WHITE PAPER

on

ALTERNATE STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS: A LIFE CYCLE APPROACH USING A SUPPLY CURVE

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DISCLAIMER STATEMENT

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1. INTRODUCTION

1.1. Background

Caltrans has several possible strategies it can implement to reduce the greenhouse gas (GHG) emissions tied to its state highway network operations and help it meet the state's climate change mitigation goals. However, even though a number of these strategies appear to be attractive, simple, and effective, many of them also have some or all of the following limitations:

- The net GHG reductions expected to result from implementing the strategy have not been quantified;
- The GHG reductions were quantified without using a full system-wide perspective for their estimates;
- Implementing the GHG reduction strategy will take time and that period has not been considered;
- The difficulties involved in implementing the GHG reduction strategy have not been assessed; and
- Most importantly, the quantification of changes in environmental impacts and the initial and life cycle costs (LCCs) of implementing the 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 because mobilizing the state's economic power and political will depend on Caltrans choosing GHG-reduction strategies that prioritize delivering the "greatest bang for the buck." In the absence of a prioritization process that considers cost-effectiveness constraints, the capacity of government, industry, and public support to implement required GHG reductions may be exceeded before the goals are met. In addition, for public support for GHG-reduction-related reforms to continue, the public must be able to see that tax payer-funded efforts to meet the state's GHG targets are being conducted in the most cost-effective ways possible.

The timeframe in which the change occurs is also important because emissions reductions achieved in the near term will have greater near-term climate benefits than emission reductions that occur later or are spread over a longer period. Typically, impact assessments use global warming potential (GWP) calculations as the indicator for quantifying and comparing GHG emissions or their reduction, although GWP does not consider the timeframe for change. However, by using an alternative indicator termed "time-adjusted warming potential" (Kendall 2012) in parallel with GWP, a temporal dimension can be added to account for the timing of emissions reductions.

A full-system and life cycle view is necessary to fully understand changes in environmental impacts and to avoid the unintended consequences that may occur for a selected strategy. 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 the benefits achieved in one part of a system may be reduced or reversed in another part that was not considered. Life cycle assessment (LCA) is a methodology that provides a full system and life cycle quantification of environmental impacts.

As LCA use has increased and broadened to answer increasingly complex questions in a number of fields, limitations and problems with the approach have also been highlighted. As a result, LCA methods and data have continued to mature, producing more robust and trustworthy results. This stands in contrast to life cycle cost analysis (LCCA), which is an already mature methodology that Caltrans regularly uses for infrastructure decision-making support.

1.2. Problem Statement, Study Purpose, and Intended Audience

California's transportation sector is a major contributor to the state's GHG emissions, and Caltrans has undertaken emissions-reduction initiatives in all 12 of its Districts. Within Caltrans, four major areas/departments/sections have taken on these initiatives: (i) planning and environment, (ii) materials, concrete, and pavements, (iii) maintenance and operations, and (iv) facilities and administration. The initiatives include several strategies, including adoption of alternative fuels and vehicles in the fleet, using material alternatives to conventional concrete and asphalt, and switching to renewable energy sources, etc. (Caltrans 2013). Caltrans plans to reduce GHG emissions to 40 percent below 1990 levels by 2030 (EO B-30-15, SB 32) and to 80 percent below 1990 levels by 2050 (EO S-3-05). However, to achieve these goals, Caltrans must be able to more specifically quantify the results that the different strategies may yield. Further, Caltrans needs to identify which strategy/alternatives can be adopted soon so the 2030 and 2050 targets can be met.

Caltrans must also be able to prioritize selecting alternatives using a consistent and transparent process that supports its decision-making. **The purpose of this white paper** is to provide Caltrans with a methodology that uses LCA and LCCA analyses to create a "supply curve" that ranks the different strategies/actions that can be taken to reduce GHG emissions and lessen any other environmental impacts that affect ecosystems and human health. For Caltrans to implement the proposed methodology, the process must be validated and assessed using currently available actions. This white paper presents the methodology and demonstrates its initial use in quantifying and ranking several potential strategies.

