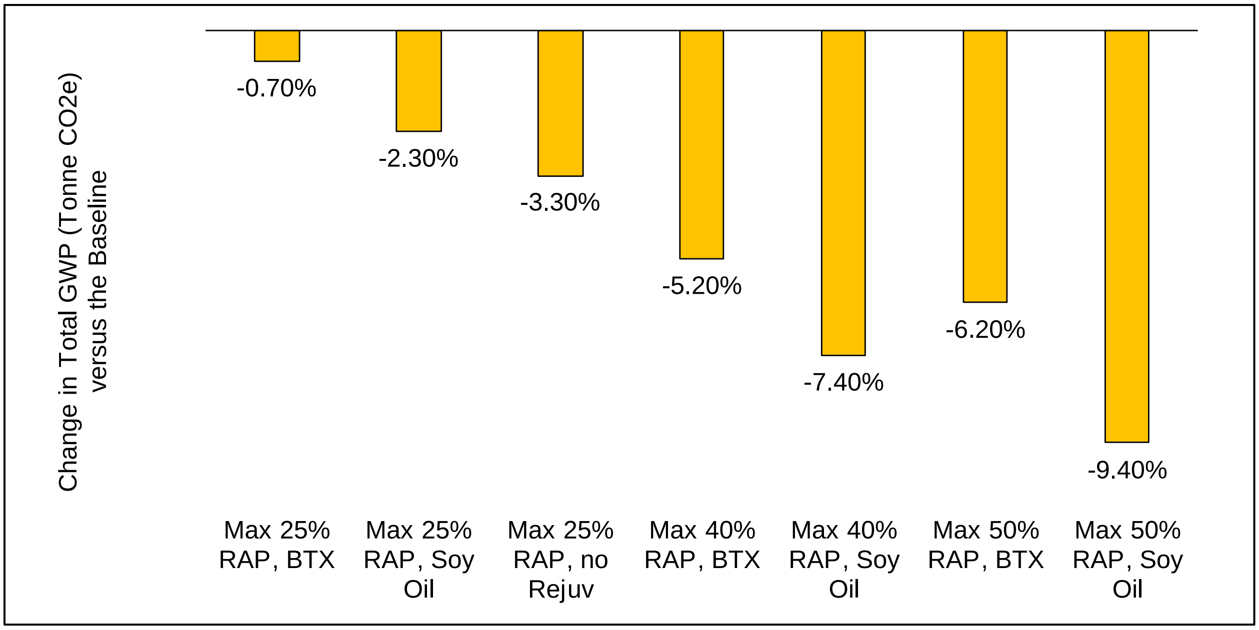

Figure 5.6: Percent change in GHG emissions compared to the baseline for mixes with higher RAP content.

5.5.2 Implications for Total Abatement Potential

The results discussed above show that increased use of RAP in HMA pavements has the potential to reduce GHG emissions and lower costs. Much smaller benefits may be obtained from the use of RAP with RHMA pavements. Use of RAP in RHMA has a much more significant effect on the cracking properties of the mix than it does in HMA, and replacement of rubberized binder with RAP binder also reduces the amount of scrap tires used in pavements for which Caltrans is subject to statutory requirements. However, before RAP percentages can be increased with HMA mixes and before RAP can be introduced into RHMA mixes, known cracking performance issues caused by these increased RAP percentages must be addressed. Once they are, additional methods for further lowering costs and reducing GHG emissions may become available.

As shown in Figure 5.3, RHMA production is as nearly as significant as HMA production in terms of material quantities that will be produced, and as shown in Figure 5.4 the environmental impacts of RHMA per kilogram are greater than those of HMA because of its higher binder content and need for higher mixing temperatures (annual RHMA GHG impacts are about 67 percent of HMA impacts). RHMA's environmental impact is offset by its capacity for use in thinner overlays than can be made with HMA while still yielding the same reflective cracking performance for applications as thin or medium thickness overlays on cracked pavement.

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

5.5.3 Time-Adjusted Global Warming

Time-adjusted warming potential (TAWP) for each of the scenarios was calculated using a tool developed by Kendall *(7)*. The results are shown for various analytical time horizons in Table 5.10. The 100-year time horizon results are compared with results from the previous section that were not adjusted for the emissions' timing. On average, the time adjustments resulted in a 13.5 percent reduction of total GHG emissions in each scenario. Table 5.10 compares the total GHG emissions for each scenario with and without time adjustments.

Table 5.10: Time-Adjusted Global Warming Potential (tonnes CO_2-e) for Each Mix

Time Horizon (Years)	Max 25% RAP, BTX	Max 25% RAP, Soy Oil	Max 25% RAP, No Rejuv.	Max 40% RAP, BTX	Max 40% RAP, Soy Oil	Max 50% RAP, BTX	Max 50% RAP, Soy Oil
50	9,962,567	9,798,901	9,696,905	9,512,832	9,283,700	9,412,763	9,085,431
100-Year TAWP	12,137,585	11,938,187	11,813,924	11,589,664	11,310,508	11,467,748	11,068,953
100-Year GWP Unadjusted	14,029,843	13,799,359	13,655,723	13,396,501	13,073,824	13,255,578	12,794,611

5.5.4 Summary of Abatement Potential Information

The information regarding the abatement potential calculations presented in this chapter is summarized in Table 5.11 for the 35-year analysis period.

Table 5.11: Summary of Abatement Potentials for Increased RAP Use in Asphalt Pavements in California

Mix	CO_2-e Change (MMT)				Average Annual over 33-Year Analysis Period		
	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Life Cycle Cost Change ($ million)	Benefit/Cost ($/tonne CO_2-e reduced)	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Life Cycle Cost Change ($ million)
Max 25% RAP, BTX	-0.10	-0.08	-237	-2,479	-0.003	-0.003	-7.2
Max 25% RAP, Soy Oil	-0.33	-0.28	-237	-727	-0.010	-0.009	-7.2
Max 25% RAP, no Rejuv	-0.47	-0.41	-534	-1,136	-0.014	-0.012	-16.2
Max 40% RAP, BTX	-0.73	-0.63	-1,008	-1,383	-0.022	-0.019	-30.5
Max 40% RAP, Soy Oil	-1.05	-0.91	-1,008	-959	-0.032	-0.028	-30.5
Max 50% RAP, BTX	-0.87	-0.75	-1,245	-1,431	-0.026	-0.023	-37.7
Max 50% RAP, Soy Oil	-1.33	-1.15	-1,245	-936	-0.040	-0.035	-37.7

6 STRATEGY 5: ALTERNATIVE FUEL TECHNOLOGIES FOR AGENCY VEHICLE FLEET

6.1 Strategy Statement and Goal

The California economic sector that contributes most to statewide emissions is transportation, and 89 percent of these emissions come from on-road transportation, primarily from the combustion of gasoline by light-duty vehicles and diesel by heavy-duty vehicles *(95)*. One statewide strategy for reducing GHG emissions is to move to a vehicle fleet that relies much more heavily on electricity than on petroleum combustion for propulsion. For heavy-duty vehicles, a second potential alternative parallel to electrification would be to produce combustible fuels, such as biodiesel, from renewable sources. Although Caltrans vehicles make up only a very small part of the statewide vehicle fleet, the department's introduction of alternative propulsion methods could contribute to reducing the fleet's GHG emissions. The case described below compares the emissions from the current fleet with those from conversion, where feasible, to vehicles using electricity and biodiesel.

This case study's goal was to examine different pathways for adopting AFVs into the Caltrans fleet, from the time of this writing until the end of the analysis period, and then calculating the resulting impacts on GHG emissions and costs from adoption of those vehicles.

6.2 Introduction

6.2.1 Abatement Strategy or Technology

The US Energy Policy Act (EPAct) of 1992 defined alternative fuels and assigned the United States Department of Energy (US DOE) to develop a regulatory program for selected state fleets as launching pads for advanced vehicles using alternative fuels *(97)*. The goal of EPAct was to increase clean energy use and improve overall energy efficiency. A brief history of legislation related to alternative fuels at the federal and state levels is provided in Appendix E.

The abatement strategy is to replace Caltrans vehicles that currently burn gasoline and diesel with alternative fuel vehicles (AFVs) wherever possible. Light-duty AFVs include various types of electric and fuel-cell cars and sport-utility-vehicles (SUV) that can replace gasoline-powered vehicles. Heavy AFVs are trucks that burn a type of diesel fuel that is partly made with renewable resources. These AFVs replace trucks burning diesel made only with petroleum. A major consideration for the replacement of gasoline-powered vehicles with electric vehicles is the travel range of the replacements.

The use of alternative fuels by the Caltrans fleet decreased 16.5 percent between 2014 and 2016, but this was reversed by large increases of 23.5 and 35.5 percent in 2017 and 2018, respectively *(96)*. The sudden trend change was mostly due to the adoption of a new type of renewable diesel, referred to as high-performance renewable diesel (HPRD). As a direct result of Caltrans adopting HPRD, use of B20 biodiesel, which had been the common biodiesel choice, has effectively dropped to zero, as shown in Figure 6.1. Figure 6.2 shows the number of alternative fuel vehicles, including electric vehicles (EVs), that Caltrans acquired between 2013 and 2018 based on data from the same source *(96)*. Caltrans acquired 253 AFVs between 2013 and 2018: 140 plug-in hybrid electric vehicles (PHEVs), 37 fuel-cell vehicles (FCVs), and 76 battery electric vehicles (BEVs).

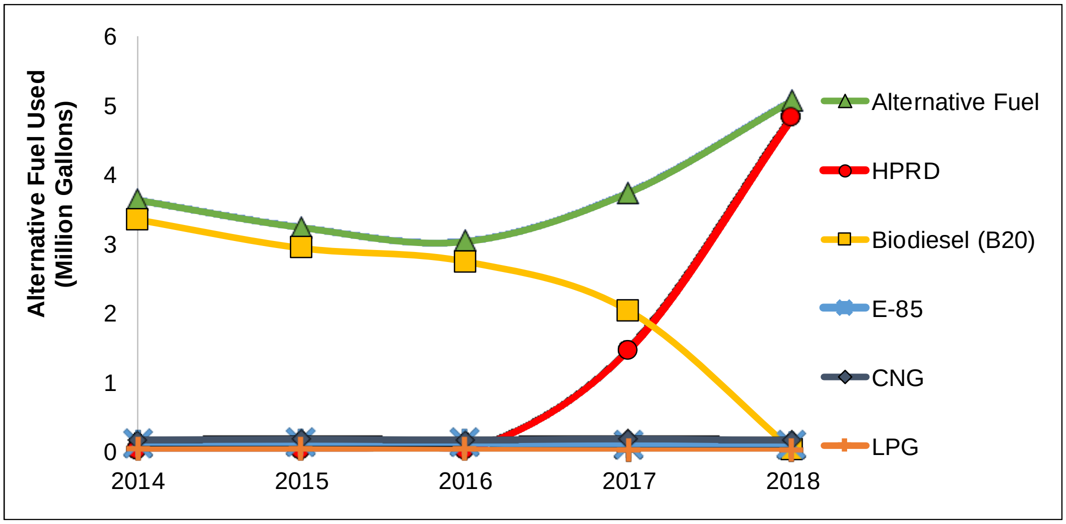

Figure 6.1: Alternative liquid fuel consumption by Caltrans fleet between 2014 and 2018.
(HPRD: High-performance renewable diesel; E-85: Fuel Blend with 85 Percent Ethanol and 15 Percent Gasoline; CNG: compressed natural gas; and LPG: liquefied petroleum gas)

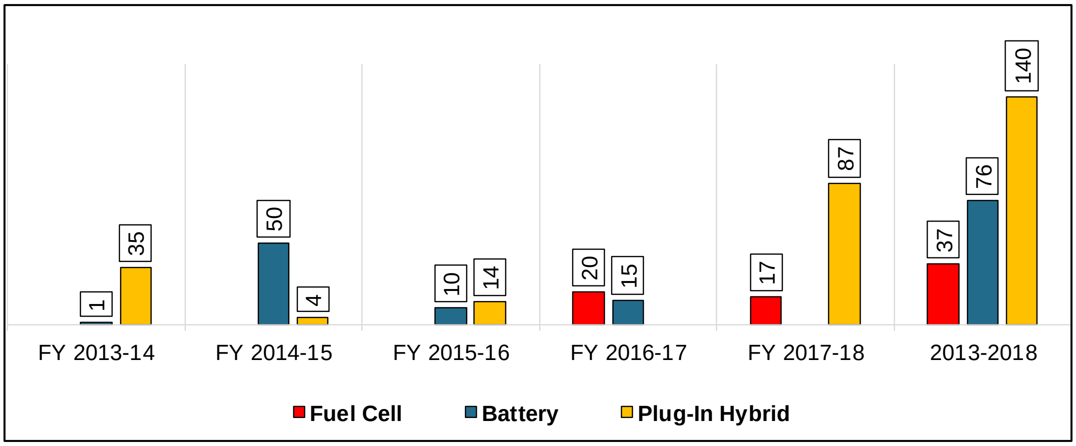

Figure 6.2**: Alternative fuel vehicles acquired by Caltrans since 2014 (96).**

6.3 Scope of the Study

6.3.1 Scope for Implementation across the Network

The study scope covers the environmental impacts and cost implications of the complete life cycle of all the vehicles in the Caltrans fleet. These life cycle stages have been subdivided into the following categories:

- Vehicle life cycle stages:
    - Vehicle production stage, which includes all the processes from raw material extraction to delivery of the vehicle to an end user; and
    - Vehicle end-of-life stage, in which the vehicle is either recycled, landfilled, or transferred to a third party and salvage value is assigned.
- Use stage:
    - Fuel emissions and costs, including:
        - all the upstream impacts of fuel production (well to pump);
        - fuel consumption in the vehicle (pump to wheel);
        - maintenance and repairs; and
        - registration fees, tax, and insurance (state vehicles are exempt from these cost items, however, relevant data were collected to get a sense of the order of magnitude compared to other cost items).

6.3.2 Functional Unit and Graphical Representation of System Boundary

The functional unit for the study is all the vehicles categorized as either an automobile, sport utility vehicle (SUV), pickup, van, or truck in the Caltrans fleet. Figure 6.3 shows the study's system boundary, which includes the complete vehicle cycle and complete fuel cycle but does not cover fueling station infrastructure.

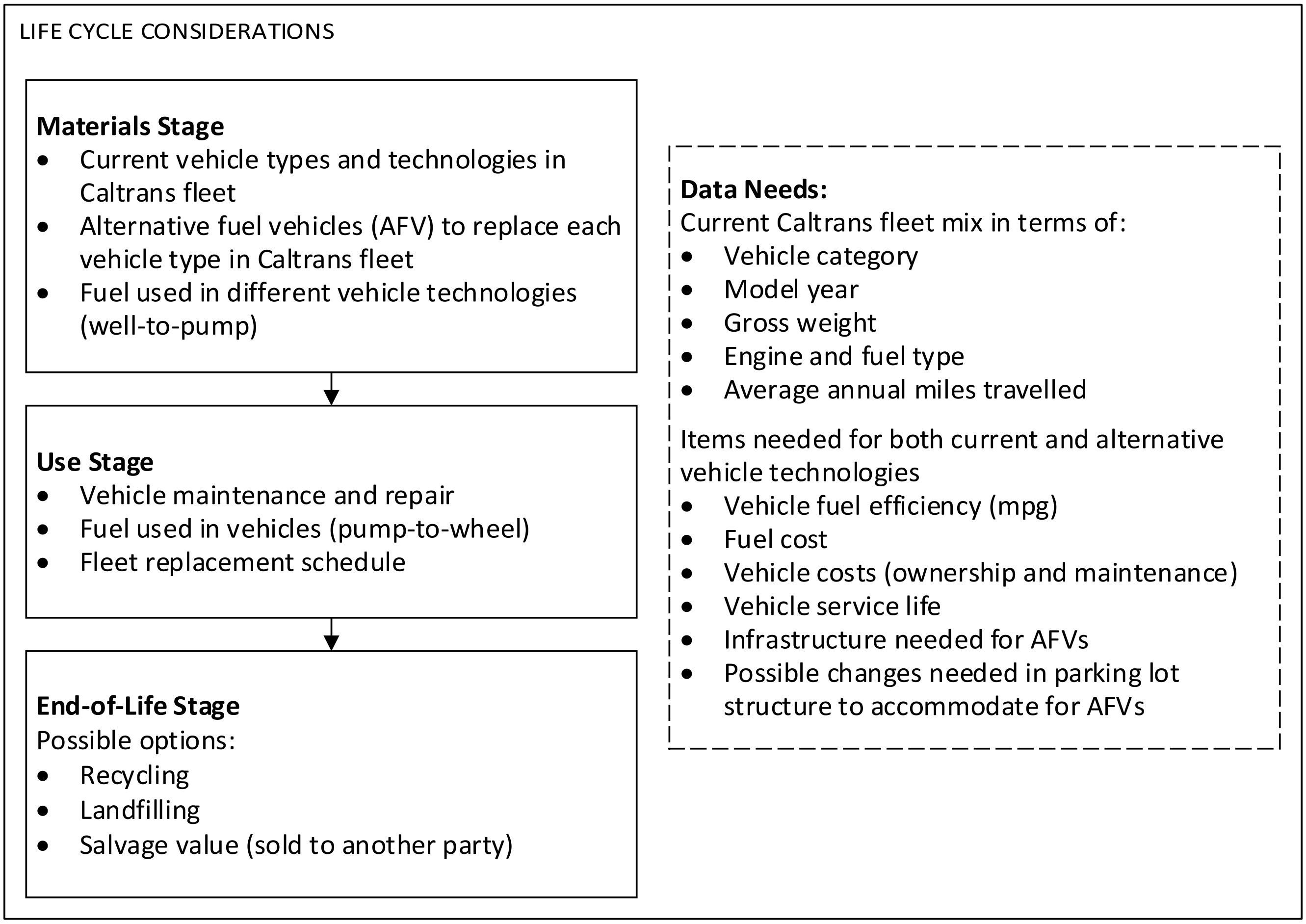

Figure 6.3: Scoping system diagram for assessing Caltrans fleet life cycle costs and environmental impacts.

6.4 Calculation Methods

6.4.1 Major Assumptions

To conduct this LCA study, a framework was developed based on the goal and scope definition phase. The framework developed, shown in Figure E.1 in Appendix E, served as a road map for the study and its main data sources are identified there. This chapter details the steps taken for the analysis and includes plots that illustrate the trends and comparisons of the results for the alternatives considered.

The first step in the framework is to determine potential vehicle replacement scenarios so a model was developed for the replacement process. The model was then run for the business-as-usual case and for three different alternative fleet vehicle replacement schedule scenarios:

- Business-as-Usual (BAU): which follows Caltrans's historical vehicle replacement practice, based on an analysis of data in a Caltrans Equipment database
- Department of General Services (DGS): following the DGS policy for vehicle replacement

- All-at-Once: changing all vehicles to AFVs in the year 2018
- Worst-Case: AFVs were assigned based on Table 6.1 for all three scenarios mentioned above. However, an extra scenario was added to calculate the impacts for a worst-case scenario in which Caltrans keeps the current fleet mix (in terms of vehicle type and fuel combination, following BAU replacement schedule) throughout the analysis period and only uses regular and HPRD diesel vehicles. This case is coded as the Worst-Case scenario in the results section.

