Supply Curves Using LCA and LCCA for Conceptual Evaluation of Proposed Policies to Improve the Environment

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Abstract. Many changes are being proposed to reduce greenhouse gas emissions by a multitude of sources, with the proposals based to varying degrees on science, economics, the potential to grow markets or shrink the markets of competitors, regulatory strategies, and attractiveness based on the ability to easily communicate the idea to the general public. Identifying, quantifying, and then selecting among the many possible strategies to achieve GHG reductions is difficult, especially without a standardized approach for comparison. A promising approach, supply curves, that has been used at a national level for developing abatement strategies for GHG reduction is proposed for use in this paper. Some of the critiques of past use of supply curves are being addressed through the use of the principles of consequential life cycle assessment and life cycle cost analysis. Pilot studies currently underway for a large state road agency and local governments will provide initial feedback on the ability to use this approach at a conceptual level for initial prioritization of alternatives. Initial results indicate that sufficient data can be gathered in a reasonable amount of time to compare alternatives and that the results can be compared on a much more consistent basis than has occurred previously.

Keywords: Greenhouse gas emissions · Life cycle assessment · Life cycle cost analysis · Supply curve · Benefit-cost · Conceptual analysis

1 Introduction

California's 2006 Climate Change Solutions Act (Assembly Bill 32) tasked many government entities, including local governments and government agencies, with reducing greenhouse gas (GHG) emissions to 1990 levels by 2020 (a 30% reduction), and 80% below 1990 levels by 2050. There is no single change that will achieve these

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ambitious goals, instead multiple changes must be made in the state's economy by many actors. Many changes are being proposed by a multitude of sources, with the proposals based to varying degrees on science, economics, the potential to grow markets or shrink the markets of competitors, regulatory strategies, and attractiveness based on the ability to easily communicate the idea to the general public. Identifying, quantifying, and then selecting among the many possible strategies to achieve GHG reductions is difficult, especially without a standardized approach for comparison.

UC Davis researchers at the University of California Pavement Research Center (UCPRC) and the National Center for Sustainable Transportation (NCST) listened to state and local policy leaders and transportation system operators over the last five years lament the difficulty of prioritizing the tens of strategies and tactics that are being proposed for changes in how they should design and operate systems to reduce greenhouse gas emissions to meet the requirements. Having worked extensively supporting state and local government in California with "life cycle thinking" data and tools for implementation of life cycle assessment for environmental impacts (including social impacts) and life cycle cost analysis for financial impacts, they believed that a process that considered the full system and the life cycle was important to provide the most beneficial and sustainable solutions while minimizing the likelihood of unintended negative consequences.

As an example, the California Department of Transportation (Caltrans) has many possible strategies to achieve greenhouse gas (GHG) emission reductions in Caltrans' operations of the state highway network to help meet the state's climate change mitigation goals. However, although many of the ideas for change appear to be attractive, simple and positive, the following is true for many of them:

- The net GHG reduction if fully successful has often not been quantified
- It has not been determined whether or not the proposed changes produce net GHG reductions, or might be found instead to cause potential increases when the full system in which they occur and the full life cycle are considered
- The time it will take to make the change happen has not been estimated,
- The process and difficulty of making the change have not been estimated, and
- Most importantly, the costs of making the change, both initial and life cycle, have often not been estimated.

A life cycle perspective is required for GHG accounting because benefits achieved during one stage of strategy's life cycle may be reduced or reversed by carbon-intensive upstream or downstream stages. Similarly, if an incomplete system view is taken benefits in one part of the system may be reduced or reversed (i.e. more carbon is emitted than business as usual) in another part of the system that was not considered. In some cases, two or more potential changes in operations are incompatible with each other in ways that will negate the benefits, and a full system view can help identify these conflicts.

The last point in the bullet list above is considered equally important with the calculation of emissions, because state government and the state's overall economy have finite capacity and political will to pay for change. The approach used in the studies described in this paper is that the greatest and fastest GHG reduction will occur if there is a prioritization in terms of GHG reduction benefit to cost. Prioritization based on benefit to cost will result in the most efficient use of existing funds to achieve the maximum reduction possible, in other words the most “bang for the buck”. Unless there is this type of a prioritization, then the capacity of the public and the state’s economy to implement the needed GHG reductions may be exceeded before the goals are reached. It is also considered important to be able to demonstrate to the public that efforts are being made to achieve GHG reduction goals in the most cost-effective ways possible in order to help maintain public support for those goals.