The white paper's intended audience is Caltrans climate-change-action decision makers who can use the proposed approach to analyze and rank the most cost-effective GHG reduction strategies as quickly as possible. The paper's other audiences include researchers, planners, and policy makers, as it advocates for them to contribute to the development of data, models, and tools for the supply curve approach.

2. METHODOLOGY

2.1. Approach and Framework

The approach taken in this white paper to support the prioritization of strategies for reducing GHG emissions is to develop what are variously called *supply curves, marginal abatement curves,* or *McKinsey curves* (named after the company that has made extensive use of them; Creyts et al. 2007). 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. 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 (or implemented strategies), the curves can show incremental contributions toward a goal and the decreasing cost effectiveness as additional actions are taken (Lutsey 2008.) The example shown in Figure 1 is adapted from Lutsey's (2008) 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 the life cycle cost. Although all the actions have a required initial cost to make the change, only some of those changes will result in life cycle cost savings. And not only do those actions reduce GHG emissions, they also improve the efficiency of the overall economy.

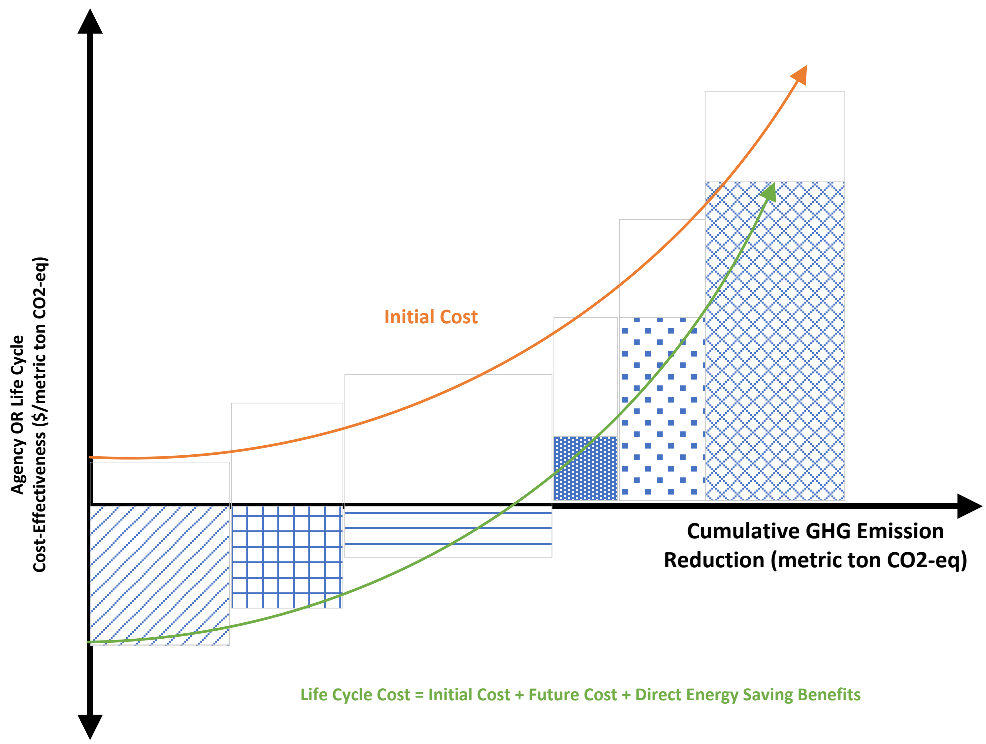

Figure 1. Example of a supply curve (adapted and recreated from Lutsey 2008).