The model developed in this analysis allows a user to pick from among the *average annual vehicle miles traveled* (AVMT) values (calculated based on vehicle type) of all 9,325 records in the model database, or the *actual AVMT* based on 2017 data provided by DGS. (Note: during the data-cleaning process, missing and false data in actual AVMTs were replaced by the average AVMT data records of similar vehicle types and model years.) The analysis results are based on the actual AVMT of the Caltrans fleet.

The salvage value of vehicles in service at the end of the analysis period for vehicle costs were calculated based on the remaining useful life of each vehicle (explained in detail in subsequent sections of this technical memorandum).

Table 6.1: AFV Substitutes Chosen for Various Vehicle Types in Caltrans Fleet (Substitute 2 defined for cases where the vehicle average daily miles traveled is larger than the 150 miles per charge of EVs.)

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

Notes: EV: electricity; E85: High-level ethanol-gasoline blends (up to 85%); DSL-R100: 100% renewable diesel; PHEV: plug-in hybrid electric vehicle

Table 6.2 shows the replacement schedule for the BAU and DGS cases. The AFV substitute for each vehicle type was chosen based on the information provided in Section 6.2.1 regarding the AFVs currently available in the market and the Caltrans AFV substitution list shown in Table 6.1. For the study, an EV mileage range of 150 miles per charge was assumed, and PHEVs rather than EVs were substituted for vehicles that had average daily VMT greater than 150. The latter assumption was made to maintain the original functionality and level of service in terms of recharging.

Table 6.2: Two Vehicle Replacement Schedules Considered in this Study

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

Note: LD: light duty, MD: medium duty, HD: heavy duty

The model developed in this study is capable of considering possible reductions in fuel efficiency of individual vehicles with time as a user input for each vehicle type. However, online research showed that if regular maintenance is conducted, only insignificant changes in fuel efficiency will occur over time. Therefore, the results presented here do not include changes to vehicle fuel efficiency over time.

The second step in the framework was to calculate the GHG emissions impacts for each vehicle replacement scenario and for the BAU case following LCA principles.

A discount rate of 4 percent was assumed for the LCC calculations, although this amount can be modified by a user. It should be noted that state vehicles are exempt from registration fees and taxes, and fleet insurance is typically handled through in-house insurance programs. However, the model has the capability of calculating these values to provide an order of magnitude for comparison purposes.

6.4.2 Calculation Methods

6.4.2.1 Caltrans Fleet Databases

Data regarding the Caltrans fleet were collected from two sources. One database was the California State Fleet database, which is publicly available on the Department of General Services website *(98)*. This database had data for all state agency fleets for reporting years 2011 to 2014 and contained more than 106 thousand rows of data related to the Caltrans fleet (out of a total of more than the 257 thousand data rows for all state agencies). Data related to passenger vehicles, vans, and trucks constituted 79,218 rows of Caltrans data across the four years of reported data.

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

DB2011-14 contained the following major data categories:

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

The second database used, which only had data for 2017, was acquired through email correspondence with the DGS and consisted of the most recent data for the Caltrans fleet. This database, referred to as DB2017 throughout this chapter, consisted of the following information:

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

Two separate databases were used because the 2017 database did not include data related to vehicle acquisitions and disposals, which were needed for this study's cost analysis section. The main use of DB2011-14 was for studying historical trends in terms of annual expenditure on buying new vehicles, typical salvage value realized, and the typical mileages at which Caltrans disposed of vehicles.

6.4.2.2 Caltrans Fleet Summary Statistics

Caltrans fleet vehicles are divided into four major categories and twelve vehicle types. Details on the fleet are reported in Appendix E, which includes information about vehicle distribution by fuel type, gross weight category, general category, and vehicle type. Pickups constitute more than 43 percent of all Caltrans vehicles, followed by trucks and passenger cars with 36 and 15 percent shares, respectively. In this report, *passenger cars* refers collectively to SUVs and to subcompact, compact, midsize, and full-size sedans. SUVs make up the largest share of passenger cars, followed by compact automobiles, with 37 and 34 percent, respectively.

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

6.4.2.3 Annual Vehicle Miles Traveled

The average annual vehicle miles traveled (AVMT) by vehicle category based on DB2017 is shown in Table E.3 in Appendix E. Light-duty trucks had the greatest AVMT, 23,172 miles per year, while medium-duty vans had the lowest,7,800 miles per year. The database included no data for the subcompact automobile category so it was assumed that subcompact sedans have the same AVMT as compact vehicles.

6.4.2.4 Vehicle Fuel Efficiency

Historical data for vehicle fuel efficiency were collected from the US Environmental Protection Agency (US EPA) website *(99)* and the Energy Information Administration (US EIA) *(100)*. These data were used to estimate fuel consumption based on the AVMT assigned to each vehicle currently in the Caltrans fleet.

The projected future vehicle fuel efficiency data were taken from the EIA website. EIA had more granular data for fuel efficiency projections, in terms of vehicle type and fuel combinations. The full dataset collected is available in the main model.

6.4.2.5 Fuel Costs

Historical prices for alternative fuels were collected from the Alternative Fuel Data Center (AFDC) *(101)*. The prices are expressed in units of “dollars per gasoline gallon equivalent (GGE).” The data in this section will be combined later with vehicle fuel efficiency values (referred to from here forward as “mpg”) to calculate the cost of “one mile traveled” for each vehicle fuel combination. LPG, B100 (diesel with 100 percent biodiesel), and E85 have consistently been the most expensive fuels among all alternative fuels since 2013, while electricity has been the least expensive.

AFDC reported that they decided not to report the price of diesel from renewable sources (RD100, a 100 percent renewable diesel) due to the lack of a reliable data source, even though RD100 has been available on the California market for several years. Because the literature survey and Internet research did not yield much reliable cost data for RD100, it was decided to assume B100 prices for R100, where needed.

Projections of future fuel prices were also taken from the EIA website. EIA only provides price projections for regular diesel; therefore, historical data were used to calculate the price ratios of B100 and B20 over regular diesel in the past three years. The calculated price ratios were then applied to EIA's projections of regular diesel prices to obtain price projections for B20, B100, and RD100. The results showed that in the US market B20 has been priced on average at 95 percent of regular diesel since 2016, while B100 was about 39 percent more expensive. The RD100 price was assumed to be the same as that of B100 diesel due to a lack of better data, as explained in the previous section. Figure E.4 in Appendix E shows the final values used in the model.

Historical data were collected to account for the energy price differences between California and the national averages, and correction factors were applied for the prices of gasoline, diesel, electricity, and natural gas (details available in Appendix E.)

6.4.2.6 Vehicle Costs

The DGS website for reporting years 2011 to 2014 provided historical data on vehicle purchase prices for all state agencies. Data were selected from DB2011-14 data from the reporting year 2014 for vehicles purchased after 2004. The selected data were used to conduct linear regression and to develop equations for vehicle price versus age for each vehicle type in the model.

Price projections for every vehicle fuel combination used in this study were obtained from EIA *(102)*. Figure E.5 shows the average annual growth rate for vehicle prices between 2018 and 2050 (it should be noted that actual projections did not necessarily follow a linear pattern).

6.4.2.7 Salvage Value

Regardless of the vehicle replacement schedule, there is salvage value in vehicles that are traded before the end of their useful service life. This salvage value needs to be accounted for, both in terms of monetary value and the environmental impact from the vehicle cycle. This section explains the calculation methodology used in the model to estimate vehicle salvage values. There were two possible approaches for considering salvage value in the analysis. One approach was to use the historical data available through DB2011-14, and the other was to use industry-wide accepted rates of vehicle depreciation with time. Both methods are discussed in Appendix E.

6.4.2.8 Vehicle Cycle Impacts

Vehicle cycle impacts include all the energy consumption and emissions due to vehicle production, stretching from raw material extraction to delivery of the new vehicle to an end user. Further, the processes at the end of a vehicle's service life (either being dumped in a landfill or transported and recycled at a recycling facility) should be included in this cycle. Other items included in the vehicle life cycle are the fluids, batteries, and tires that the vehicle used over its lifetime. Almost all the data used for vehicle cycle impacts in this study were collected from the GREET model *(103)*, unless stated otherwise.

The vehicle cycle impacts were reported in four main categories: 1) components, 2) assembly, disposal, and recycling (ADR), 3) batteries, and 4) fluids. The components category consists of the following items: body, powertrain, transmission, chassis, traction motor, generator, electronic controller, and hydrogen storage.

To account for changes in vehicle weights over the study's 33-year analysis period, weight projections by vehicle type were taken from EIA *(104)*. However, there were two challenges to address: 1) EIA does not provide weight projections for different fuel technologies and only has data based on vehicle type; and 2) truck vehicle cycle GHG emissions were not available in any major sources. The approach to addressing these challenges is explained in Appendix E.

6.4.2.9 Fuel Use Impacts (Well-to-Wheel Impacts)

Vehicles use also contributes to the environmental impacts attributable to fuel use, which consists of two separate stages:

- *Fuel production stage impacts.* These include the energy consumption and environmental impacts of all the upstream fuel production processes and those that make the fuel available at the pump; collectively these are called well-to-pump (WTP) impacts. The terminology was coined to refer to conventional, petroleum-based fuels originating from crude oil extracted from wells. However, the term now applies to fuels manufactured using other pathways.
- *Impacts from fuel combustion by vehicles.* This refers to emissions attributable to use-stage vehicle fuel combustion. This stage is referred to as pump-to-wheel (PTW).

The collective impacts of WTP and PTW are referred to as well-to-wheel (WTW) impacts. WTW impacts are expressed in grams of CO_2-e per mile of travel. Figure E.6 shows boxplots of WTP, PTW, and WTW impacts for different vehicle fuel technologies. While EVs and FCVs have the highest WTP impacts, their zero tailpipe emissions during the use stage (zero PTW impacts) make them better options than internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), and PHEVs when the full impacts of WTW are considered.

Each vehicle technology's GHG impact variability, as shown in the boxplots, is due to the alternative feedstocks/pathways available for each vehicle fuel technology. The bar chart at the lower right corner of the figure shows the maximum-to-minimum WTW impact ratio for each vehicle fuel technology. The extremely large ratios of ICEVs and EVs, 34.2 and 24.2 respectively, show how drastically different feedstock/pathways can change these vehicles' WTW emissions.

Note: The data used to develop the charts in Figure E.6 were taken from the GREET WTW Calculator tool released in November 2018 *(105)*. For EVs, the following electricity sources were considered in the calculator: coal, coal boiler (combined heat and power), forest residue, geothermal, natural gas combined cycle (combined heat and power), and solar. The "2017 California" electricity grid mix was used.

6.4.2.10 WTW and Vehicle-Cycle Impact

Results from using the final data model to quantify vehicle-cycle and fuel-cycle impacts are presented in Appendix E, Figure E.7. This figure includes plots of the results for light-duty vehicles. The results of ICEVs (labeled "GAS" in the figure) have the highest total GHG emissions per mile, with 448 grams of CO_2-e per mile, followed by HEVs, FCVs, and PHEVs with 336, 307, and 268, respectively. EVs have the best performance, producing 233 grams of CO_2-e per mile, 48 percent less than ICE vehicles. The assumption was made that the emissions from electricity used in California, rather than the less emissions-intensive electricity produced in California would be used for this study. In 2017, the amount of electrical energy used in the state exceeded the electrical energy produced there by 48 percent *(106)*. Vehicle operation constitutes the main portion of total GHG emissions for ICEVs, HEVs, and PHEVs, with 74.1, 71.5, and 42.4 percent, respectively, while for EVs and FCVs this number is zero since they have no tailpipe GHG emissions.

6.4.3 Data Sources and Data Quality

Table 6.3 shows the data sources used to develop the study's model and a quality assessment of each.

Table 6.3: Data Sources Used in This Study and Data Quality Assessment

Categories	**Data Sources**	**Data Quality**							
		Reliability	**Geography**	**Time**	**Technology**	**Comp-leteness**	**Reproduc-ibility**	**Represen-tativeness**	**Uncer-tainty**
Data Type									
Caltrans Fleet Mix and Average Miles Traveled per Year by Vehicle Type	Caltrans Fleet Database 2017@DGS website	Excellent	Excellent	Excellent	Excellent	Very Good	N	Excellent	Low
Historical MPG Values by Vehicle Type	USEPA	Excellent	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Projections of MPG by Vehicle Type	EIA	Very Good	Very Good	Excellent	Excellent	Excellent	N	Excellent	High
Depreciation Rate	DGS + Literature	Very Good	Excellent	Excellent	Excellent	Excellent	Y	Excellent	Medium
LCA-Related									
Vehicle-cycle Impacts for Light-Duty Vehicles	GREET + AFLEET	Excellent	Excellent	Very Good	Excellent	Excellent	Y	Excellent	Low
Vehicle-cycle Impacts for Trucks	Based on (GREET + AFLEET) Data	Very Good	Excellent	Very Good	Good	Good	Y	Good	Medium
Fuel Impacts (WTP, PTW, and WTW)	GREET + AFLEET	Excellent	Excellent	Excellent	Excellent	Excellent	Y	Excellent	Low
Projections of Vehicle Weight	EIA	Very Good	Very Good	Excellent	Excellent	Excellent	N	Excellent	High
Cost-Related									
Energy Cost Comparison of CA vs US Averages	EIA	Excellent	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Historical Price of Alternative Fuels	AFDC	Excellent	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Projections of Alternative Fuel Prices	EIA	Very Good	Very God	Excellent	Excellent	Excellent	N	Very Good	High
Historical Price of Vehicle by Vehicle Type	Caltrans Fleet Database 2011-14@DGS website	Excellent	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Projections of Vehicle Price by Vehicle and Fuel Technology Combination	EIA	Very Good	Very Good	Excellent	Excellent	Excellent	N	Very Good	High
Registration Fees	CA DMV website	Excellent	Excellent	Excellent	Excellent	Excellent	N	Excellent	Low
Maintenance and Repair Cost per Vehicle Type	GREET + AFLEET	Very Good	Very Good	Very Good	Very Good	Very Good	N	Excellent	High

6.4.4 Limitations or Gaps

The analysis in this technical memorandum has the following limitations and gaps that need to be evaluated in future research:

- The study's analysis does not include the cost and environmental impacts of building and maintaining fueling infrastructure.
- Maintenance and upkeep of parking spaces for the fleet have not been included in the study's system boundary.
- California is aggressively moving towards decarbonization/minimization of GHG emissions in all its economic sectors, and especially the electricity sector, with measures such the Renewable Portfolio Standard *(107),* which mandates that at least 50 percent of the electricity in the California grid mix must come from renewable sources by 2030. Therefore, one fuel pathway expected to have major reductions in WTP impacts is electricity. However, the expected WTP reductions that would occur from meeting the 50 percent target for the electricity mix have not been considered in this study, mainly because this is an initial study with only limited scope. However, the fact that more than 80 percent of the state fleet consists of medium-duty pickups and trucks for which an EV option is not now available reduces the current significance of this issue.
- As with the preceding item, no consideration was given to potential changes in the price of gasoline and diesel over the analysis period.

6.5 Results and Discussion

6.5.1 Numerical Results from Case Studies

The results of the case studies are shown in Table 6.4 to Table 6.7. Figure 6.4 compares LCC across all four cases. Figure 6.5 focuses on GHG emissions at various stages of the vehicle and fuel cycles. 8 in Appendix E compares the total fuel consumption during the analysis for each fuel. The fuel consumption with time for each of the cases is presented in Appendix E in Table E.8.

The data in Table 6.4 show that the total LCC of the BAU case, without considering registration fees and insurance costs, has an NPV of $2.355 billion compared to values of $2.512, $2.425, and $1.996 billion respectively for the DGS, All-at-Once, and Worst-Case scenarios; this BAU value is equivalent to 7.4 and 3.3 percent respective cost increases over the DGS and All-at-Once cases, but a 16.9 percent decrease compared with the Worst-Case scenario.

In all four cases, the purchase of new vehicles was the largest portion of total net costs, ranging between 59 and 83 percent.

Fuel costs were the second-largest expense item for all cases, ranging between 30 and 35 percent of total net costs. On average, maintenance and repair made up about 24 percent of total net costs.

The DGS case salvage value was highest among the four cases, as the policy would require changing vehicles when they are newer than has been done in Caltrans historical practice. In the DGS case the salvage value equaled -48 percent of total net costs, while in the other three cases this value was approximately 30 percent.

Looking at the GHG emissions data in Table 6.5, benchmarking of the fleet GHG emissions in the year 2017 shows that WTW impacts are more than 69,000 tonnes of CO_2-e. A total GHG emissions value for 2017 that included vehicle-cycle impacts could not be calculated as vehicle purchase data for the year 2017 were unavailable.

Total GHG emissions during the analysis period from 2018 to 2050 reached close to 1.46 MMT of CO_2-e for the BAU case, while the results for the DGS, All-at-Once, and Worst-Case scenarios the results were approximately 1.43, 1.32, and 2.25 MMT. These numbers show 2 and 9 percent total GHG emissions savings for the DGS and All-at-Once scenarios compared to BAU.

The Worst-Case scenario results show the consequences of inaction. If Caltrans did not adopt AFVs and maintained its current mix of vehicle technologies and fuels, the result would be a 54 percent increase in its fleet’s GHG footprint in the time between the present and the year 2050. The total fuel consumption by fuel type for each case is presented in Table 6.6.

The negative well-to-pump (WTP) values over the analysis period that appear in Table 6.5 are due to AFV use, even in the BAU case. These values include emissions from production of both the electricity used in California and liquid fuels. For the WTP process, the increasing use of bio-based diesel results in net carbon sequestration and hence to fewer GHG emissions.

Table 6.7 shows a breakdown of GHG emissions for the cases with negative GWP values for WTP. The fuel in these cases are E85 from corn or 100 percent renewable diesel from forest residue, and the negative GWP for WTP is only due to the fuel feedstock across all cases, which includes sequestered carbon dioxide, after inclusion of processing and transportation to the pump. The fuel cycle values presented in this table were taken directly from the 2018 Excel-based model GREET 1 *(103).* (Use the fuel vehicle combinations in the fourth column of Table 6.7 to access the data by searching within the GREET 1 *Excel* file.)

The assumptions and calculation details for the LCA of each fuel are presented in separate tabs in the GREET main file. For the specific case of renewable diesel from forest residue, the main reference used for the input data and assumptions was Jones et al. *(108)*. The background, assumptions, and calculation methods used to calculate the fuel cycle impacts of all the different vehicle fuel combinations provided in GREET and used in this study are available in Elgowainy et al. *(109)*, Cai et al. *(110)*, Elgowainy et al. *(111)*, and Cai et. al *(112)*.