The ability to quantify the full-system, life cycle effects of decisions and changes in systems is advancing and improving using the life cycle assessment (LCA) approach and related analysis processes. The limitations and problems with LCA are also being identified so that more robust and trustworthy results can be produced. The methodology for life cycle cost analysis (LCCA) is already mature and used within Caltrans for support of decision-making regarding infrastructure choices.

The timeframe for change is also important because emission reductions that occur sooner will have greater beneficial impact than emission reductions that occur later or are spread out over a longer period of time. This is not accounted for in current global warming potential (GWP) calculations. Time-adjusted warming potential (Kendall 2012) should be used to account for the timing of emission reductions. Use of time-adjusted warming potential will help identify strategies providing the “fastest bang for the buck”.

This study discusses and shows early examples of use of a GHG mitigation “supply curve” framework to support decision-making by Caltrans. The supply curve, as used in these studies, provides a method for selecting the most cost-effective strategies for mitigation by undertaking the following process for each strategy: it (1) quantifies the net effects on GHG quantity over the strategy’s lifecycle, (2) considers the time required to make the change happen, (3) explores the process and difficulty of making the change happen, and (4) calculates the initial and lifecycle costs of the strategy.

This approach is being used for two studies:

1. To evaluate possible changes that Caltrans can make in its operations to reduce greenhouse gas emissions
2. To evaluate proposed actions for transportation in climate action plans that have been developed by cities and counties in California to reduce greenhouse gas emissions

2 The Approach

The approach used is to support strategic prioritization of approaches for reducing GHG emissions using what are called “marginal abatement curves”, “supply curves”, or “McKinsey curves” after the company that has made extensive use of them (Creyt et al. 2007). Supply curves illustrate the economics associated with changes and policies made for climate change mitigation. In particular, the work done by Lutsey and Sperling (2009) demonstrated how alternatives within the transportation sector can be quantified and compared using available information, and also compared with alternatives in other sectors of the economy. Transportation is particularly important in

California because it is responsible for approximately 41% of annual GHG emissions in the state. This percentage has increased and actual transportation emissions have increased as other sectors of the economy, particularly generation and use of electrical energy, have decreased (CARB 2018).

A generic example of a supply curve, adapted from Lutsey, is shown in Fig. 1. To implement the development of supply curves, a set of questions are answered and calculations are completed using the best available information about the proposed changes box (the complete set of questions and calculations are described later in the paper). The supply curve uses the best estimate of the benefit on the x-axis, with each box representing a proposed change and the width of the box indicating the size of the benefit. Reduction of greenhouse gas emissions is shown in the example, however this could be a performance metric for other environmental goals, such as air pollution which is a major concern in California, as well.

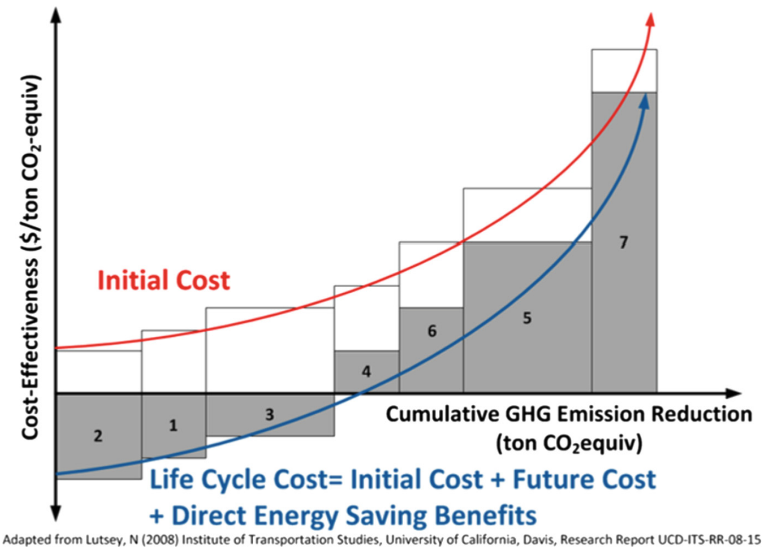

Fig. 1. Generic supply curve considering initial cost and life cycle cost.