To develop the LCA and LCCA analyses, a list of the information required to help create a supply curve for each proposed strategy was compiled as shown in the list below. The information needed to assess each strategy's implementation potential was also compiled and included in the list; these items include a definition of the strategy, its technology and the system it would change, the strategy's state of readiness, its responsible stakeholders, and the factors that would drive the change. The following is the information to be gathered:

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 (NASA, 2012)
    a. TRL 1: basic principles observed
    b. TRL 2: technology concept formulated
    c. TRLs 3 and 4: experimental proof of concept/technology validated in lab
    d. TRLs 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 sources and data used to develop the information listed above need to be fully documented, and include:

- 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

2.2. Scenarios Considered for the Supply Curve

Caltrans and the research team discussed six strategic pilot case studies to test the methodology and to see what results the strategies would yield. A detailed LCA and LCCA for each strategy has been published in a technical memorandum (Harvey et al. 2020). That technical memorandum provides the details, assumptions, calculation methods, and results of each strategy. The results from each strategy were then used to develop this paper's GHG reduction supply curve.

The six strategies were grouped into three categories. The three categories and the strategies under each are listed and described below.

1. Pavement-Management Related
   a. *Fuel use reductions through pavement network roughness management*

      Pavement condition affects vehicles' fuel economy and GHG emissions through rolling resistance (that is, through the energy lost due to the interaction between the vehicle and the pavement). Specifically, vehicle fuel use increases on rougher pavement surfaces. Currently, Caltrans and most other US state departments of transportation use a single measure of pavement roughness—characterized as a pavement's IRI value—to trigger maintenance and rehabilitation (M&R) treatments for all the segments in their entire highway network. An alternative approach would be to keep roads in a smoother condition (that is, keeping roughness lower) through more frequent M&R treatments where the volume of traffic and resultant fuel savings is sufficient to more than compensate for the GHG emissions from the increased intensity of treatments, resulting in an overall reduction in GHG emissions. This would be achieved by lowering the IRI level that triggers a treatment on those roads. However, the existing IRI trigger would continue to be used where traffic volumes are too low to compensate for the emissions generated by the more frequent treatments. The life cycle costs for Caltrans to keep higher traffic-volume pavements smoother may be the same or lower because the treatment cost to restore a pavement's smoothness is often less if the pavement is less damaged. To implement this GHG emissions-reducing strategy, a road network must first be divided into *lane-segments* (in the Caltrans PMS, which considers each lane separately, 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. After that, an "optimized" IRI trigger value that minimizes the total GHG emissions resulting from the treatment process and the smoothness-induced fuel use improvement is identified for each lane-segment. This suggested approach is tested in this strategy.

b. *Increased use of reclaimed asphalt pavement (RAP)*
A significant portion of the environmental impacts attributable to Caltrans each year results from projects it awards to contractors to maintain its close to 50,000 lane-miles of California highway infrastructure. At the end of their service life, the asphalt pavements in those many lane-miles can be milled and the reclaimed asphalt pavement (RAP) from them can be reused in new hot mix asphalt (HMA). Use of RAP in HMA both reduces aggregate consumption and, more importantly, helps reduce the amount of virgin asphalt binder needed in new mixes. For years, Caltrans only allowed contractors to use up to 15 percent RAP (by weight) in HMA, and this is considered as the base scenario for this strategy. But recently Caltrans made the use of up to 25 percent RAP in new mixes less onerous by allowing a simple change of grade for the virgin binder instead of the previously required laboratory testing. In keeping with the nature of this change, and to go beyond it, the goal of this examination was to calculate how much GHG emissions can be reduced by increasing the maximum RAP content in HMA mixes from 15 percent to 25, 40, and 50 percent and to scale those results to the California network.

2. Renewable-Energy-Generation Related
   a. *Energy harvesting using piezoelectric devices under the pavement surface*
   Within the past decade, compression-based piezoelectric generation has been explored as an in-pavement energy generation source. A popular piezoceramic is composed of lead zirconate titanate and is thus referred to as a *PZT sensor.* PZT sensors generate a voltage when they are compressed. Individual PZTs can be housed together to create a larger piezoelectric transducer. By embedding a row of PZT transducers in a highway pavement (2 inches below the pavement surface), the traffic load over the transducers will generate voltage spikes that can be harvested. In-pavement piezoelectric energy generation is roughly a function of traffic load and speed: the more vehicles that pass, the heavier they are, and the faster they travel, the higher the power output will be. This technology is tested in this strategy.