Table 6.4: Comparison of Life Cycle Cost (in millions of dollars) across Cases

Cost Item	BAU		DGS		All-at-Once		Worst-Case	
	Value	% of Net Cost	Value	% of Net Cost	Value	% of Net Cost	Value	% of Net Cost
Fuel	1,323	35%	1,299	32%	1,322	34%	949	30%
Purchase of New Vehicle	2,263	59%	3,313	83%	2,400	62%	2,052	64%
Registration Fees	34	1%	49	1%	36	1%	32	1%
Insurance	359	9%	343	9%	356	9%	359	11%
Maintenance Repair	920	24%	923	23%	925	24%	827	26%
Salvage Value	-1,090	-29%	-1,916	-48%	-1,178	-31%	-1,022	-32%
Total Net Cost	3,809	100%	4,010	100%	3,861	100%	3,198	100%
Net Present Value	2,355	62%	2,512	63%	2,425	63%	1,996	62%
Total Net Cost (w/o R&I)*	3,417	90%	3,618	90%	3,469	90%	2,807	88%
Net Present Value (w/o R&I)	2,124	56%	2,281	57%	2,195	57%	1,765	55%
Change in NPV vs BAU (w/o R&I)	0.0	N/A	156.8	N/A	70.8	N/A	-358.7	N/A
Percent Change in NPV vs BAU (w/o R&I)	0.0%	N/A	7.4%	N/A	3.3%	N/A	-16.9%	N/A

* without including registration fees and insurance costs

Table 6.5: Comparison of Total GHG Emissions between 2018 and 2050 (Tonnes of CO_2-e) and Cost of GHG Abatement (dollar per Tonne of CO_2-e abated)

GHGs (tonne CO_2-e)	2017 Emissions	BAU	DGS	All-at-Once (in 2018)	Worst-Case Scenario
Well to Pump (WTP)	12,679	-1,110,670	-1,185,363	-1,289,950	352,826
Pump to Wheel (PTW)	56,885	2,218,095	2,179,817	2,245,951	1,570,324
Well to Wheel (WTW)	69,564	1,107,425	994,454	956,001	1,923,150
Net Vehicle Cycle	N/A	384,514	461,520	401,785	353,849
Total GHG Emissions (WTW + Net Vehicle Cycle)	69,564	1,459,127	1,433,508	1,321,527	2,245,997
Change in GHG Emissions vs BAU	N/A	0	-25,619	-137,600	786,870
Percent Change vs BAU	N/A	0%	-2%	-9%	54%
Abatement Cost ($/Tonne CO_2-e)	N/A	$0.0	$6,119	$514	N/A

Table 6.6: Comparison of Total Vehicle On-Board Liquid Fuel Consumption (in 1,000 of gasoline or diesel gallon equivalent [GGE or DGE]) between 2018 and 2050 by Fuel Type across All Cases

Fuel Type	BAU	DGS	All-at-Once (in 2018)	Worst-Case Scenario
CNG	306	184	85	2,216
DSL	0	0	0	0
DSL-B20	0	0	0	0
DSL-HPR	23,165	14,293	5,272	132,344
DSL-R100	193,487	201,675	216,699	0
E85	7,395	5,484	4,846	22,629
ELEC	6,247	6,729	6,998	182
GAS	13,893	7,572	2,494	70,794
HEV	68	45	18	785
HYD	90	44	4	249
LPG	204	204	204	5,814
PHEV	1,950	1,856	1,782	743
Total	**246,805**	**238,085**	**238,401**	**235,757**
% Change vs BAU	**0.0%**	**-3.5%**	**-3.4%**	**-4.5%**

Table 6.7: Breakdown of GHG Emissions for Cases with Negative WTP

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

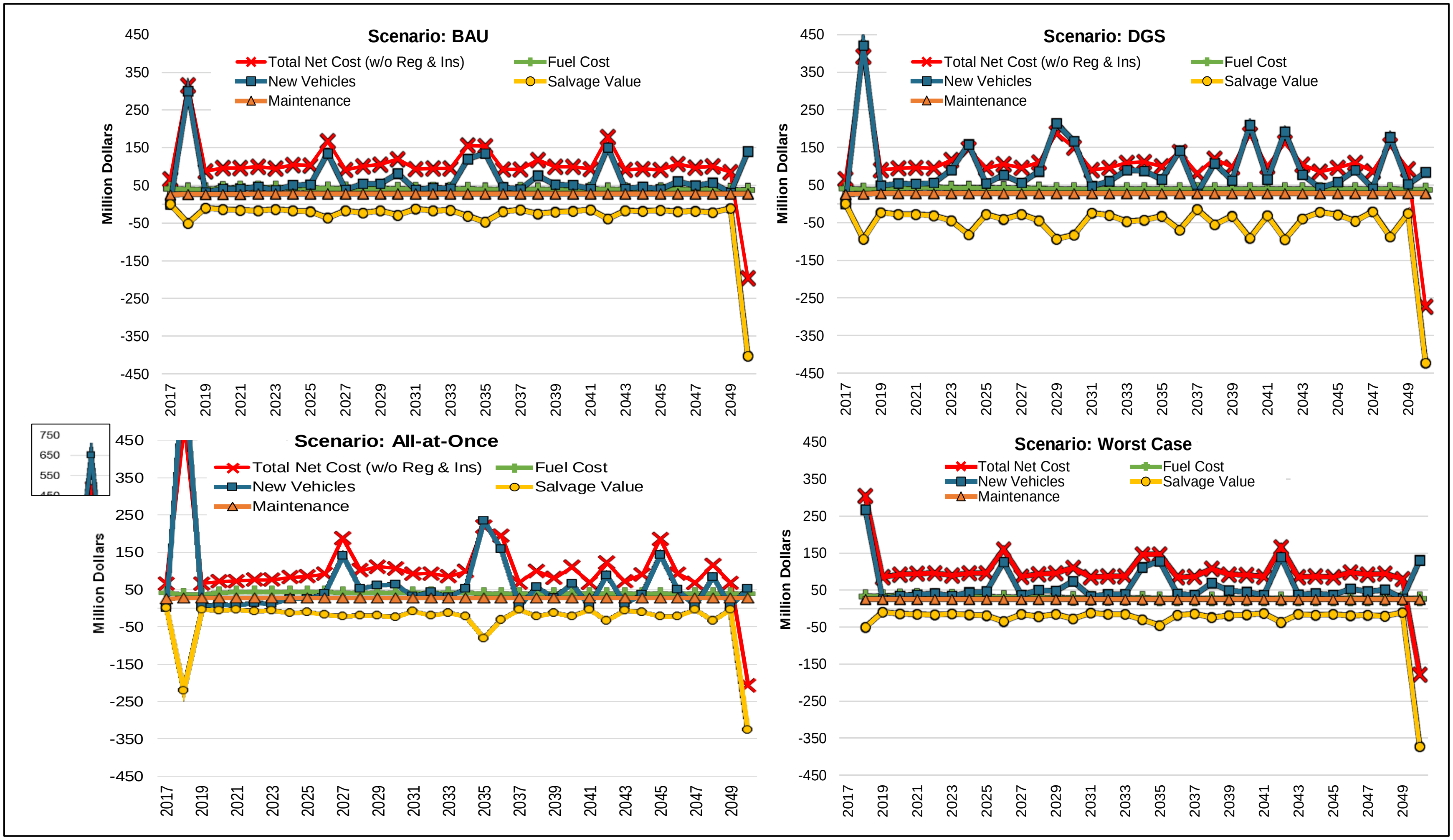

Figure 6.4: Comparison of life cycle cash flow across four scenarios.

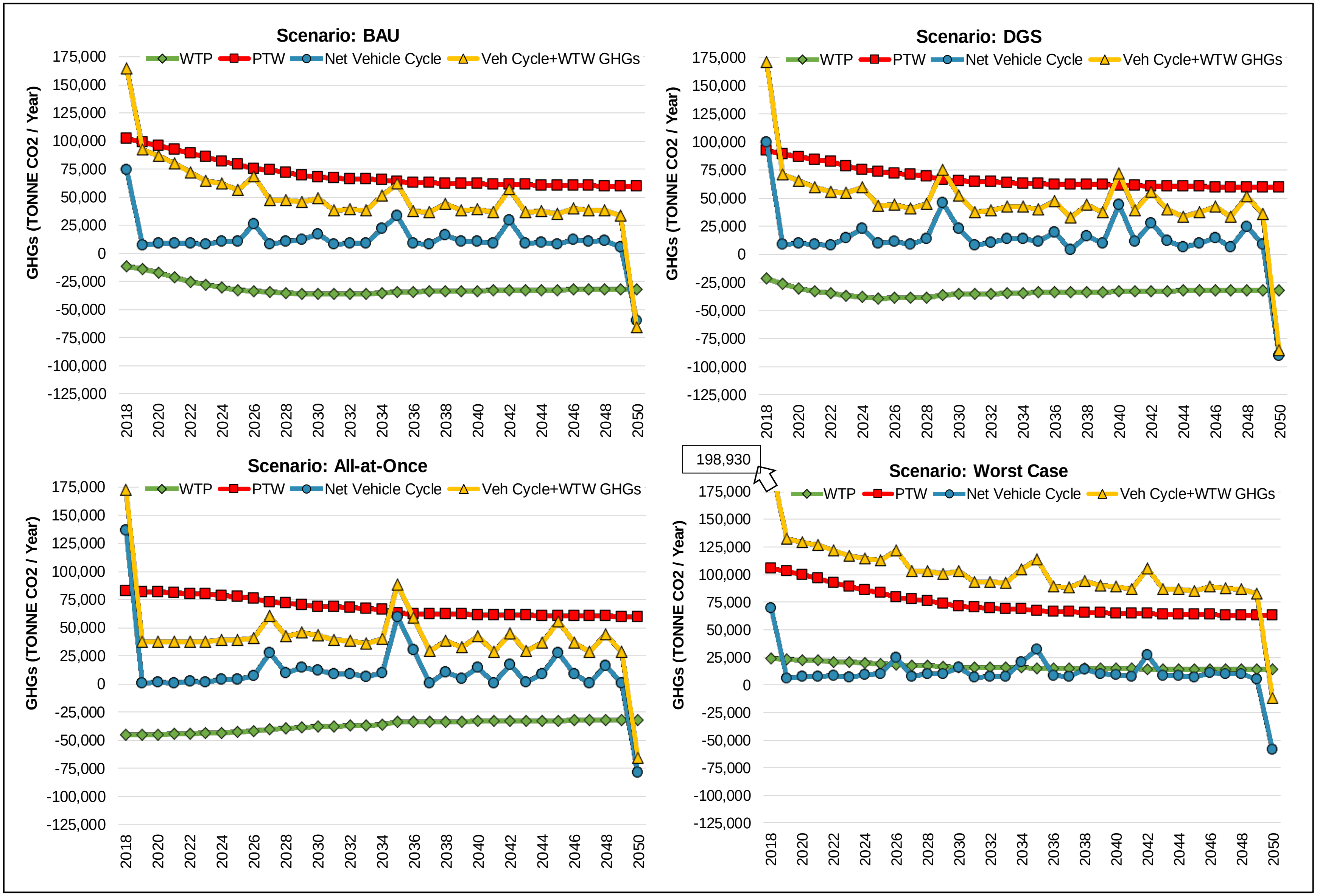

Figure 6.5: Comparison of GHG emissions across four scenarios: total GHG emissions, vehicle-cycle emissions, and emissions due to various fuel life cycle stages (WTP, PTW, and WTW.)

6.5.2 Implications for Total Abatement Potential

Compared to the BAU scenario, the abatement costs for each fewer tonne of GHG that results from the DGS and All-at-Once scenarios will cost Caltrans approximately $6,119 and $514, respectively. The DGS scenario's high cost is due to its significant decrease in mileage at the time of replacement (47 percent reduction on average across all vehicle types, with reductions ranging between 17 percent for medium-duty trucks to 61 percent for light-duty pickup trucks.) Therefore, even though the entire fleet is replaced in the All-at-Once scenario's first-analysis year, the scenario's LCC is still lower than implementing the gradual but more frequent DGS schedule.

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6.5.3 Time-Adjusted GHG Emissions

The time-adjusted warming potential (TAWP) results for each case over the analysis period are presented in Table 6.8. Including an emissions time adjustment in the GWP calculations yielded a 20 percent reduction compared to results from GWP calculation that did not include the adjustment because the emissions reductions are well distributed over the analysis period.

Table 6.8: Time-Adjusted Global Warming Potential (in MMT of CO_2-e) of Each Case over the Analysis Period 2018-2050

Analytical Time Horizon	BAU	DGS	All-at-Once (in 2018)	Worst-Case Scenario
50	1.16	1.13	1.03	1.73
100	1.32	1.29	1.19	2.00
500	1.43	1.41	1.30	2.20
With no Time Adjustment	1.46	1.43	1.32	2.25

6.5.4 Summary of Abatement Potential Information

Information regarding the abatement potential calculations presented in this chapter is summarized in Table 6.9 for the 35-year analysis period.

Table 6.9: Summary of Abatement Potential for Using Alternative Fuel Technology for Agency Vehicle Fleet

Cases	35-Year Analysis Period				Average Annual over 35-Year Analysis Period		
	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Life Cycle Cost Change ($ million)	Cost/ Benefit ($/tonne CO_2-e reduced)	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Life Cycle Cost Change ($ million)
BAU	0.000	0.00	0	N/A	0.00E+00	0.00E+00	0.00
DGS	-0.026	-0.03	157	6,120	-7.76E-04	-7.76E-04	4.75
All-at-Once	-0.138	-0.14	70	511	-4.17E-03	-4.17E-03	2.13
Worst-Case	0.787	0.79	-359	No Abatement	2.38E-02	2.38E-02	-10.89

7 STRATEGY 6: SOLAR AND WIND ENERGY PRODUCTION ON STATE RIGHT-OF-WAYS

7.1 Strategy Statement and Goal

Another strategy for reducing GHG emissions from the California economy's energy sector is to increase statewide electric power generation from renewable sources such as solar and wind, and to reduce the amount of electricity derived from nonrenewable sources such as natural gas and coal—the primary nonrenewable sources for in-state and out-of-state power production respectively. This scenario evaluates the net greenhouse gas impacts of generating solar and wind energy on appropriate locations in Caltrans right-of-ways since the department owns more than 15,000 miles of highway centerline, with a large but unknown amount of acreage in those right-of-ways. (Note: the solar energy generated in this scenario does not include any generated from pavements.)

7.2 Introduction

7.2.1 Caltrans Plans and Documentation

Reducing California's reliance on fossil fuels will require increasing the state's energy production using alternative sources. The current percentage of renewables in the state's electric grid mix is approximately 18 percent, but the state has set goals for its grid mix to include 25 percent renewable energy by 2025 and 50 percent by 2030. To meet these goals, Caltrans must explore additional ways to implement renewable energy technologies. Changing how it uses land under its jurisdiction offers Caltrans two possibilities; Caltrans could install solar photovoltaic (PV) panels and wind turbines along highway right-of-ways and in highway clover leaf interchanges, and it could install PV panels over parking spaces it manages. Taking these approaches could be doubly advantageous: not only would they help combat global climate change by reducing the consumption of energy derived from nonrenewable sources and lessening GHG emissions, but they would also bring down energy consumption costs.

To date, Caltrans has implemented 74 solar projects and has proposed 14 more, but these have all been on buildings *(113)*. And while no documentation was found online regarding solar panel installations implemented by Caltrans along highway right-of-ways or as solar canopies, these ideas were frequently found in the literature. The first discussion found of solar panel use along the highway right-of-way appeared in a 2010 Caltrans presentation that explored this idea for the highways around Sacramento *(114)*. This idea appeared again in a report prepared for Caltrans by ICF International *(115)*. In the most recent Sustainability Roadmap, Caltrans frequently mentioned solar canopies as a potential GHG reduction strategy *(113)*. No proposal was found in the literature regarding the installation of wind turbines or solar panels on Caltrans right-of-ways.

7.2.2 Abatement Strategy or Technology

The proposed abatement strategy is to install solar PV panels and wind turbines on highway right-of-ways, as well as solar PV canopies in Caltrans parking lots, which include Park & Ride and rest areas. In this study, the installation of standard crystalline silicon solar cells and 250 kW wind turbines are considered. This type of wind turbine typically has an average ground-to-blade height of 45 meters. These technologies are two of the most mature renewable energy generation technologies that have been implemented around the world.

7.3 Scope of the Study

7.3.1 What Is the Scope for Implementation across the Whole Network

This study considers the installation of small wind turbines in highway clover leaf interchanges, and the installation of solar panels both along highway right-of-ways and in Caltrans-owned or -operated Park & Ride and rest areas. In the study, upfront costs and GHG emissions are estimated for the installation, maintenance, and disposal of the technologies. Then, GHG emissions reductions and the income generated from selling this energy to local utilities are calculated. Last, the results are compared to a do-nothing scenario.

Installation of wind turbines at junctions and interchanges along Interstates 5, 10, and 15 was considered. In California, these three interstates span 1,335 center line miles. For the solar PV panel installations on the highway right-of-way, it was assumed that one row of panels could be installed along the length of those three highways, but this number may be actually larger or smaller depending on (1) where panels cannot be installed, (2) where there is space to install more than a single row, and (3) the space required between panels to prevent shading. For solar canopy installations, this study considered Caltrans-owned Park & Ride parking lots across California as well as the parking lots in rest areas along the I-5, I-10, and I-15 corridors.

7.3.2 Description of the Functional Unit, Graphical Representation of System Boundary

The three functional units for this study are the installation of wind turbines at 303 sites in the middle of clover leaf interchanges or in the areas available at junctions; installation of 100 miles of crystalline silicon PV cells along the state highways' right-of-ways; and installation of PV canopies covering the 34,000 parking spaces across Caltrans-owned rest areas. The environmental impacts on GHGs are reported in tonnes of CO_2-e. The materials, maintenance and rehabilitation (M&R), use, and end-of-life (EOL) stages are included in the system boundary, as shown in Figure 7.1. The analysis period is from the year 2015 to the year 2050. Degradation rates of the technologies and an annual discount rate of 4 percent are considered.