In the approach being used, LCA is used to estimate the benefit by comparing 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 based on ISO 14044 (2006) data quality parameters as discussed related to pavements in the Federal Highway Administration Pavement LCA Framework (Harvey et al. 2016): time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, and reproducibility. The documentation of the LCA for the supply curve needs to include a data quality assessment, which must be taken into consideration when comparing alternative proposed changes on the supply curve.

The y-axis of the supply curve shows the cost of the change per unit of benefit. Two values are calculated for each proposed change using the best available information: the initial cost of implementation and the long-term or life cycle cost. 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.

The proposed changes are put in rank order of cost effectiveness, with color coding to identify the level of uncertainty of the information used for the analysis (not shown in the example in Fig. 1). All changes have an implementation cost, but some changes will potentially result in a life cycle cost savings. Those changes that are to the left on the curve should be considered for implementation first, because they provide the most improvement for the least cost. Those that have negative life cycle costs 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 identifies the cumulative effect of changes towards the overall GHG reduction goal, and the increasing cost of achieving that goal. As with all economic analyses regarding public policy, the economic analysis should consider not only the overall costs, but who pays the costs or receives the savings, and whether those costs or savings are equitable.

The purpose of developing supply curves to review alternatives is 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 must be used with caution, and are only one of the tools available to support decision-making regarding GHG and other pollutant reduction, not the only one. A number of limitations of supply curves have been identified, including omission of ancillary benefits of greenhouse gas emission abatement, poor consideration of uncertainty in the data, lack of consideration of dynamic interactions over time, and lack of transparency concerning their assumptions. Supply curves based on the individual assessment of abatement measures suffer from additional shortcomings such as not considering interactions, non-economic costs, and behavioral changes, as well as incorrect counting of benefits, and inconsistent baselines (Kesicki and Akins 2012). It has been suggested that supply curves be used more for comparisons of alternatives than for quantifying cumulative progress to abatement (Huang et al. 2016). The ability of supply curves to predict future abatement has been critiqued because of the lack of considerations of longer-term changes in markets driven by consumer changes, the timing of policy actions, actions taken by other actors in the market, and changes in future technologies (Morris et al. 2012). 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 curves, but they must be kept in mind when using supply curves to support decision-making.

These critiques are intended to be addressed somewhat by the use of LCA and LCCA approaches by the additional information that is intended to be gathered as part of the development of the supply curves, and in particular the use of consequential LCA which assumes that decisions will result in changes in the market rather than attributional LCA which assumes that market will not change.

The full set of questions that for which information is being gathered for the supply curve studies are as follows:

1. Define the action intended to create change in GHG emissions.
2. Define the system in which the change occurs.
3. Estimate whether the market will change or the action only changes market share.
4. State who the change will impact
5. State who is responsible for implementing the change
6. State who pays for costs of the change or benefits from savings
   a. Government, level of government
   b. Producers without pass through to consumers
   c. Consumers
7. State what the method used to create the change will be:
   a. Market
   b. Market incentives
   c. Regulation
   d. Legislation
   e. Public programs incentivizing change
   f. Education
8. Show estimates or calculations of what effects the change intended to reduce GHG emissions will have on these these other environmental and resource use indicators:
   a. Air pollution
   b. Water pollution
   c. Energy use
      i. Renewable
      ii. Non-renewable
      iii. Renewable energy source used as material
      iv. Non-renewable energy source used as material
   d. Water use
   e. Use of other natural resources
9. State how the effectiveness of the change in reducing GHG reductions (the performance indicators) will be measured, modeled or estimated once implemented.
10. State who will be responsible for measuring, modeling or estimating the performance metrics.
11. Supply curve calculation development questions:
    a. Expected change in GHG emissions per unit of change in the system.
    b. Expected maximum units of change in the system.
    c. Time to reach maximum units of change.
    d. Expected shape of change rate:
       i. Linear
       ii. Increasing to maximum
       iii. Decreasing to maximum
       iv. S-shaped
    e. Estimated initial cost per unit of change
    f. Estimated life cycle cost per unit of change

The information used to develop the answers to all 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, Completely Unknown

The recommendation is to submit supply curves and their documentation to outside critical review by interested stakeholders before using them for decision-making and documentation of the critiques and responses by the supply curve developers, following ISO LCA principles.