   b. *Solar and wind energy production on state right-of-ways*
   A strategy for reducing GHG emissions in California 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. To date, Caltrans has implemented 74 solar projects and has proposed 14 more, but these have all been on buildings (Fox et al. 2018). 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. This case evaluates the net GHG impacts of generating solar energy and wind energy on appropriate locations in Caltrans rights-of-ways—since the department owns more than 15,000 miles of highway centerline, with a large but unknown amount of acreage in those rights-of-ways—and by placing solar PV canopies over Caltrans-owned parking lots. (Note: the solar energy generated in this strategy does not include any generated from placing solar panels in pavements).

3. Caltrans-Operations Related
   a. *Automation of bridge tolling systems*
   All-electronic tolling (AET) technologies are available through contractors statewide. This case study examined the effects on GHG emissions resulting from implementation of AET

technology as a replacement for existing cash-collecting toll booths. AET systems use a transponder device or license plate recognition technology that does not interrupt traffic flow. At seven state-owned toll bridges, drivers currently pay their toll either with cash or via an electronic transaction with a FasTrak device. Cash-paying vehicles must stop at a tollbooth and then re-accelerate to reach to free-flow traffic speed. Although an AET system requires a reliable electronic system and real-time management, it improves traffic flow and reduces additional fuel consumption by eliminating cash tollbooth stops. Other studies have shown that a vehicle consumes more fuel and emits more pollutants when accelerating from a stop to free-flow speed, with the exact amounts determined by the vehicle type, traffic condition, and driving pattern.

b. *Alternative fuel technologies for agency vehicle fleet*
Transportation is the California economic sector that contributes most to statewide GHG emissions, and 89 percent of these emissions come from on-road transportation, primarily from the combustion of gasoline by light-duty vehicles and of diesel by heavy-duty vehicles (CARB 2018). One statewide strategy for reducing GHG emissions is to move to a vehicle fleet that relies much more heavily for propulsion on electricity than on petroleum combustion. A second potential alternative means of heavy-duty vehicle propulsion that could be used in parallel to electrification of light-duty vehicles is use of combustible fuels, such as biodiesel, that are produced 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 statewide fleet's GHG emissions.

The analysis period for each strategy was considered to be of 35 years (2015 – 2050) except for Strategies 1.b and 3.b, for which the analysis period was 33 years (2018 – 2050).

Each strategy assessment had its own set of assumptions and limitations, which are documented in the technical memorandum (Harvey et al. 2020). A quality assessment of each strategy's data is also summarized in the technical memorandum.

3. RESULTS AND DISCUSSION

3.1. Supply Curve (GHG Abatement Cost Curve)

The supply curves created from the six pilot strategy assessments are shown in Figure 2 and Figure 3. The summary of results shown in the supply curves can be seen in Table 1. The results shown in Table 1 include those for alternative assumptions as part of the sensitivity analysis for each project, where there were alternatives to be considered. The results shaded green in the table are assumptions that led to more optimistic results, meaning greater GHG abatement and/or a lower cost/GHG abatement value. These alternatives are plotted in Figure 2. The results shaded orange are for assumptions that resulted in more pessimistic results based on the same criteria, and these are plotted in Figure 3. In some cases the results moved in different directions for total abatement and cost-effectiveness. For example, one assumption compared with another can lead to greater abatement but at a higher cost per unit of abatement. The combination of LCA and LCCA in the supply curves allows the effects of different scenarios to be compared for both performance measures.