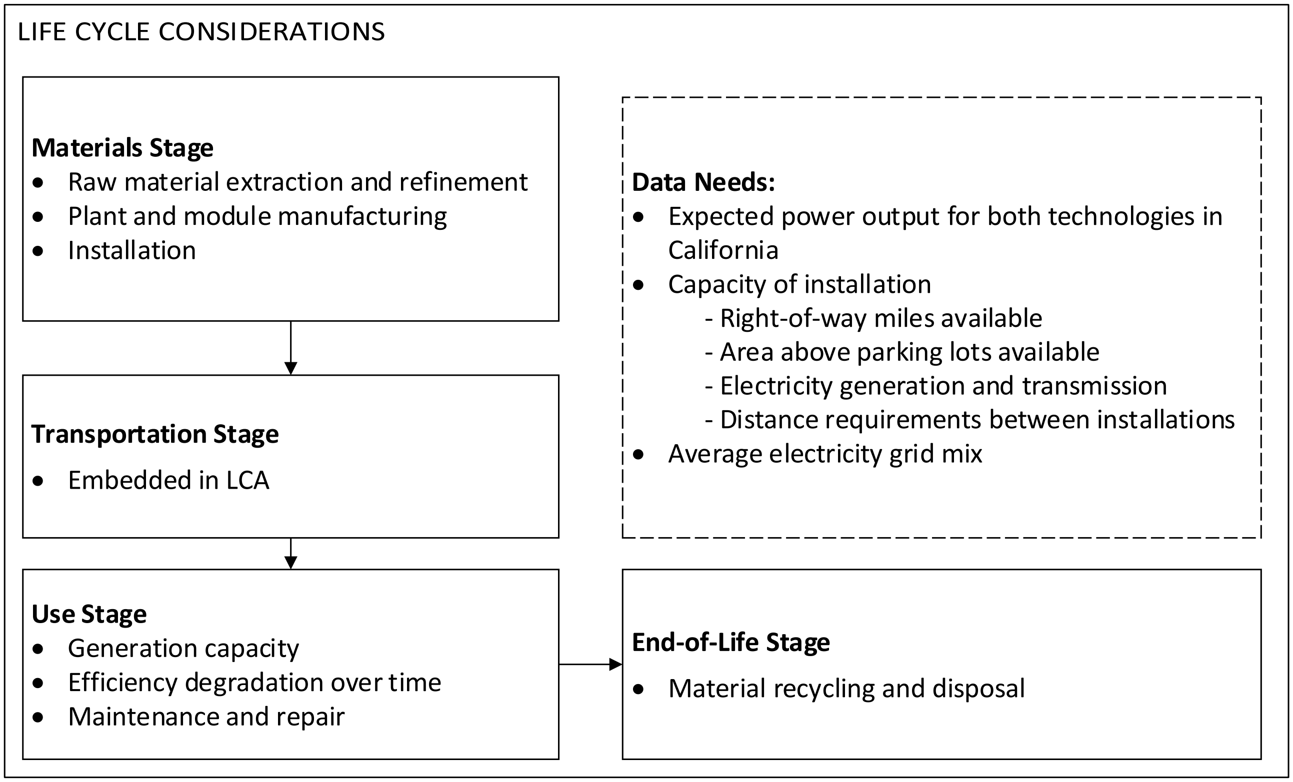

Figure 7.1: Scoping system diagram for life cycle (environmental impacts and cost) considerations.

7.4 Calculation Methods

7.4.1 Major Assumptions

No tax breaks, rebates, subsidies, or incentives for these installations were considered. It was also assumed that the installation process of wind turbines and solar panels along the highway right-of-way has negligible effects on traffic. Additionally, only one size PV panel and turbine were considered for installation, although different areas could warrant different capacities and sizes. The study also assumed that transmission losses occurring during connection to the grid are negligible.

The cost and environmental impacts of disassembly and end of life were assumed to be negligible relative to be less than 5 percent of all other costs and environmental impacts and were not included in the analysis. The disassembly would occur at the same time as replacement and the only cost would be the additional time to take down the old assemblies. Wind turbines are primarily recyclable metals, which have some costs and environmental impacts but should be much less than the original production. Cost impacts of removal of solar panels were similarly assumed to be small. Less information is available about end of life of solar panels because of their long lives (generally decades). Most parts of solar panels are recyclable, except for the plastic.

7.4.2 Calculation Methods

Wind Turbines

For the total emissions produced by a wind turbine, this study used the results published by Smoucha et al. *(116);* those results included manufacturing, transportation, and installation. Smoucha et al. included emission values for turbines with capacities rated from 50 kW to 3.4 MW. When those values were checked against the emission values reported by Vestas for a 2 MW Vestas turbine, it was found that Vestas estimated higher values *(117)*. The Smoucha study's emissions values were also assessed against emissions from a 1.6 MW turbine, and the two were found to be comparable despite there being a size difference. Based on these findings, the emissions reported by Smoucha et al. were considered in this study, in particular, the life cycle GHG emissions value of 148 tonnes of CO_2-e per 250 kW turbine. A capacity factor of 0.25 was used, which is within the range of the capacity factors used in the studies reviewed. Additionally, the US Energy Information Agency (EIA) found the median wind plant capacity factor in California to be about 0.26 when considering large-scale facilities *(118)*. A study by Staffell and Green *(119)* found the average performance degradation rate of wind turbines to be 1.6 percent per year, which was accounted for in the performance analysis. Finally, a lifetime of 20 years was used for wind turbines, as was used in earlier life cycle assessments *(120, 121)*. At the end of the analysis period, about five to seven years of useful life remain, so the salvage value was accounted for.

To determine the number of potential sites where turbines could be installed, 407 junctions and clover leaf interchanges were manually assessed to determine the approximate area available at each site. A study by the National Renewable Energy Laboratory (NREL) found the permanent direct land use of wind turbines (which includes the wind turbine, turbine pad, electric infrastructure, access roads, etc.) to be 0.75 ± 0.75 acres per MW; in other words, up to 1.5 acres per MW *(122)*. This upper bound was used in this study, so that each 250 kW turbine was assumed to require 0.375 acres. This number was used to filter out sites that were too small. Ultimately, there were 303 sites that could potentially accommodate the installation of a 250 kW turbine. A wind turbine typically takes two months to install and, therefore, it was assumed that across the state about 101 turbines could be installed per year, taking three years to reach maximum capacity. Under this assumption, there were 17 "teams" of installers who could each install six turbines each per year. This number is used in future assessments of the technology deployment rate.

It was also found from the literature that the capital cost estimates for wind turbines, their installation, and connection to the grid can range from $1 to $2.2 million per MW of rated capacity. This accounts for between 80 and 90 percent of their life cycle cost (LCC), with the remaining cost for maintenance and repair, and disposal *(123)*. A separate study of large-scale wind project LCCs found the cost of California-based projects in 2016 and

2017 to be about $2.15 million per MW *(124)*. These projects exhibit economies of scale that the proposed installations by Caltrans would not, which suggests that the true cost per MW may be higher. This current study used a cost of $537,500 per 250 kW turbine.

PV Solar Panels

Although most of the literature on solar PV presents life cycle GHG impact results in grams of CO_2-e per kWh, each study is different due to differing assumptions about technology efficiency, irradiance, lifetime, and other factors. A study by Hsu et al. *(125)* harmonized the GHG values from several studies, and found the life cycle GHG emissions per unit energy produced to be 52 g of CO_2-e per kWh. This output was combined with the harmonization assumptions made in the study to find an emissions value per meter-squared of PV panel. This value was 276 kg CO_2-e per meter-squared.

It was assumed that 100 W solar PV panels measure 39.7 by 26.7 inches (surface area of about 0.7 meters-squared) and are arranged vertically (that is, when they are installed each panel takes up 26.7 inches parallel to the ground and extends 39.7 inches vertically) to maximize installation density. Installing 100 miles of panels in this orientation would provide a rated capacity of 23.6 MW. It should be noted that the panels can either be installed adjacent to each other or with space between them to prevent shading, but ultimately 100 miles of panels are installed. The power-to-area value above was used to calculate the number of PV panels required to generate 1 kW of power and 1.93 tonnes of CO_2-e over its life cycle. Stated differently, this is the life cycle emissions quantity generated by seven square meters of PV solar panels. It was assumed that a 1 kW panel would produce 4.5 kilowatt-hours (kWh) per day on average in California, as was found in one estimate *(126)*. The initial cost of the solar panels was found using the leveled cost of energy for solar PV published by the US EIA *(127)*, which is reported in dollars per MWh. This value was multiplied by the amount of energy produced by the panel in its first year. Hsu et al. *(125)* also mentioned that solar PV typically has a performance degradation rate of 0.5 percent per year, and this value was used in the performance analysis. Additionally, a lifetime of 25 years was assumed, given that previous studies assumed a lifetime between 20 and 30 years *(125, 128)*. At the end of the analysis period, between 15 and 18 years of useful life remain, so the salvage value was accounted for.

As for solar panel installations in parking lots, Caltrans Park & Ride locations and rest areas include nearly 34,000 parking spots that could be covered by PV panels. That estimate includes parking spaces in all the state's Park & Ride locations and rest areas along I-5, I-10, and I-15. The Park & Ride estimate comes from a 2019 inventory shared by a Park & Ride coordinator *(129)*, and is an update to the publicly released 2018 values *(130)*. The parking spot count in rest areas was determined by Internet map reviews of the rest areas along the three major interstates and a manual count of the existing parking spaces. Since no existing solar PV installations were found, this study assessed the installation of solar carports on all parking spaces. Details about solar canopy structures can be found in Appendix F.

The cost for the solar carports was assumed from the baseline prices listed by Solar Electric Supply Incorporated, a California-based company *(131)*. Their listed base prices for solar carports with capacities ranging from 50 kW to 250 kW were between \$1.30 and \$1.50 per watt. This study used the median value of \$1.40 per watt, although the true costs could be higher since installation varies by site. Installation times can also vary from site to site, but a representative from Baja Carports noted that installing 100 spaces typically requires between two and three months. Using that value, the study assumed that one installation team can install solar carports over approximately 500 parking spaces per year, and it assumed as before that with 17 teams working across the state, 8,500 carports could be installed per year. At that rate, all spaces would be covered by the fourth year.

Grid Mix

The carbon intensity of the grid was determined by combining the expected grid mix over time developed as part of the EIA Annual Energy Outlook *(132)* with the emissions values per fuel source outlined in the GREET 1 model *(103)*. Emissions values per kWh of electricity were calculated through the year 2050. Two prices were used since the price of generated electricity is uncertain. Under the high-price case, it was assumed that utilities would provide net-metering benefits, an arrangement in which the energy generated by the solar panels installed is used to offset other electricity charges that Caltrans incurs across the state (for example, the electricity used in its buildings and to illuminate highways). In this case, a price of \$0.152 per kWh was used, which is the average electricity price across all California sectors according to a report released by the EIA *(70)*. Under the low-price case, utilities would purchase the electricity generated by the panels at a significantly lower rate, between \$0.03 and \$0.04 per kWh, as set by the California Public Utilities Commissions *(71)*. For this case, a value of \$0.035 per kWh was used. Because of variability in electricity pricing among the state's many utility companies, and their freedom to adopt one or more of the pricing scenarios described above, the results in this study provide the range of costs that the strategies would achieve if deployed.

7.4.3 Data Sources and Data Quality

An assessment of the data sources used in the calculation methods can be seen in Table 7.1.

Table 7.1: Data Quality Assessment

Categories	**Data Sources**	**Data Quality**							
		Reliability	**Geography**	**Time**	**Technology**	**Completeness**	**Reproducibility**	**Representativeness**	**Uncertainty**
Data Type									
Annual solar energy generation	Sendy *(126)*	Fair	US	Good	Very Good	Fair	Yes	Yes	Low
Solar PV degradation rate	Hsu *(125)*	Very Good	US	Fair	Very Good	Very Good	Yes	Yes	Low
Annual wind energy generation	Smoucha *(116)*	Very Good	US	Fair	Very Good	Very Good	Yes	Yes	Low
Turbine degradation rate	Staffel *(119)*	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
LCA-Related									
Wind Turbine	Smoucha *(116)*	Good	EU	Fair	Very Good	Very Good	Yes	Yes	Low
Solar Panel	Hsu *(125)*	Very Good	US	Fair	Very Good	Very Good	Yes	Yes	Low
Electricity	US EIA *(70)*	Very Good	US	Good	Very Good	Very Good	Yes	Yes	Low
Steel	EcoInvent *(73)*	Good	Global	Fair	Very Good	Fair	Yes	Yes	High
Cement Concrete	Saboori *(74)*	Very Good	US	Very Good	Very Good	Very Good	Yes	Yes	Low
Cost-Related									
Wind Turbine	Wiser *(124)*	Very Good	US	Very Good	Very Good	Good	Yes	Yes	Low
Solar Panel	US EIA *(70)*	Good	US	Good	Very Good	Good	Yes	Yes	High
Electricity	US EIA *(70)*, CPUC *(71)*	Very Good	US	Very Good	Very Good	Good	Yes	Yes	Low
Steel	Focus Economics *(75)*	Good	US	Very Good	Very Good	Good	Yes	Yes	Low
Solar Carport	Solar Electric Supply Inc. *(131)*	Very Good	US	Very Good	Very Good	Good	Yes	Yes	Low

7.4.4 Limitations or Gaps

The following is a list of limitations or gaps identified in this study. These are sources of uncertainty that could affect the proceeding results.

- **Additional time required for designing, planning, and permitting.** Installation timelines for these technologies could vary widely due to differences in the sites' landscapes, local jurisdictions, available developers, and more. Designs and plans for each site would need to be created and the appropriate permits would need to be obtained, processes that could take from a few months to over a year. However, this study begins its analysis after these processes have been completed, and subsequently considers only the installation rate of the technologies.
- **Effects of PV glare on driver safety**. This is a potential drawback to PV installation along the highway, as mentioned in a Caltrans report on strategies to address climate change *(115)*.
- **Effects of wind turbine noise on the surrounding community.** Wind turbines are associated with low-frequency vibrations that have led to complaints from residents who live near them. While it is likely that the wind turbines will be installed far from any communities, these effects could also be experienced by drivers, though exposure would be for much shorter times. The specification sheet of the WES 250, 250 kW turbine states that the noise generated during an 8 m/s wind is 45 decibels (dB) at a 100 m distance *(133)*. At a frequency of about 20 Hz, the noise adjusted for human perception of different noise at different frequencies is about 5 dBA (adjusted decibels). For reference, the noise level of breathing is 10 dBA, so to the human ear the noise generated by turbines at 100 meters sounds half as loud as breathing *(134)*.
- **Transmission losses.** It is unclear whether electricity transmission losses between the renewable energy generation sites and the grid would be significant; electricity transmission depends largely on the distance between the installed technology and the nearest grid connection.
- **Effects on afternoon ramp load**. Electricity demand rises sharply in the afternoon and early evening as people return home. These times coincide with decreased solar energy production output. As solar power capacity has increased in California, particularly from non-utility scale installations, this has led to a requirement that carbon-intensive peaker plants make up the difference between supply and demand. Adding more solar energy to the grid could therefore exacerbate this steep ramp-up of carbon-intensive peaker plants, and intentionally result in higher carbon-intensity electricity being generated. If this were to occur it would reduce the net benefit of supplying solar power. This consideration was not included in the analysis in this study.
- **Urban heat island reduction due to covering building roofs and parking areas**. Shading building roofs and parking areas could reduce the urban heat island effect. This could reduce the amount of energy used for cooling buildings, but alternatively it could increase the energy used to heat them in colder

months. Shading parking lots with solar panels can lower temperatures in parked cars and reduce the cooling loads and energy consumed to run car air conditioners. For vehicles with internal combustion engines heating uses waste engine heat. For electric vehicles heating uses battery energy. Therefore, since overall cooling is a significantly higher energy load than heating, the net benefit favors vehicle shading.

- **Job creation in the renewable energy industry**. The installation and maintenance of these technologies would generate jobs, which could be considered as a socioeconomic benefit.
- **Time-of-day pricing**. Some utilities charge different rates for electricity that depend on the time of day it is consumed. For example, SMUD, the Sacramento-based utility, charges time-of-day rates that are higher on summer weekdays from 5 to 8 PM than throughout the rest of the day. This strategy is meant to minimize the afternoon ramp load (explained above).
- **Change in price of electricity over time.** The rate at which the price of electricity will presumably increase over time was not accounted for. However, with an increasing number of renewables and a better levelized cost of electricity (LCOE), it was uncertain exactly how electricity prices will shift; this in turn would affect the calculation of the return on investment in this energy generation method. These effects were not considered in the analysis.

7.4.5 Sensitivity/Uncertainty Methods

Wind turbines are assumed to operate with a capacity factor of 25 percent over the course of a year. In other words, the turbine is assumed to operate at its rated capacity for 25 percent of the time, or 2,190 hours out of the total 8,760 hours in one year. A sensitivity analysis was conducted to test the effect of lowering the capacity factor to 20 percent, while holding all other LCA and cost parameters constant. This change in capacity factor will decrease the turbines' annual output, which will affect their GHG reduction capacity as well as revenue generation.

7.5 Results and Discussion

7.5.1 Numerical Results from Case Studies

Cumulative emissions of the three considered strategies over the analysis period can be seen in Figure 7.2. Emissions and cost-related results are summarized in Table 7.2.

This study estimated that a single 250 kW turbine has life cycle production emissions of 148 tonnes of CO_2-e and an agency cost of $537,500. Operating at a 25 percent load capacity, this turbine would generate 547.5 MWh in its first year. For solar PV technologies, this study estimated that a 1 kW solar PV system emits 1.93 tonnes of CO_2-e and costs about $1,040. These results are in line with the rule-of-thumb cost of $1 per watt. Based on these assumptions, a solar PV system would produce 1.64 MWh in its first year. These generation values were used for both the highway and canopy installations. The costs for the initial and replacement highway installations were the same as the aforementioned $1,040 per kW. For canopy installations, the initial installation cost was $1,350 per kW, while the replacement cost was again $1,040 per kW.

An estimated 303 250 kW wind turbines could be installed in highway junctions and clover leafs, resulting in a total rated capacity of 75.75 MW. In each of the first three years 101 turbines would be installed, and they would be replaced after 20 years. The installation, M&R costs, and salvage value had a net present value of $216 million and generated 90,000 tonnes of CO_2-e in GHG emissions. Taking into account the emissions reductions benefits achieved by selling the generated electricity to local utilities, this strategy achieved net emissions reductions of 686,000 tonnes of CO_2-e. Using a high electricity price achieved by getting rebates on purchased electricity, the net present value of profits would be $188 million. If the electricity generated were considered as excess energy and a lower price were received for it, the net present value of costs would be $142 million.

Considering solar PV on the highway right-of-way, 1,335 miles of PV panel would provide 307 MW of rated capacity. Full capacity is reached after three years, and the technologies are replaced after 25 years. The installation, M&R costs, and salvage value had a net present value of $361 million and generated 593,000 tonnes of CO_2-e in GHG emissions. Taking into account the emissions reductions benefits achieved by selling the generated electricity to local utilities, this strategy achieved net emissions reductions of 1,394,000 tonnes of CO_2-e over the life cycle. A high electricity price would result in a net present value of profits of $1,002 million, while a lower price would result in a net present value of costs of $47 million.

Regarding solar canopy installations, the assumed installation over 34,000 parking spots would provide a total rated capacity of 63 MW. Full capacity is reached after four years, and the technologies are replaced after 25 years. The installation, M&R costs, and salvage value would have a net present value of $100 million and generate 177,000 tonnes of CO_2-e in GHG emissions. Taking into account the emissions reductions benefits achieved by selling the generated electricity to local utilities, this strategy would achieve net emissions reductions of 262,000 tonnes of CO_2-e. A high electricity price would result in a net present value of profits of $173 million, while a lower price would result in a net present value of costs of $37 million.

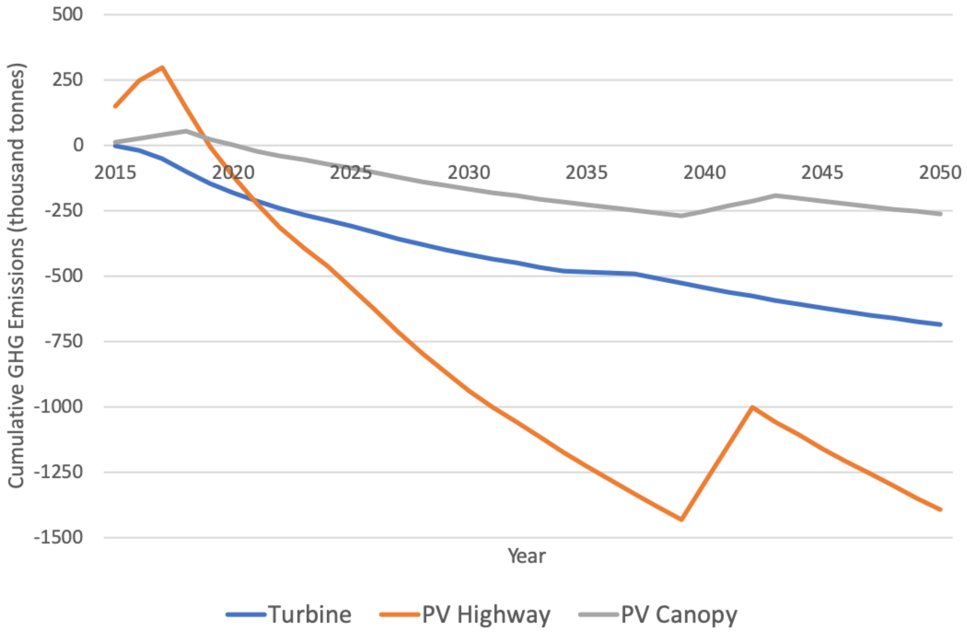

Figure 7.2: Cumulative emissions reductions for the three separate strategies considered.

7.5.2 Implications for Total Abatement Potential

The initial turbine installation cost, considering only agency cost, was $315 per tonne reduction of CO_2-e. The net LCC, which includes income from electricity net metering, was a -$274 per tonne reduction of CO_2-e (net savings) in the high-price case, and a $180 per tonne reduction of CO_2-e (net cost) in the low-price case. The net LCC of the PV installation along the highway right-of-way considering only agency cost was a $258 per tonne reduction of CO_2-e. The LCC effectiveness, which would include income from electricity net metering, was a -$719 per tonne reduction of CO_2-e (net savings) in the high-price case and a $34 per tonne reduction of CO_2-e in the low-price case. The cost-effectiveness of solar canopy installation in rest areas considering only agency cost was a $381 per tonne reduction of CO_2-e. The LCC effectiveness, which would include income from electricity net metering, was a -$661 per tonne reduction of CO_2-e (net savings) in the high-price case, and a $141 per tonne reduction of CO_2-e in the low-price case.

Considering all three strategies, the installation and M&R had a net present value of $676 million. Taking into account the emissions reductions benefits achieved by selling the generated electricity to local utilities, this strategy achieved net emissions reductions of 2,342,000 tonnes of CO_2-e over the analysis period. A high electricity price resulted in a net present value of -$1,363 million (net profit), while a lower price resulted in a net present value of $208 million (net cost). The overall combined cost-effectiveness of the three strategies considering only agency cost is $289 per tonne reduction of CO_2-e. The LCC effectiveness over the analysis period, which would include income from electricity net metering, was a -\$582 per tonne reduction of CO_2-e (net savings) in the high-price case, and an \$89 per tonne reduction of CO_2-e in the low-price case (net cost). These results can be seen in Figure 7.3.

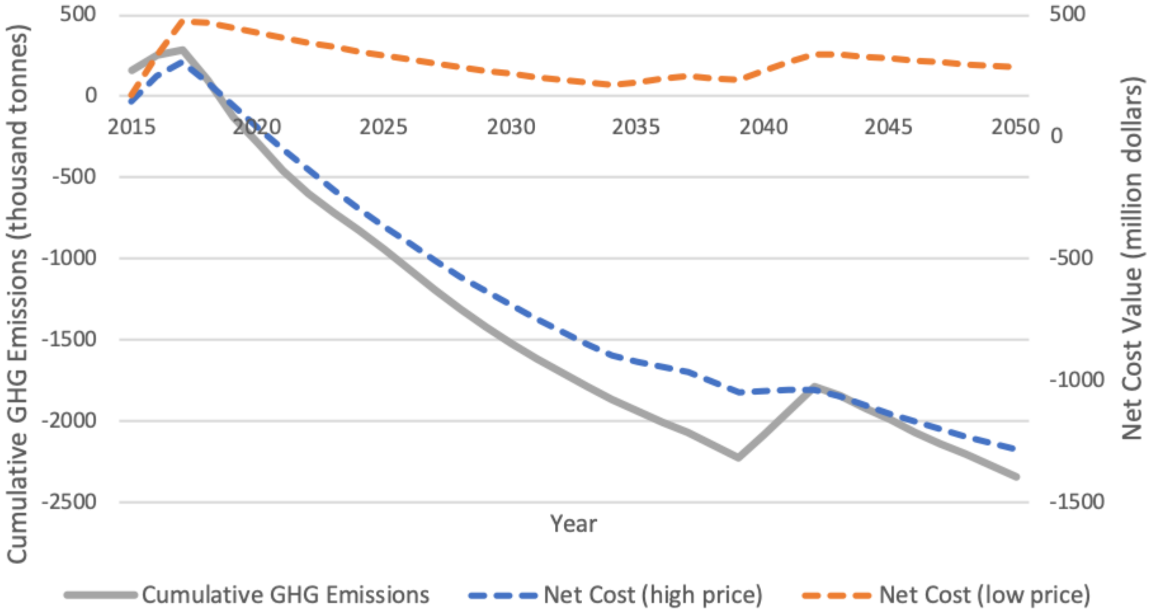

Figure 7.3: Cumulative net emissions and net costs for both the high and low prices for the electricity generated by installing all three strategies considered in the chapter.

Table 7.2: Cost (Agency, LCC, and Cost Effectiveness) Results for This Study

Strategy	**Agency Cost (\$ million USD)**	**LCC Cost – Low Electr. Price (\$ million USD)**	**LCC Cost – High Electr. Price (\$ million USD)**	**Cost Effectiveness – Agency**	**Cost Effectiveness – Low Electr. Price (\$ per tonne)**	**Cost Effectiveness – High Electr. Price (\$ per tonne)**
Wind Turbine	216	142	-188	315	180	-274
PV along Highway	361	47	-1,002	258	34	-719
Solar Canopy	100	37	-173	381	141	-661
Total	676	208	-1,363	289	89	-582

7.5.3 Time-Adjusted GHG Emissions

The initial analysis of the turbine installation estimated the net reduction in GHG emissions to be 686,000 tonnes of CO_2-e. However, using the time-adjusted emissions methodology developed by Kendall *(7)*, the 100-year net reduction in emissions has a present-day value of 601,000 tonnes of CO_2-e. For the highway solar PV installations, the initial analysis found the net GHG reduction to be about 1,394,000 tonnes of CO_2-e, but the time-adjusted value was closer to 1,217,000 tonnes of CO_2-e. For the solar canopy installations, the initial analysis found net GHG reduction to be about 262,000 tonnes of CO_2-e, but the time-adjusted value was closer to 228,000 tonnes of CO_2-e. Proceeding with all three installations reduces GHG emissions by 2,342,000 tonnes of CO_2-e over the analysis period, but the time-adjusted value is closer to 2,045,000 tonnes of CO_2-e.

7.5.4 Sensitivity/Uncertainty Analysis

Under the lower capacity factor of 0.2, the wind turbine system generates net profits of $94 million and results in a GHG emissions reduction of about 530,000 tonnes of CO_2-e, and the total emissions reduction across all installations is 2,187,000 tonnes of CO_2-e. The cost-effectiveness of all installations when the turbines operate under the lower capacity factor considering only agency cost is $309 per tonne reduction of CO_2-e. The LCC effectiveness over the analysis period, which would include income from electricity net metering, is a -$587 per tonne reduction of CO_2-e with a high electricity price, and a $103 per tonne reduction of CO_2-e with a low electricity price. Using the time-adjusted emissions methodology, the 100-year net reduction in emissions has a present-day value of 1.98 million tonnes of CO_2-e.

If the turbine output is lowered, both the emissions reduction potential and the cost-effectiveness are reduced, the latter more so with lower electricity prices. Changes from the assumed value of the solar energy output would have similar effects.

7.5.5 Summary of Potential Abatement Information

Information regarding the potential abatement calculations presented in this chapter is summarized in Table 7.3 for the 35-year analysis period.

Table 7.3: Summary of Abatement Potential for Using Solar and Wind Energy Production on State Right-of-Ways

Cases	35-Year Analysis Period				Average Annual over 35-Year Analysis Period		
	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Life Cycle Cost Change ($ million)	Cost/Benefit ($/tonne CO_2-e reduced)	CO_2-e Change (MMT)	Time-Adjusted CO_2-e Change (MMT)	Life Cycle Cost Change ($ million)
High Electricity Price	-2.342	-2.045	-1,363	-582	-0.0669	0.0584	-38.94
Low Electricity Price	-2.342	-2.045	208	89	-0.0669	0.0584	5.94
Lower wind capacity factor (high elec. price)	-2.187	-1.979	-1,282	-587	-0.0625	0.0565	-36.63
Lower wind capacity factor (low elec. price)	-2.187	-1.979	226	103	-0.0625	0.0565	6.46

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APPENDIX A: PAVEMENT ROUGHNESS AND MAINTENANCE PRIORITIZATION

Relationship between M&R Spending and Pavement GHG Emissions

Figure A.1 shows examples of different scenarios from the worst to the best in terms of cumulative GHG emissions (construction and vehicle/user) and M&R cost (agency only). The first hypothetical case is the do-nothing scenario (free fall) case in which the cost to the agency is zero (in terms of maintaining/fixing the roads) but the GHG emissions will be the highest due to poor road surface conditions resulting in excess fuel consumption by the vehicles. The second hypothetical case is the ideal case of the road surface being perfectly smooth (IRI = 0). In this case, GHG emissions will be the lowest as hypothetically best (because least possible IRI value that can be achieved practically is 20 inches/mile (0.3 m/km) possible ride surface is being maintained at the network level however, it comes at a very high agency cost. Both the hypothetical cases are the extreme possibilities that do not exist however, all the possible scenarios that can be investigated lie in between them. Practically, the two extreme cases that can exist are also shown in Figure A.1 called out as “Unlimited” budget scenario and “Practically Ideal” scenario. Current practice or any optimization that can be done is in between these two extreme practical cases, that is, maintaining the state highway network to Caltrans standards with no spending limit and improving the pavement surface to the lowest possible roughness (IRI = 20 in/mile).

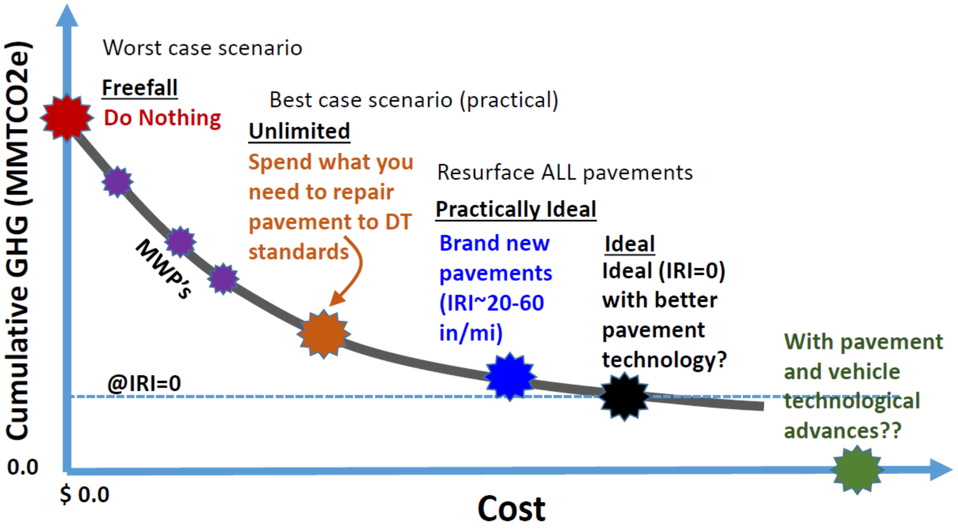

Figure A.1: Spending versus pavement GHG emissions *(32)*.
(DT = decision tree)

Factorial to Attain Different CO_2 Emission Factors

Simulations were performed for a factorial in order to determine the vehicle CO_2-e emission factor for each vehicle type as a function of IRI and MPD under each combination of other factorial variables using MOVES. The factorial included two pavement types (asphalt and concrete), two road types (urban and rural), two road access types (restricted-access and unrestricted access), ten years (2012 to 2021), five vehicle types (passenger car, 2-axle truck, 3-axle truck, 4-axle truck, and 5-or-more axle truck). For each factorial combination, factors were determined using the models as shown below;

- CO_2 emission factors in the unit of metric ton per 1000 miles of VMT

$$[b1 * MPD (mm)] + [b2 * IRI (m/km)] + intercept \qquad \textbf{Eq (1)}$$

Table A.1: Questionnaire A for the Case Study "1. Pavement Roughness and Maintenance Prioritization"[5]

Question Number	Question	Answer
1	Define change	a. Existing: current pavement management system decision trees. b. Change: Use the optimal M&R timing to minimize the GHG emissions. This would occur in the pavement management system.
2.	Define the state of readiness of the change of technology (using approach adapted from NASA)	- TRL 5 and 6: technology validated and demonstrated in relevant environment at less than full scale
3.	Define system in which change occurs	- Caltrans-owned and operated state highway network. - Manage through PaveM. - To be approved by CA transportation commission (CTC). - Cost to be carried within existing budgets unless other funds found. - Budget constraint optimization and unconstrained optimization. - Cannot be the only criteria for funding M7R. - Mostly applicable to high traffic routes.
4.	Will the market change or is it just changes in market share?	Not applicable.
5.	Who is responsible for change?	Caltrans, California Transportation Commission, legislature.
6.	Who is responsible for implementing change?	Caltrans
7.	Who pays for change	a. Government, level of government Ans: State government, passed on to consumers b. Producers without pass through to consumers Ans: Not applicable c. Consumers Ans: Not applicable
8.	What will drive change (X)	a. Market b. Market incentives c. Regulation X d. Legislation X e. Internal Policy X f. Public programs incentivizing change g. Education

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[5] Note: the wording of the questions shown in the questionnaires shown in the appendices has been modified in the text of Chapter 1 of the report. Future use of the questionnaire will use the modified wording.

Question Number	Question	Answer
9.	What will the change do to these other environmental indicators	*LCA WILL ANSWER* i. Air pollution ii. Water pollution iii. Energy use 1. Renewable 2. Nonrenewable 3. Renewable energy source used as material 4. Nonrenewable energy source used as material iv. Water use v. Use of other natural resources
10.	What are the performance metrics in addition to GHG reduction and cost?	- Safety changes - Measurement of International Roughness Index (IRI), change of IRI on high volume routes, traffic volumes, construction work zone, material purchases, travel speed - Road user cost
11.	Supply curve calculation questions:	a. Expected change in GHG output per unit of change in system 12.7 MMT of GHG emissions. b. Expected maximum units of change in system (LCA). c. Time to reach maximum units of change (reasonable time to be implementable), policy question. d. Expected shape of change rate (dependent on the funding): i. Linear ii. Increasing to maximum iii. Decreasing to maximum (if prioritized) iv. S-shaped e. Estimated initial cost per unit of change (-$159 per tonne of GHG emission) f. Estimated life cycle cost per unit of change (LCCA)

APPENDIX B: ENERGY HARVESTING USING PIEZOELECTRIC TECHNOLOGY

Table B.1: Questionnaire B for the Case Study "Energy Harvesting Using Piezoelectric Technology"

Question Number	Question	Answer
1	Define change	a. Existing: Currently only used at one weigh-in station b. Change: Install piezoelectric transducers along typical vehicle paths on highways to generate electricity.
2.	Define the state of readiness of the change of technology (using approach adapted from NASA)	TRL 5: technology validated in relevant environment at less than full scale
3.	Define system in which change occurs	Caltrans-owned and operated state highway network. Mostly applicable to high traffic routes. Cost to be carried within existing budgets unless other funds found.
4.	Will the market change or is it just changes in market share?	Slight or negligible changes in market share.
5.	Who is responsible for change?	Caltrans, CTC, legislature, local electricity providers.
6.	Who is responsible for implementing change?	Caltrans
7.	Who pays for change	a. Government, level of government State gov, passed on to consumers b. Producers without pass through to consumers n/a c. Consumers n/a

Question Number	**Question**	**Answer**
8.	What will drive change (**X**)	a. Market b. Market incentives c. Regulation **X** d. Legislation **X** e. Internal Policy **X** f. Public programs incentivizing change g. Education
9.	What will the change do to these other environmental indicators	***LCA WILL ANSWER*** i. Air pollution ii. Water pollution iii. Energy use 1. Renewable 2. Nonrenewable 3. Renewable energy source used as material 4. Nonrenewable energy source used as material iv. Water use v. Use of other natural resources
10.	What are the performance metrics in addition to GHG reduction and cost?	a. Safety changes b. Changes to road maintenance and repair c. Road user cost
11.	Supply curve calculation questions:	a. Expected change in GHG output per unit of change in system: 7,980 tonnes of CO_2-e per lane-mile b. Expected maximum units of change in system: 100 c. Time to reach maximum units of change (reasonable time to be implementable), policy question. 5 years d. Expected shape of change rate (dependent on the funding): i. Linear ii. Increasing to maximum iii. Decreasing to maximum (X) iv. S-shaped e. Estimated initial cost per unit of change: $608.35 per tonne CO_2-e reduction f. Estimated life cycle cost per unit of change: Between -$167.12 (high price) and $430.14 (low price)

APPENDIX C: AUTOMATION OF BRIDGE TOLLING SYSTEMS

The Probabilistic Queuing Models to Estimate Queue Lengths on Tollbooths

$$P_0 = \frac{1}{\sum_{n_c=0}^{N-1} \frac{\rho^{n_c}}{n_c!} + \frac{\rho^N}{N!(1-\rho/N)}} \qquad \text{Eq. 3.1}$$

$$P_n = \frac{\rho^n P_0}{n!} \qquad for\ n \leq N \qquad \text{Eq. 3.2}$$

$$P_n = \frac{\rho^n P_0}{N^{n-N} N!} \qquad for\ n \geq N \qquad \text{Eq. 3.3}$$

$$P_{n>N} = \frac{\rho^{N+1} P_0}{N!N(1-\rho/N)} \qquad for\ n \geq N \qquad \text{Eq. 3.4}$$

where

P_0 = probability of having no vehicles in the system,

P_n = probability of having *n* vehicles in the system,

$P_{n>N}$ = probability of waiting in a queue (the probability that the number of vehicles in the system is greater than the number of open tollbooth),

n = number of vehicles in the toll system,

N = number of open tollbooths,

n_c = tollbooth number, and

ρ = traffic intensity (arrival rate/departure rate).

$$\bar{t} = \frac{\rho + \frac{\rho^{N+1} P_0}{N!N}\left[\frac{1}{(1-\rho/N)^2}\right]}{\lambda} \qquad \text{Eq. 3.5}$$

where

$\bar{t}$ = average time spent in the toll system, in unit time per vehicle, and

λ = arrival rate.