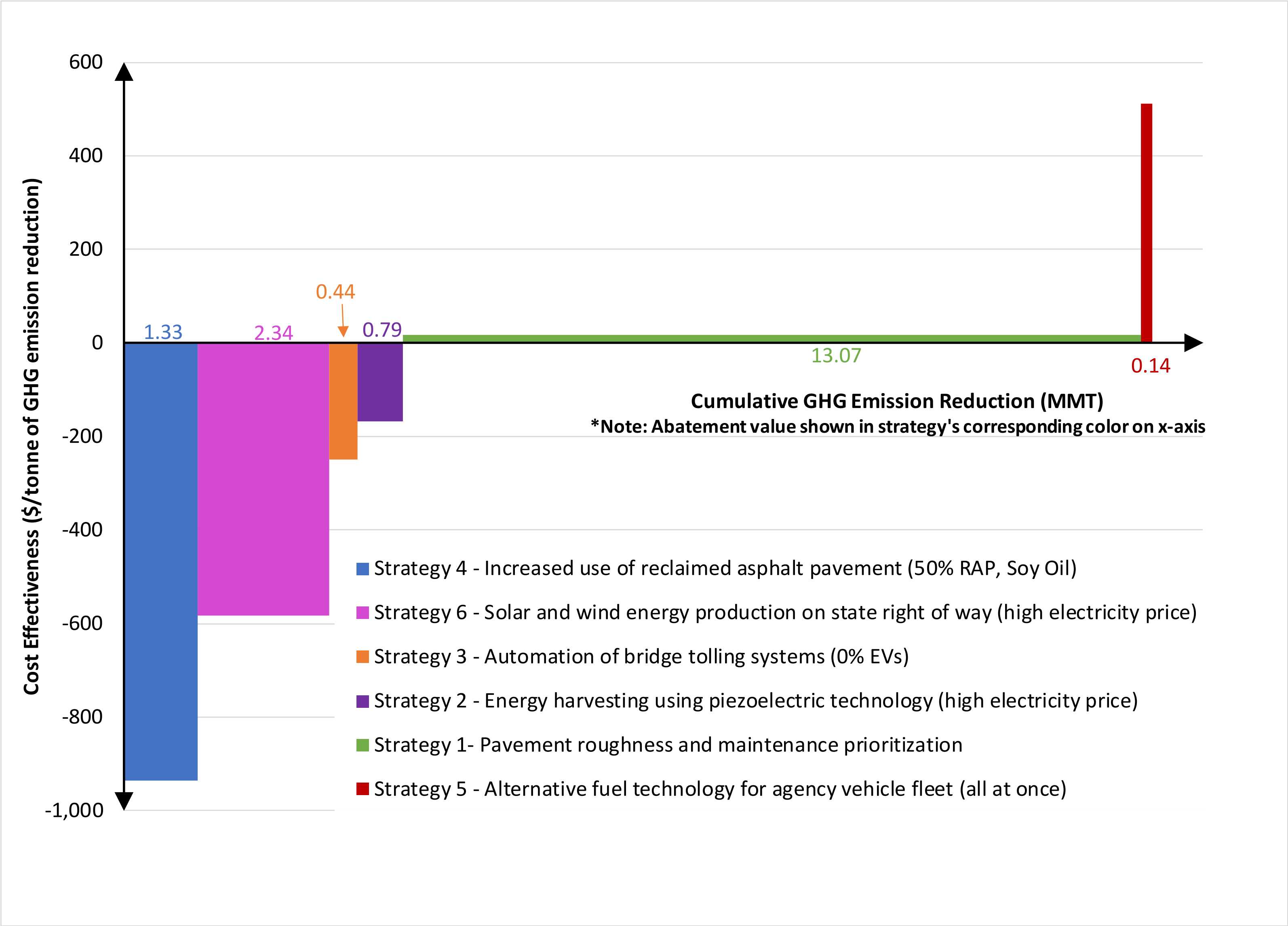

Figure 2: Supply curve for six pilot case studies for optimistic case scenarios considering both GHG reduction and cost-effectiveness from sensitivity analysis.