Table C.1: Questionnaire C for the Case Study "Automation of bridge tolling systems"

Question Number	Question	Answer
1	Define change	a. Existing: FasTrak and cash b. Change: All-electronic tolling (AET) system
2.	Define the state of readiness of the change of technology	- TRL 5 and 6: technology validated and demonstrated in relevant environment at less than full scale
3.	Define system in which change occurs	- AET systems at seven Caltrans-owned and operated toll bridges
4.	Will the market change or is it just changes in market share?	Not applicable.
5.	Who is responsible for change?	Caltrans, CTC, legislature
6.	Who is responsible for implementing change?	Caltrans
7.	Who pays for change	a. Government, level of government Ans: State government through toll revenue or Federal grant program b. Producers without pass through to consumers Ans: Not applicable c. Consumers Ans: Not applicable
8.	What will drive change (X)	a. Market b. Market incentives X c. Regulation X d. Legislation X e. Internal Policy X f. Public programs incentivizing change X g. Education
9.	What will the change do to these other environmental indicators	*LCA WILL ANSWER* i. Air pollution ii. Water pollution iii. Energy use 1. Renewable 2. Nonrenewable 3. Renewable energy source used as material 4. Nonrenewable energy source used as material iv. Water use v. Use of other natural resources
10.	What are the performance metrics in addition to GHG reduction and cost?	- Safety changes -rear-end collision - Queue length, average travel time per vehicles in a queue, average travel speed, annual average daily traffic, hourly traffic volume
11.	Supply curve calculation questions:	a. Expected change in GHG output per unit of change in system: 0.44 MMT b. Expected maximum units of change in system (LCA). c. Time to reach maximum units of change (reasonable time to be implementable), policy question. d. Expected shape of change rate (dependent on the funding): i. Linear ii. Increasing to maximum iii. Decreasing to maximum (if prioritized) iv. S-shaped e. Estimated initial cost per unit of change: $4.6 million f. Estimated life cycle cost per unit of change: $54.1 million

APPENDIX D: INCREASED USE OF RECLAIMED ASPHALT PAVEMENT

Table D.1: Amount of HMA and RHMA in MMT

Year	HMA	RHMA	Total
2018	2.11	1.91	4.02
2019	2.19	1.98	4.17
2020	2.24	2.03	4.27
2021	5.14	4.66	9.80
2022	8.69	7.87	16.56
2023	11.90	10.79	22.69
2024	11.43	10.36	21.79
2025	9.59	8.69	18.29
2026	9.10	8.25	17.35
2027	7.26	6.58	13.83
2028	12.32	11.17	23.48
2029	11.13	10.09	21.21
2030	8.13	7.37	15.50
2031	8.93	8.09	17.02
2032	8.76	7.94	16.70
2033	10.37	9.40	19.76
2034	12.07	10.94	23.01
2035	9.86	8.94	18.80
2036	8.11	7.35	15.45
2037	7.56	6.85	14.42
2038	8.76	7.94	16.70
2039	12.64	11.46	24.10
2040	8.66	7.85	16.51
2041	11.47	10.40	21.87
2042	5.99	5.43	11.41
2043	6.07	5.50	11.57
2044	10.49	9.51	20.00
2045	9.19	8.32	17.51
2046	8.23	7.46	15.69
2047	9.30	8.43	17.73
2048	9.40	8.52	17.92
2049	9.26	8.39	17.65
2050	9.16	8.30	17.47
Total	**285.51**	**258.76**	**544.27**

Table D.2: Baseline M Designs for HMA and RHMA

Item	HMA	RHMA
Aggregate	81.0%	92.5%
Bitumen	4.0%	5.8%
Crumb Rubber Modifier	0.0%	1.5%
Extender Oil	0.0%	0.2%
RAP	15.0%	0.0%

Table D.3: GHG Emissions (tonnes of CO2-e per year) due to HMA and RHMA during the Analysis Period

Year	HMA (Max 15% RAP)	HMA (Max 25% RAP)	HMA (Max 40% RAP)	HMA (Max 50% RAP)	RHMA
2018	104,409	103,702	99,020	97,979	114,701
2019	108,165	107,432	102,582	101,503	118,827
2020	110,755	110,005	105,039	103,934	121,673
2021	254,304	252,581	241,179	238,642	279,373
2022	429,757	426,846	407,577	403,290	472,122
2023	588,943	584,954	558,548	552,672	647,000
2024	565,516	561,686	536,330	530,688	621,264
2025	474,580	471,366	450,087	445,353	521,364
2026	450,378	447,327	427,134	422,641	494,775
2027	359,021	356,589	340,492	336,910	394,413
2028	609,494	605,366	578,038	571,957	669,577
2029	550,561	546,832	522,146	516,654	604,834
2030	402,144	399,420	381,390	377,378	441,787
2031	441,822	438,830	419,020	414,612	485,376
2032	433,480	430,544	411,108	406,784	476,212
2033	512,934	509,460	486,462	481,345	563,499
2034	597,174	593,129	566,354	560,396	656,042
2035	488,037	484,731	462,849	457,981	536,147
2036	401,039	398,323	380,341	376,340	440,573
2037	374,194	371,659	354,882	351,149	411,081
2038	433,536	430,599	411,161	406,836	476,273
2039	625,507	621,270	593,225	586,984	687,169
2040	428,491	425,589	406,377	402,102	470,731
2041	567,653	563,808	538,357	532,693	623,611
2042	296,170	294,164	280,885	277,930	325,366
2043	300,215	298,182	284,721	281,726	329,810
2044	519,113	515,597	492,322	487,143	570,287
2045	454,448	451,370	430,994	426,461	499,247
2046	407,142	404,385	386,130	382,068	447,278
2047	460,109	456,992	436,363	431,772	505,466
2048	465,163	462,013	441,156	436,515	511,018
2049	457,947	454,845	434,312	429,743	503,090
2050	453,316	450,246	429,920	425,398	498,003
Total	**14,125,517**	**14,029,843**	**13,396,501**	**13,255,578**	**15,517,988**

Table D.4: Cost Savings per Year across the Whole Network for each HMA Scenario

Year	HMA (Tonne)	Cost Savings vs. Baseline (Million $)		
		HMA (Max 25% RAP)	HMA (Max 40% RAP)	HMA (Max 50% RAP)
2018	2.11	3.22	13.68	16.90
2019	2.19	3.34	14.18	17.51
2020	2.24	3.42	14.52	17.93
2021	5.14	7.84	33.33	41.17
2022	8.69	13.25	56.33	69.58
2023	11.90	18.16	77.19	95.36
2024	11.43	17.44	74.12	91.56
2025	9.59	14.64	62.20	76.84
2026	9.10	13.89	59.03	72.92
2027	7.26	11.07	47.06	58.13
2028	12.32	18.80	79.89	98.68
2029	11.13	16.98	72.16	89.14
2030	8.13	12.40	52.71	65.11
2031	8.93	13.63	57.91	71.53
2032	8.76	13.37	56.82	70.18
2033	10.37	15.82	67.23	83.05
2034	12.07	18.42	78.27	96.69
2035	9.86	15.05	63.97	79.02
2036	8.11	12.37	52.56	64.93
2037	7.56	11.54	49.05	60.59
2038	8.76	13.37	56.82	70.19
2039	12.64	19.29	81.98	101.28
2040	8.66	13.21	56.16	69.38
2041	11.47	17.51	74.40	91.91
2042	5.99	9.13	38.82	47.95
2043	6.07	9.26	39.35	48.61
2044	10.49	16.01	68.04	84.05
2045	9.19	14.02	59.56	73.58
2046	8.23	12.56	53.36	65.92
2047	9.30	14.19	60.31	74.50
2048	9.40	14.35	60.97	75.31
2049	9.26	14.12	60.02	74.15
2050	9.16	13.98	59.42	73.40
Total	**285.51**	**435.6**	**1,851.4**	**2,287.0**

Table D.5: Questionnaire 5 for the Case Study "Increased Use of Reclaimed Asphalt Pavement (RAP)"

Question Number	Question	Answer
1	Define change	Caltrans allows contractors to use up to 15 percent of RAP (by weight) in HMA, which is considered as the baseline, or base scenario, in this chapter. The goal of this study is to calculate how much reduction in GHG emissions can be achieved by increasing the maximum RAP content in HMA mixes (15, 25, 40, and 50 percent)
2.	Define the state of readiness of the change of technology (using approach adapted from NASA)	TRL 5 and 6: technology validated and demonstrated in relevant environment at less than full scale
3.	Define system in which change occurs	The system includes all the state transportation network under jurisdiction of Caltrans. The study is cradle-to-gate; therefore, the system boundary only includes the material production stage.
4.	Will the market change or is it just changes in market share?	The market does not change, only share of RAP in Caltrans projects related to hot mix asphalt is increased.
5.	Who is responsible for change?	Caltrans will permit this change in California state highway projects.
6.	Who is responsible for implementing change?	The contractors will be implementing the change in pavement projects.
7.	Who pays for change	a. Government, level of government State gov, passed on to consumers b. Producers without pass through to consumers c. Consumers Implementation of this strategy does not result in cost increase. In fact, it results in savings both in cost and environmental impacts.
8.	What will drive change	a. Market X b. Market incentives c. Regulation d. Legislation e. Internal Policy X f. Public programs incentivizing change g. Education Permission (and possible mandate) from Caltrans, cost savings for contractors and the state. Education and public outreach can also help. The change will result in energy saving, reduction of GHG emissions, and decrease in use of natural resources (virgin aggregates and asphalt binder).
9.	What will the change do to these other environmental indicators	*LCA WILL ANSWER* i. Air pollution ii. Water pollution iii. Energy use 1. Renewable 2. Nonrenewable 3. Renewable energy source used as material 4. Nonrenewable energy source used as material iv. Water use v. Use of other natural resources

Question Number	Question	Answer
10.	What are the performance metrics in addition to GHG reduction and cost?	Reduction in annual GHG emissions due to material consumption in GHG emissions. Reduction of project costs related to material procurement and transportation in Caltrans projects.
11.	Supply curve calculation questions:	a. Expected change in GHG output per unit of change in system (LCA). b. Expected maximum units of change in system (LCA). c. Time to reach maximum units of change (reasonable time to be implementable), policy question. d. Expected shape of change rate (dependent on the funding): i. Linear ii. Increasing to maximum iii. Decreasing to maximum iv. S-shaped Assumed the change is implemented across the whole network at once (in year one). For each one percent increase in RAP content of HMA mixes in Caltrans projects, on average around 70 thousand tonnes of CO_2-e can be abated each year. The maximum amount of change can be achieved by switching to a maximum of 50 percent RAP content in HMA mixes which will allow Caltrans to save close to 0.75 MMT of CO_2-e between 2018 and 2050. e. Estimated initial cost per unit of change (LCCA) -$3.43, -$9.15, -$11.82 per tonne of HMA for increasing RAP content to 25, 40, and 50, percent, respectively, compared to 15 percent RAP. f. Estimated life cycle cost per unit of change (LCCA) Same as above.

APPENDIX E: ALTERNATIVE FUEL TECHNOLOGY FOR AGENCY VEHICLE FLEET

Table F.1: Acronyms Used in the Chapter

Word	Stands for
Acq	Acquired
ADR	Assembly, Disposal, and Recycling
AFLEET	Alternative Fuel Life Cycle Env and Economic Transp.
AFV	Alternative Fuel Vehicle
ANL	Argonne National Laboratory
B100	Blend of 100% Biodiesel by Volume
B20	Blend of 20% Biodiesel and 80% Diesel by Volume
BEV	Battery Electric Vehicle
BI	Bi-Fuel
BtOH	Butyl Alcohol
CAFÉ	Corporate Average Fuel Economy
CD	Charge Depleting
CD	Conventional Diesel
CG	Conventional Gasoline
CIDI	Compression-Ignition Direct-Injection
CNG	Compressed Natural Gas
Comb.	Combination
CS	Charge Sustaining (PHEV)
DE	Dedicated
Ded.	Dedicated
DEF	Diesel Exhaust Fluid
DGE	Diesel Gallon Equivalent
Disp.	Disposed of
DME	Dimethyl Ether
DSL	Diesel
E85	High-Level Ethanol-Gasoline Blends 51-83% Ethanol
ELEC	Electricity
EPAct	Energy Policy Act
EREV	Extended Range Electric Vehicle
EtOH	Ethanol
ETW	Equivalent Test Weight
EV	Electric Vehicle
FC	Fuel Cell (without Reformer/Battery)
FCV	Fuel-Cell Vehicle
FFV	Flex Fuel Vehicle (Generally E85)
GAS	Gasoline
GC	Grid-Connected
GCI	Gas Compression Ignition
GGE	Gallon of Gasoline Equivalent
GI	Grid-Independent
GREET	GHG, Regulated Emissions, and Energy Use in Transp.
GV	Gasoline Vehicle
GVWR	Gross Vehicle Weight Rating
H2	Hydrogen
H2-g	Gaseous Hydrogen
HD	Heavy Duty
HDT	Heavy-Duty Truck
HEV	Hybrid Electric Vehicle
HHV	Diesel Hydraulic Hybrid

Word	Stands for
HI	Hybrid Internal (Combustion/Battery)
HPRD	High-performance Renewable (Diesel)
HEV	HEV
HYD	Hydrogen
LD	Light-Duty
LDT	Light-Duty Truck
LDV	Light-Duty Vehicle
LL	Low-Level
LNG	Liquefied Natural Gas
LPG	Liquified Petroleum Gas (also Propane)
LSD	Low-sulfur Diesel
M85	85% Methanol
MD	Medium Duty
MDT	Medium-Duty Truck
MeOH	Methanol
MMBtu	Million British Thermal Unit (1 Btu = 1,055 Joules)
MPDGE	Mile(s) Per Diesel Gallon Equivalent
MPG	Miles per Gallon
MPGEE	Mile(s) Per Gasoline Gallon Equivalent
MY	Model Year
NRP	Nonrecycled Plastic
OandM	Operation and Maintenance
PC	Passenger Car
PH	Plug-in Hybrid
PHEV	Plug-in Hybrid Electric Vehicle
PM2.5	Particulate Matter, Diam. of 2.5 Micrometers or Less
PUT	Pickup Truck
RD100	100% Renewable Diesel
RD20	20% Renewable Diesel, 80% Petroleum-based
Ren	Renewable
RF	Fuel Cell with Reformer Battery
RFG	Reformulated Gasoline
RFO	Residual Fuel Oil
SI	Spark-Ignition
SUV	Sport Utility Vehicle
TBW	Tire and Brake Wear
Ts	Tractors
ULS	Ultralow-sulfur Diesel
Veh.	Vehicle
VIN	Vehicle Identification Number
VMT	Vehicle Miles Traveled
Voc.	Vocational
WTP	Well-to-Pump
WTW	Well-to-Wheels

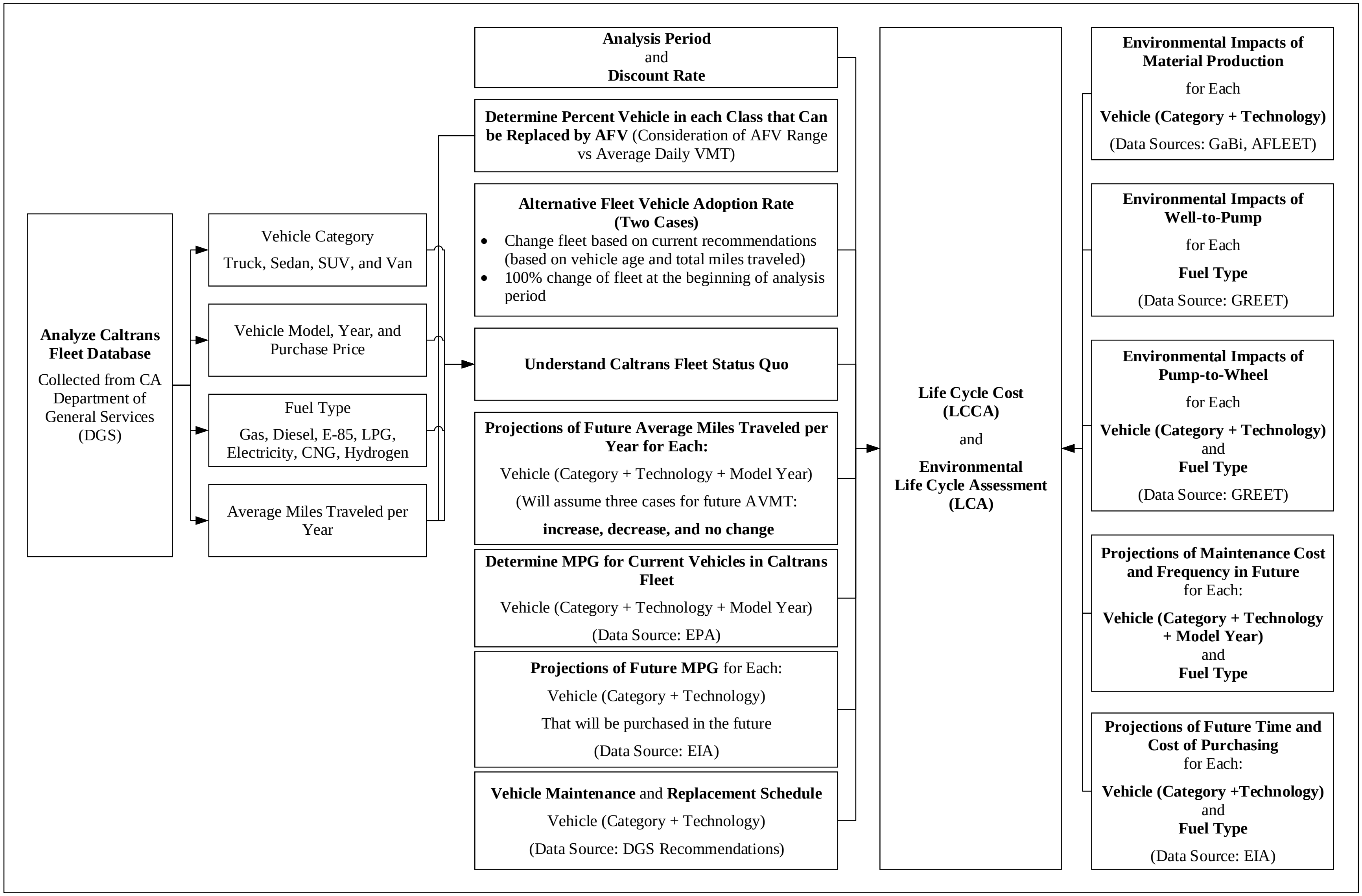

Figure E.1: Flowchart of model development used for this study.