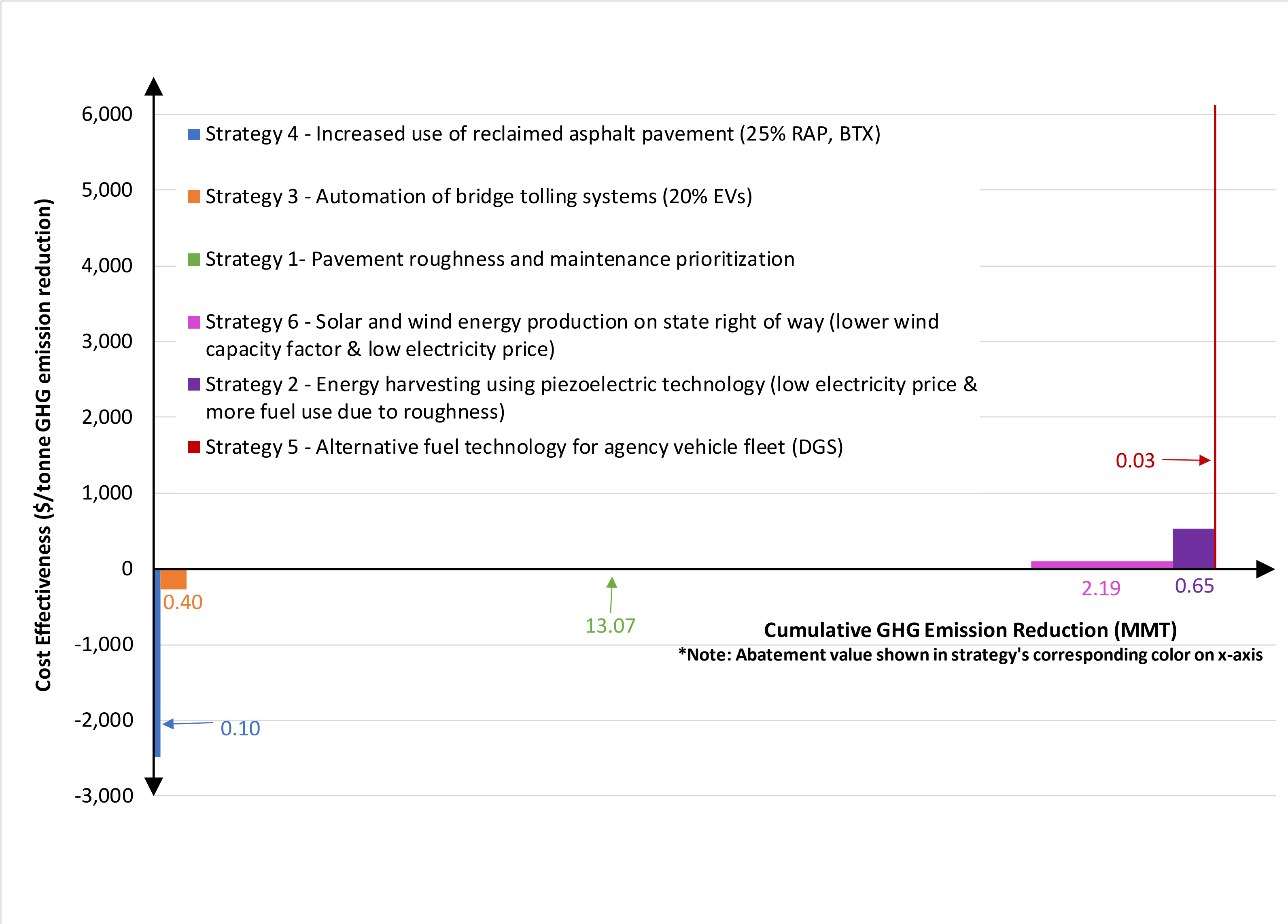

Figure 3: Supply curve for six pilot case studies for pessimistic case scenarios considering both GHG reduction and cost-effectiveness from sensitivity analysis.

Table 1. Summary of Results from Six Pilot Case Studies Used for Example Supply Curves

Strategies	Sensitivity Cases	CO_2-e change (MMT)	Agency Life Cycle Cost Change ($ million)*	Agency Cost/Benefit ($/tonne CO_2-e reduced)*
Strategy 1- Pavement roughness and maintenance prioritization	Five-year (years 25 to 30) average projected to last five years of 35-year analysis period	-13.1	216	16.7
	30-year average projected to last five years of 35-year analysis period	-13.6	330	24.6
Strategy 2 - Energy harvesting using piezo-electric technology	High Electricity Price	-0.798	-133	-167.12
	Low Electricity Price	-0.798	343	430.14
	Increased fuel use from pavement roughness (high electricity price)	-0.646	-91	-125.66
	Increased fuel use from pavement roughness (low electricity price)	-0.646	386	531.9
Strategy 3 - Automation of bridge tolling systems	0% EV	-0.444	-110.4	-249
	10% EV	-0.427	-110.4	-259
	20% EV	-0.409	-110.4	-270
Strategy 4 - Increased use of reclaimed asphalt pavement	Max 25% RAP, BTX	-0.1	-237	-2,479
	Max 25% RAP, Soy Oil	-0.33	-237	-727
	Max 25% RAP, No Rejuvenator	-0.47	-534	-1,136
	Max 40% RAP, BTX	-0.73	-1,008	-1,383
	Max 40% RAP, Soy Oil	-1.05	-1,008	-959
	Max 50% RAP, BTX	-0.87	-1,245	-1,431
	Max 50% RAP, Soy Oil	-1.33	-1,245	-936
Strategy 5 - Alternative fuel technology for agency vehicle fleet	DGS	-0.026	157	6,120
	All-at-Once	-0.138	70	511
	Worst-Case	0.787	-359	No Abatement*
Strategy 6 - Solar and wind energy production on state right of way	High Electricity Price	-2.342	-1,363	-582
	Low Electricity Price	-2.342	208	89
	Lower wind capacity factor (high electricity price)	-2.187	-1,282	-587
	Lower wind capacity factor (low electricity price)	-2.187	226	103

* Negative cost indicates a cost savings; user costs are not shown for the examples.

3.2. Discussion

Looking at the results, it is clear that keeping the highest-traffic sections of the highway network smoother (Strategy 1) results in the largest GHG abatement, given the assumptions made in the analysis, which are detailed in the technical memorandum (Harvey et al. 2020). This abatement costs Caltrans money but has a low abatement unit cost. The most cost-effective strategy is increased use of RAP

(Strategy 4), but this strategy has a perverse effect in that the lowest-cost rejuvenating agent capable of blending the RAP into the mix well also has a higher GHG impact. Therefore, if this lowest-cost rejuvenator is used, the GHG emissions reduction is very small. However, in both cases the large cost savings to the contractor of using RAP to replace virgin asphalt binder is assumed to be passed on to Caltrans through the low-bid contracting method. The most expensive strategy per unit of GHG saved appears to be changing the Caltrans vehicle fleet to electric cars and biodiesel trucks (Strategy 5), regardless of the rate of change considered (all at once, or following DGS policy). Automated bridge tolling (Strategy 3) is always cost-effective, but that cost-effectiveness decreases as vehicles using the bridges become more electrified (a perverse conclusion that often occurs in these types of analyses). The cost-effectiveness of both increasing solar and wind energy from Caltrans right-of-ways and parking lots (Strategy 6) and of installing piezoelectric energy collection devices under pavements (Strategy 2) is highly dependent on the price given to Caltrans for the energy delivered, either saving or costing Caltrans money per unit of GHG reduced. Further consideration must also be given to implementation readiness because solar and wind technologies are proven technologies while piezoelectric energy generation devices are in the early stages of development and many questions remain about the efficacy of putting these devices under pavement.

Consideration of the cost-effectiveness of keeping parts of the highway network smoother (Strategy 1) would have been an important sensitivity to consider, but no information regarding the impacts of pavement roughness on electric vehicle energy consumption is available yet.

In summary, the supply curve approach shown in this white paper and in the supporting technical memorandum (Harvey et al. 2020) demonstrates the curve's ability to quantify GHG reductions for full-scale implementation of the pilot projects by Caltrans and their cost-effectiveness. This project has also shown that the approach can indicate how to prioritize alternative projects based on their cost-effectiveness and their uncertainty-related risks.

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