History of Legislation Related to Alternatives Fuels at Federal and State Level

Key Statutes related to Alternative Fuels

The Energy Policy Act (EPAct) of 1992[6] defined alternative fuels and assigned the United States Department of Energy (US DOE) to develop a regulatory program for selected state fleets as launching pads for advanced vehicles using alternative fuels. Energy Policy Act of 1992 considers the followings as alternative fuels:

- Methanol, ethanol, and other alcohols
- Blends of 85% or more of alcohol with gasoline
- Natural gas and liquid fuels domestically produced from natural gas
- Liquefied petroleum gas (propane)
- Coal-derived liquid fuels
- Hydrogen
- Electricity
- Fuels (other than alcohol) derived from biological materials, including pure biodiesel (B100)
- P-Series[7]

Major federal statutes that established key transportation regulatory activities[8] are listed below:

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

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[6] *https://afdc.energy.gov/files/pdfs/2527.pdf*

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

[8] *https://epact.energy.gov/key-federal-statutes*

Major Initiatives in California

Senate Bill 522[9], passed in 2003, adopted the recommendations from the California State Vehicle Fleet Fuel Efficiency Report and required the collection of statewide fleet data and the publishing of annual public reports about the fleet composition.

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

Executive Order B-16-12[11]**,** issued by Governor Brown in 2012, directed state fleets to increase the purchase of ZEVs through the normal course of fleet replacement, requiring them to have at least 10 percent of light-duty vehicle purchases from ZEVs by 2015. This target would increase to 25 percent by 2020.

Senate Bill 1275, the Charge Ahead California Initiative[12], passed in 2014 established a state goal of one million zero-emission and near-zero-emission vehicles in service by 2020.

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

The California State Administrative Manual[13] set the ZEV purchasing policy for state agencies, which includes the "ZEV and hybrid vehicle first" policy which requires departments to purchase light-duty following this priority structure: (1) pure ZEVs, (2) PHEVs, and (3) hybrids. The policy also increased the ZEV purchasing mandate annually by 5 percent so that it will be 50 percent by 2025. Section 3627 of the State Administrative Manual[14] mandates the use of renewable diesel instead of conventional diesel and biodiesel fuel for bulk transportation fuel purchases. Section 3620.1[15] of the Manual sets the vehicle fuel efficiency requirements, expressed in miles per gallon (mpg) of fuel, for light-duty passenger vehicles to 38 and light-duty trucks, vans, and sport utility vehicles (SUVs) to 22.2.

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[9] *https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200320040SB552*

[10] *https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200720080AB236*

[11] *https://www.gov.ca.gov/news.php?id=17472*

[12] *http://www.leginfo.ca.gov/pub/13-14/bill/sen/sb_1251-1300/sb_1275_bill_20140921_chaptered.pdf*

[13] *http://sam.dgs.ca.gov/TOC/4100.aspx*

[14] *https://www.documents.dgs.ca.gov/sam/SamPrint/new/sam_master/sam_master_file/chap3600/3627.pdf*

[15] *https://www.documents.dgs.ca.gov/sam/SamPrint/new/sam_master/sam_master_file/chap3600/3620.1.pdf*

AFVs Currently Available in the Market

A literature survey was conducted to identify AFVs options currently available in the market in each vehicle category. The most reliable and comprehensive database available is the Alternative Fuel Data Center (AFDC) website (maintained by the US DOE.) Figure E.2 shows the number of AFVs (by make and model) available for different vehicle categories based on fuel type. Hybrid electric vehicles (HEVs) and PHEVs are the most common types for automobiles, while E85 vehicles offer the greatest number of alternatives for SUVs, pickups, and vans. CNG, B20 (diesel with 20 percent bio-based diesel), and LPG are dominant choices for trucks.

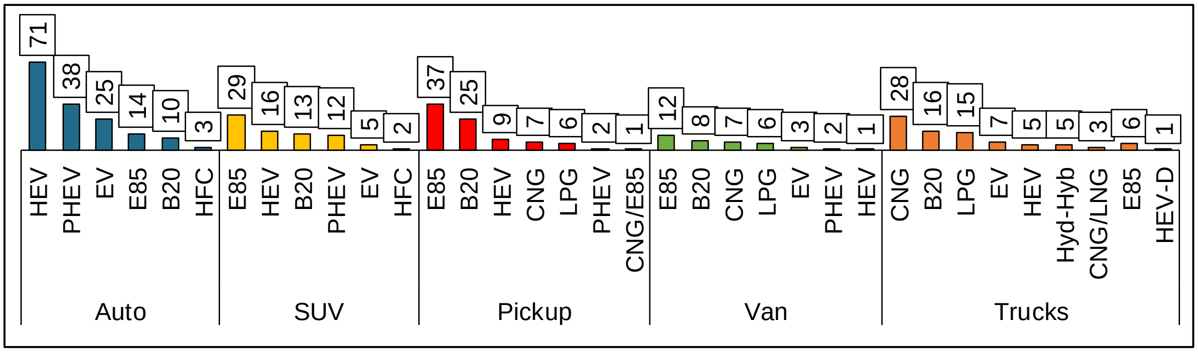

Figure E.2: Current number of model offerings for AFVs by vehicle category *(101)*.

Table E.2: Vehicle Categories and Types in Caltrans Fleet

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

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

There are 9,325 vehicles in Caltrans fleet as of 2017. Figure E.3 shows the fleet statistical summary by graphing vehicle distribution by fuel type, gross weight category, general category, and vehicle type. Pickups constitute more than 43 percent of all Caltrans vehicles, followed by trucks and passenger cars with 36 and 15 percent shares, respectively.

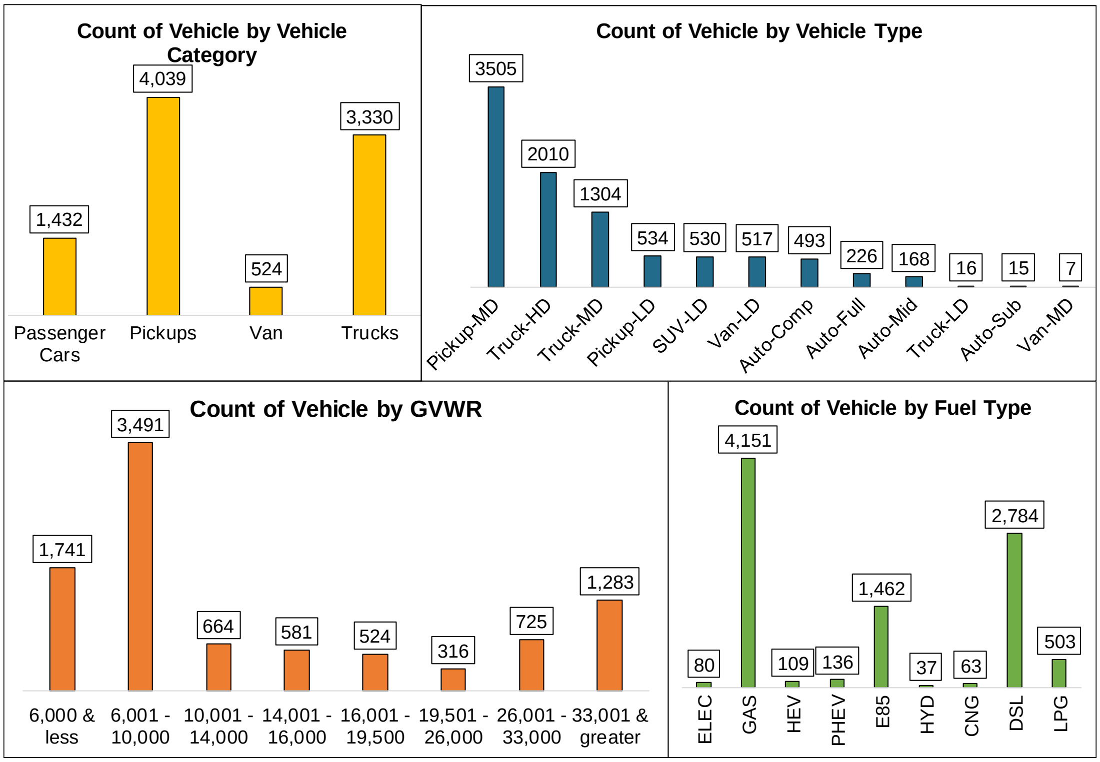

Figure E.3: Summary statistics of Caltrans fleet in 2017.

Table E.3: Average Annual Vehicle Miles Traveled by Vehicle Category (DB2017)

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

Projections

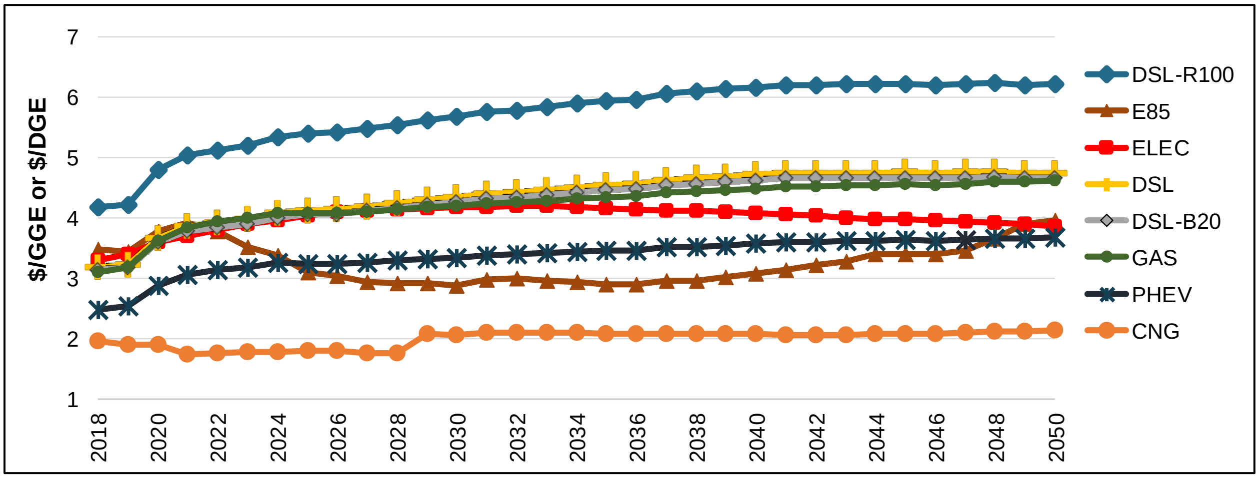

Figure E.4: Projection of future prices of fuels. [16]
(Note: DGE is diesel gallon equivalent, GGE is gasoline gallon equivalent.)

Consideration of Difference in California Fuel Prices versus National Averages

To account for differences in energy prices in California versus national averages, historical data were collected for gasoline, diesel, electricity, and natural gas. Annual average gasoline prices in California has consistently been higher, and more variable, compared to national averages in almost every year since 2004 (with the highest price volatility in 2008.) Diesel prices had a similar trend as gasoline. Natural gas prices were as high as 60 percent more expensive in California prior to 1998. However, natural gas has consistently been cheaper in California compared to the US average since 1998. The numbers shown in Table E.4 were used to convert prices from previous sections to account for differences in regional prices in California versus national averages.

Table E.4: Price Ratio of Alternative Fuels (California over US averages)

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

Fleet Replacement Schedule

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

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[16] *https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2018andcases=ref2018andsourcekey=0*

Historical trends in acquiring new vehicles and disposal of old vehicles by the Caltrans fleet were studied by using DB2011-14 data and the costs associated with historical acquisitions, and disposals were calculated. Table E.5 shows the average total miles driven and the average vehicle age when disposed of by Caltrans. Medium- and heavy-duty trucks had the highest "vehicle age when sold" of 17 years and the highest "mileage when sold" was for medium-duty pickups and light-duty trucks with 173,957 and 163,485 miles, respectively.

Table E.5: Average Age and Miles of Caltrans' Disposed Vehicles, by Vehicle Type (DB2011-14)

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

DGS published a fleet replacement policy in 2017 for the age and mileage for replacing fleet vehicles based on vehicle type (whichever reach the threshold earlier). The DGS policy is presented here in Table E.6.

Table E.6: Current DGS Policy for Fleet Replacement[17]

Vehicle	Age of Vehicle (in months)	Vehicle Mileage
GVWR* up to 8,500 Pounds		
Law Enforcement Vehicles	60	100,000
Sedans	72	65,000
Mini Vans	96	80,000
Cargo Vans	60	65,000
Pickup Trucks	60	65,000
Sport Utility Vehicles	84	85,000
GVWR of 8,501 – 16,000		
Law Enforcement Vehicles	60	100,000
All Trucks, Vans, and SUVs	72	70,000
GVWR of 16,001 – 26,000		
All Trucks, Vans, and SUVs	132	115,000

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[17] *https://www.documents.dgs.ca.gov/osp/sam/mmemos/MM17_05.pdf*

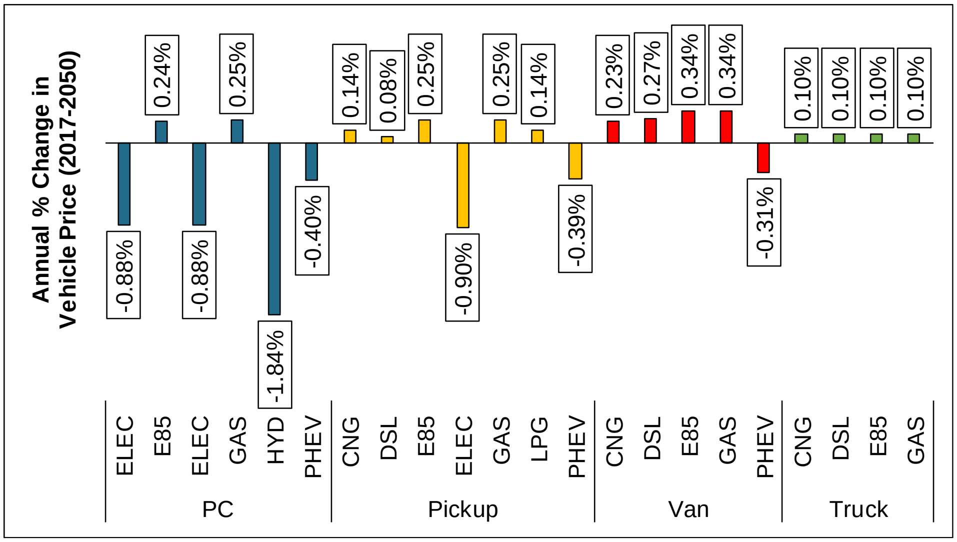

Figure E.5: Average annual growth rate in vehicle price based on EIA. [18]

Salvage Value

Salvage Value Based on Historical Data

Table E.7 shows the salvage value as a percentage of the original purchase price for each vehicle type and the average age at which vehicles were disposed of by Caltrans. Heavy-duty trucks on average retained the maximum percentage of their initial value (13 percent) among all vehicle types at the disposal stage. Furthermore, the average age of heavy-duty trucks when sold was greatest among all vehicle types (17.1 years). The lowest salvage value among all vehicles with disposal count of more than 100 was for mid- and full-sized sedans (7 percent of their original value.)

Industry-Wide Accepted Typical Salvage Values

It is typically assumed that a brand-new vehicle loses about 30-50 percent of its initial value within the first three years (depending on the market and the vehicle's make and options, among other factors.) The depreciation rate after three years is assumed to be linear through the typical average life of the vehicle, which in turn depends on vehicle type.

Table E.7: Salvage Value as P of the Original Purchase Price, Based on Data from DB2011-14

Vehicle	Age	Salvage Value as % of Original Price	Count
Auto-Sub	10.4	5%	3
Auto-Comp	9.3	9%	1,309
Auto-Mid	9.5	7%	853
Auto-Full	10.3	7%	555
SUV-LD	11.4	8%	523
SUV-MD	10.5	7%	4
Pickup-LD	11.1	14%	1,149
Pickup-MD	12.1	10%	3,779
Van-LD	11.5	8%	867
Van-MD	14.7	9%	31
Truck-LD	15.8	9%	11
Truck-MD	16.7	9%	947
Truck-HD	17.1	13%	1,605

Addressing the Vehicle-Cycle Impacts Challenges

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

1. First, the weight of light-duty vehicles of different fuel technologies were collected from AutoNomie website[19]. The collected data were compared to determine the percentage increase in vehicle weight compared to conventional ICEV for each of the vehicle fuel technologies. The results show that electric option on average results in a 39 percent increase in vehicle weight compared to conventional gasoline option. The plug-in hybrid, hybrid, and diesel options result in 26, eight, and four percent increase in vehicle weight compared to gasoline option, respectively.
2. Then it was assumed that a similar trend in weight increase exists for trucks with different fuel technologies.

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[19] *https://www.autonomie.net/docs/Annex%202%20-%20Vehicle%20Energy%20Consumption.xlsx*
Maintained by Argonne National Laboratory, this website presents research findings of the U.S. Department of Energy Vehicle Technologies Office (VTO) and Fuel Cell Technologies Office (FCTO) “to support new technologies to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing. VTO works in collaboration with industry and research organizations to identify the priority areas of research needed to develop advanced vehicle technologies.”

3. As CNG option was missing in the light-duty vehicle options, further literature survey was conducted to determine extra weight needed for CNG tanks that need to be added to the truck. Data taken from a recent study by NHTSA[20], compares the weight of diesel and CNG options for the truck fuel tank at different capacities. Based on the collected data it was assumed that the CNG option for trucks on average add 6 percent to the truck weight compared to the diesel option (details of the calculations available in the main model.)
4. The available vehicle-cycle GHG emissions data for light-duty vehicles were divided by vehicle mass to calculate vehicle-cycle GHG intensity (in terms of CO_2-e per kg of the vehicle), as shown in Table E.8. The calculated GHG intensities were used to calculate vehicle-cycle GHG emissions of trucks with various fuel technologies.

As stated earlier, EIA does not differentiate between vehicle fuel technologies and only provides weight projections based on vehicle type. To address this challenge and also calculate vehicle-cycle impacts for all the vehicle type and fuel combinations in the model, the following data were used:

- Percent increase in vehicle weight compared to the gasoline option, for each of the alternative vehicle technologies
- Vehicle-cycle GHG intensity by vehicle fuel technology (the data in Table E.8)
- Weight projections by vehicle type from EIA

Average useful life (in VMTs) for light-duty vehicles, pickup, and vans were taken from GREET and the values for trucks were taken from EPA compliance and fuel economy data center[21]. These values were converted to average useful life (in years) by using average annual VMT of each vehicle category based on DB2017 data. The results are shown in Table E.9.

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[20] *https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812194_commercialmdhdtruckfuelefficiency.pdf*

[21] *https://www.epa.gov/compliance-and-fuel-economy-data*

Table E.8: Vehicle-Cycle GHG Emissions by Fuel Type (kg CO_2-e per kg of the vehicle)

Vehicle	Weight (lbs.)	GHG (kg CO_2)	kg CO_2 / kg Vehicle
CNG	3,500	6,547	4.12
DSL	3,308	6,188	4.12
DSL-B20	3,308	6,188	4.12
DSL-R100	3,308	6,188	4.12
E85	3,644	5,979	3.62
ELEC	3,324	7,234	4.80
GAS	3,183	5,996	4.15
HEV	3,429	6,401	4.12
HYD	3,644	9,925	6.00
LPG	3,500	6,547	4.12
PHEV	3,756	7,560	4.44

Table E.9: Average Service Life by Vehicle Type

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

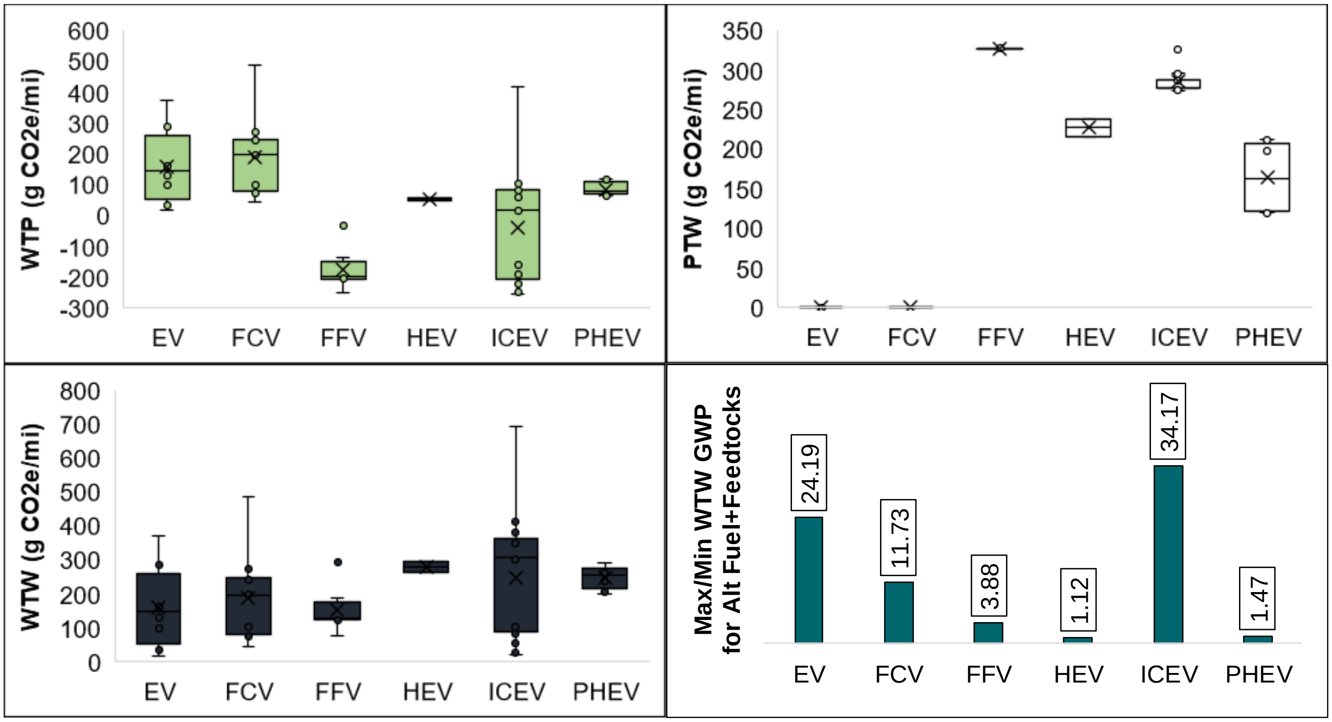


Figure E.6: WTP, PTW, and WTW by fuel type only, and max/min GWP for different feedstocks.

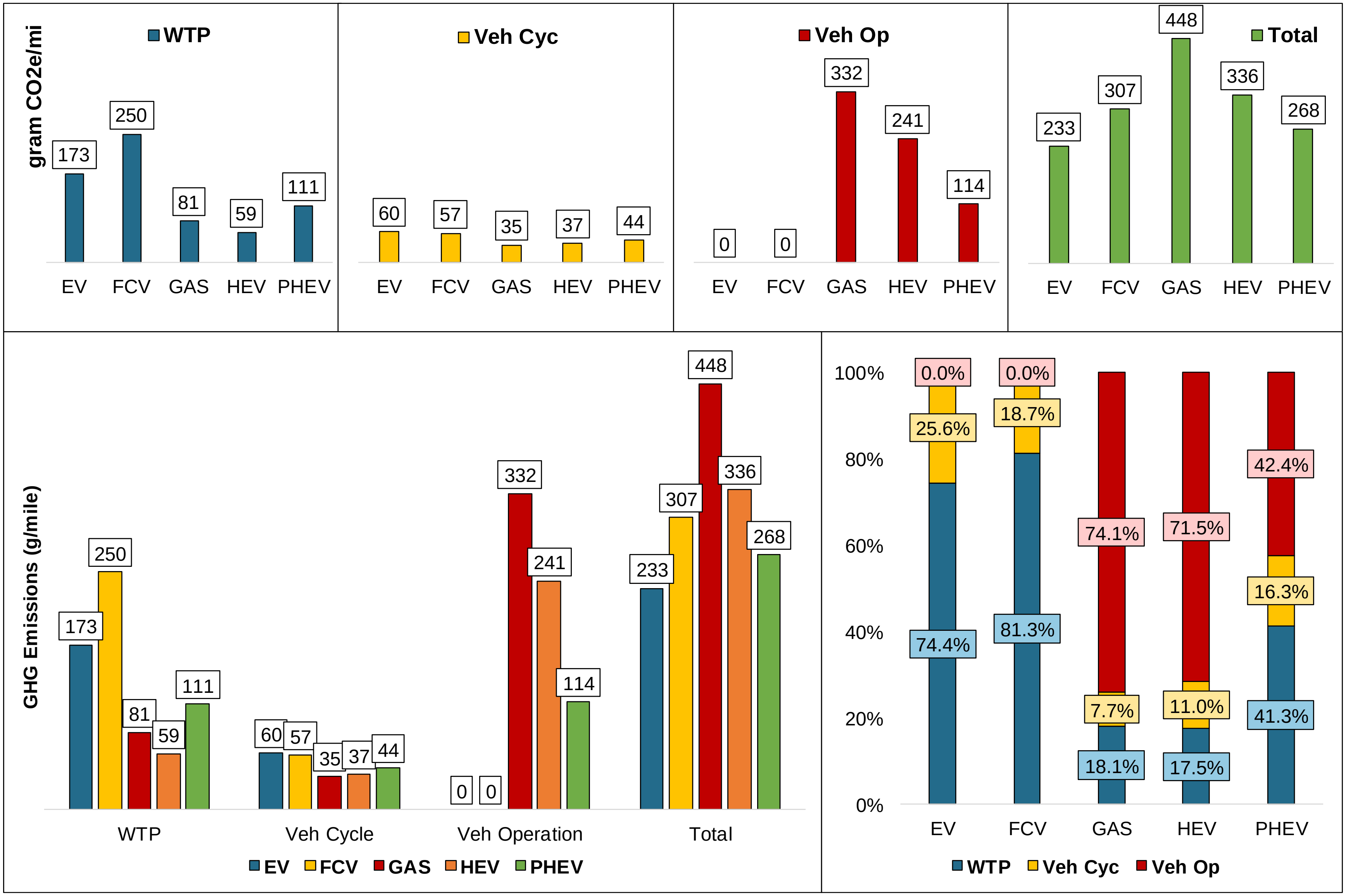
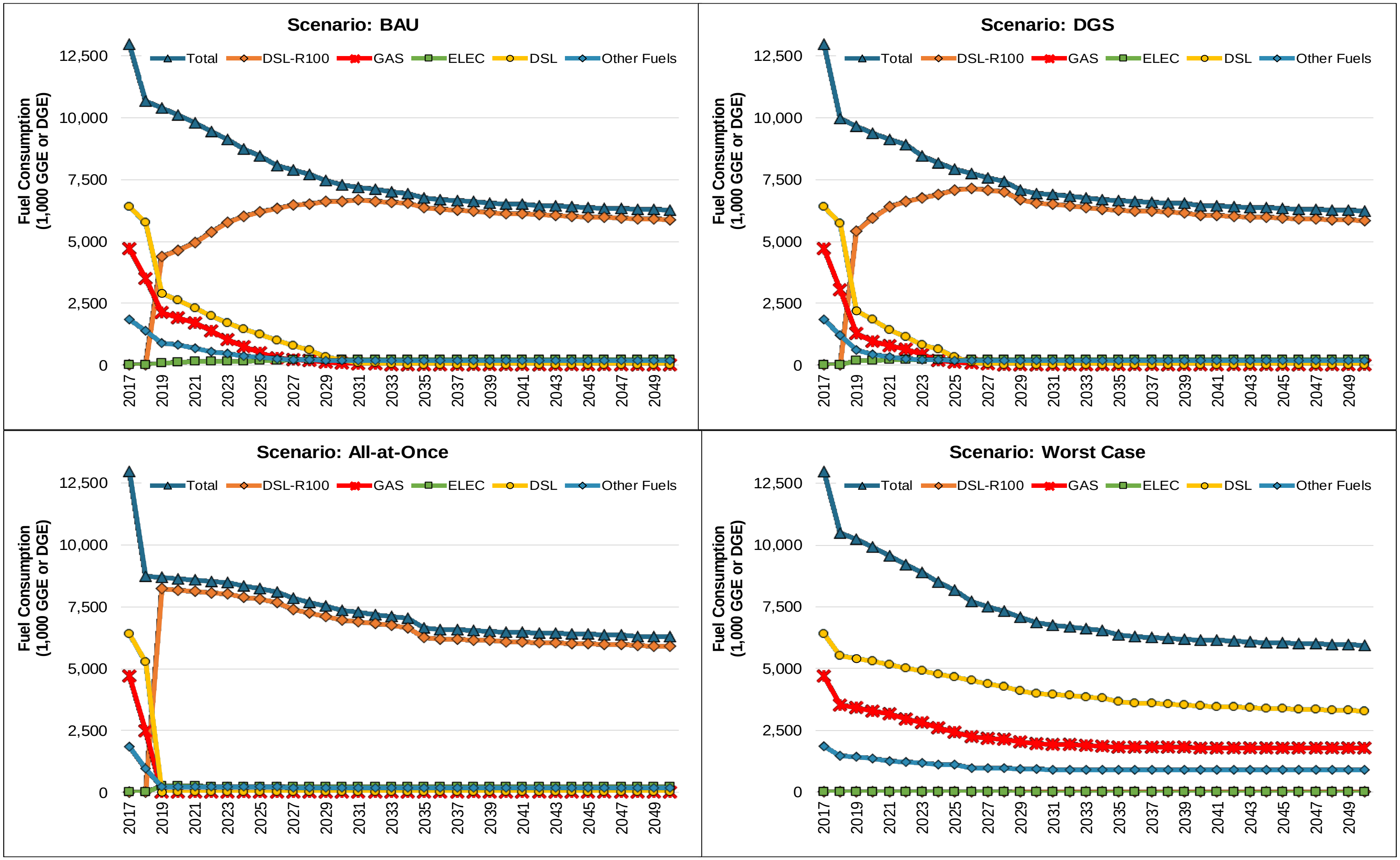


Figure E.7: WTW and fuel cycle comparison of different light-duty vehicle types.



Scenario: BAU

Scenario: DGS

Scenario: All-at-Once

Scenario: Worst Case

Figure E.8: Comparison of fuel consumption across scenario.

Table E.10: Questionnaire E for the Case Study “Alternative Fuel Technology for Agency Vehicle Fleet”

Question Number	Question	Answer
1	Define change	Converting all Caltrans fleet vehicles to AFVs at once versus converting at the typical end of vehicle life cycle
2.	Define the state of readiness of the change of technology (using approach adapted from NASA)	TRL 5 and 6: technology validated and demonstrated in relevant environment at less than full scale
3.	Define system in which change occurs	Caltrans fleet vehicles that fall in any of the four categories: passenger car, pickup, van, truck. Currently there are 9,325 vehicles that fit the criteria in Caltrans fleet.
4.	Will the market change or is it just changes in market share?	The whole market (Caltrans fleet) will change.
5.	Who is responsible for change?	Caltrans
6.	Who is responsible for implementing change?	Caltrans fleet services
7.	Who pays for change	a. Government, level of government Caltrans b. Producers without pass through to consumers n/a c. Consumers n/a
8.	What will drive change (X)	a. Market b. Market incentives X c. Regulation X d. Legislation X e. Internal Policy X f. Public programs incentivizing change g. Education
9.	What will the change do to these other environmental indicators	*LCA WILL ANSWER* i. Air pollution ii. Water pollution iii. Energy use 1. Renewable 2. Nonrenewable 3. Renewable energy source used as material 4. Nonrenewable energy source used as material iv. Water use v. Use of other natural resources Regulations exist mandating gradual AFVs adoption for state agencies. Will result in reduction of GHG emissions, increase use of renewable energies, and significant decrease in urban area pollution.
10.	What are the performance metrics in addition to GHG reduction and cost?	a. GHG emissions, b. annual fuel consumption, c. costs

Question Number	**Question**	**Answer**
11.	Supply curve calculation questions:	a. Expected change in GHG output per unit of change in system b. Expected maximum units of change in system: One c. Time to reach maximum units of change (reasonable time to be implementable), policy question d. Expected shape of change rate (dependent on the funding): i. Linear ii. Increasing to maximum iii. Decreasing to maximum iv. S-shaped (Expected) e. Estimated initial cost per unit of change f. Estimated life cycle cost per unit of change: Total saving in GHG emissions versus BAU: -267,994 tonnes of CO_2-e. Total cost of change (extra cost versus BAU) between 2018-2050: 60.8 million dollars Cost of abatement: $227 per tonne of CO_2-e abated.

APPENDIX F: SOLAR AND WIND ENERGY PRODUCTION ON STATE RIGHT-OF-WAY

Details of Solar Canopy

The solar canopies are assumed to be wide enough to cover two parking spaces, with support beams placed every three parking spaces. Under this arrangement, the structure provides area to support 48 solar panels that measure 1 by 1.6 meters each. This would provide space for 130,000 meters-squared of PV panel, which results in an installed rated capacity of 18.6 MW. It is further assumed that canopies are, on average, installed in groups of five, such that 30 parking spots (15 long and 2 wide) are covered by one cohesive solar canopy. The supporting structure is assumed to be all steel, as per the material specifications released by Carport Structures Corporation (2019). The design of the modeled solar canopy was derived from a product bulletin released by Structural Solar (2013) and the solar canopy design specifications released by Carport Structures Corporation.

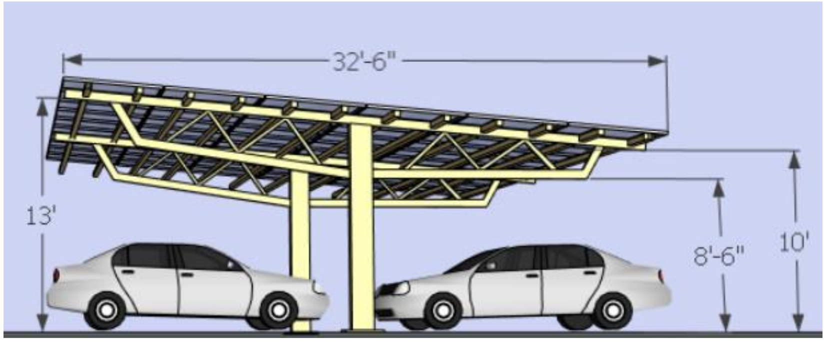


Figure F.1: A solar canopy design showing approximate dimensions of the structure (Structural Solar, 2013).

The simplified carport structure model was similar to that seen in Figure F.1, but it only included the vertical support beams, the lengthwise beams that span the two adjacent parking spaces, and the numerous smaller beams to support the solar panels. One change, however, was to include a cement concrete base that is two and a half feet tall which is meant to protect the structure from vehicle-related damage; the vertical support beam was shortened accordingly. The structure may need minor repairs after 25 years, but these are considered negligible, and it is therefore assumed that the structure does not need to be replaced until after 2050.

Table F.1: Questionnaire F for the Case Study "Solar and Wind Energy Production on State Right-of-Way"

Question Number	Question	Answer
1	Define change	a. EXISTING: Solar has been installed on building rooftops. b. CHANGE: Install wind mills and solar panels in all physically possible places with a reasonable payback period.
2.	Define the state of readiness of the change of technology (using approach adapted from NASA)	Solar canopies over parking spaces: TRL 9: actual system proven in operational environment elsewhere or less-than-full market penetration. Wind turbines in interchanges and solar panel along right-of-ways: TRL 5 and 6: technology validated and demonstrated in relevant environment at less than full scale.
3.	Define system in which change occurs	Caltrans-owned and operated state highway network and other land/property assets. Cost to be carried within existing budgets unless other funds found, bonds, CAP and Trade, or additional state funding increase in budget. Budget constraint optimization and unconstrained optimization. Cannot be the only criteria for funding.
4.	Will the market change or is it just changes in market share?	No
5.	Who is responsible for change?	Caltrans. State transport agency, CTC, legislature, energy commission, CPUC
6.	Who is responsible for implementing change?	Caltrans
7.	Who pays for change	a. Government, level of government State gov, passed on to consumers b. Producers without pass through to consumers n/a c. Consumers n/a
8.	What will drive change (X)	a. Market b. Market incentives X c. Regulation X d. Legislation X e. Internal Policy X f. Public programs incentivizing change g. Education
9.	What will the change do to these other environmental indicators	*LCA WILL ANSWER* i. Air pollution ii. Water pollution iii. Energy use 1. Renewable 2. Nonrenewable 3. Renewable energy source used as material 4. Nonrenewable energy source used as material iv. Water use v. Use of other natural resources
10.	What are the performance metrics in addition to GHG reduction and cost?	a. Safety changes b. KWh diff times of the day and diff seasons, aesthetics, noise.

Question Number	Question	Answer
11.	Supply curve calculation questions:	a. Expected change in GHG output per unit of change in system: 2.34 MMT CO_2-e b. Expected maximum units of change in system: One c. Time to reach maximum units of change (reasonable time to be implementable), policy question: Four years d. Expected shape of change rate (dependent on the funding): i. Linear ii. Increasing to maximum iii. Decreasing to maximum iv. S-shaped (Expected) e. Estimated initial cost per unit of change: $288.78 per ton CO_2-e reduction f. Estimated life cycle cost per unit of change: Between -$582.18 (high electricity price) and $88.63 (low electricity price)