3 Applications in Studies Currently Underway

This approach is currently be piloted for proposed changes in the operations of the California Department of Transportation (funded by Caltrans), and for alternative strategies being included in climate action plans under development by California local and regional planning agencies (funded by NCST).

For the Caltrans study, the above methodology is currently being applied as a pilot for six mitigation strategies that could be implemented by Caltrans. These strategies were selected to provide a wide range of topics with which to test the evaluation process:

1. Efficient maintenance of pavement roughness
2. Energy harvesting through piezoelectric technology
3. Automating bridge tolling systems
4. Increased use of reclaimed asphalt pavement
5. Electrification for light vehicles and use of bio-based diesl as alternative fuels for the Caltrans fleet, and
6. Installing solar and wind energy technologies within the state highway network right-of-way

A description of one of these potential changes and initial findings from the study that is currently underway are described below. The analysis period is from 2019 to 2050, which is the state's target year for achieving GHG reduction goals.

Efficient Maintenance of Pavement Roughness

Pavement condition affects the fuel use of vehicles and therefore both greenhouse gas (GHG) emissions and the cost of transportation, while maintaining pavement condition is a direct cost to road agencies. Pavement condition affects the fuel use of vehicles through rolling resistance, i.e. energy losses due to interaction between vehicles and the pavement. The relative impact of the three elements of rolling resistance (roughness, texture and structural deflection) on fuel economy and GHG emissions from on-road vehicles depends primarily on the level of pavement roughness in California.

Alternative maintenance strategies and condition trigger levels for treatment are being considered using the Caltrans pavement management system for the full 80,000 lane-km state network, and using materials and construction emissions factors developed by Wang et al. (2014) and IRI progression models developed by Jeremy Lea and Ester Tseng of the UCPRC, which are implemented in the PMS. Current decision trees consider cracking first, and then an IRI of 2.7 m/km (170 inches/mile) to trigger treatment. Alternatives considered are use in the decision trees of the IRI trigger of 3.6 m/km (224 inches/mile) used prior to 2012, and a potential future alternative that focuses on keeping sections with higher traffic volumes smoother to maximize the reduction in GHG balancing greater material and construction emissions versus fuel savings per vehicle multiplied by the number of vehicles based on Wang et al. (2014). Triggers are 1.6 m/km (100 inches/mile) for the highest trafficked sections transitioning to the current 2.7 m/km for the rest of the network. Alternative budget scenarios are also being analyzed.

Because the calculation were already set up in the PMS, most of the work for consisted of hand testing the implementation in the code, and developing the scenarios. The results indicate that on the order of 1 to 2 million metric tons (MMT) of GHG emissions can be reduced on average with increased spending on maintenance and rehabilitation to maintain smoother pavement out of total emissions for the state of about 450 MMT. The benefit to direct agency cost ranges from about $150 to more than $600/MMT reduction. These numbers can be compared with the price of carbon on the California carbon market of between $10 and $20/MMT.

Inclusion of road user fuel savings dramatically reduces the life cycle costs, in some cases resulting in net savings considering agency and user, however, consideration must be given to increased fuel use from lower prices and smoother roads. The optimized IRI triggers are the remaining scenario to be tried.

4 Summary and Conclusions

Governments and road agencies have goals for reducing GHG emissions and other environmental impacts and also face cost constraints. In democracies, there is a need to maintain public support for policies and practices to achieve these critical environmental goals by choosing the most cost-effective alternatives, and honestly, transparently, and effectively communicating the approach used in decision making, the expected benefits and costs, and the metrics for measuring the performance of the decision makers in delivering the results. Many potential changes in the policies and practices of road agencies are being proposed, both internally and externally. However, there is often a lack of quantitative information regarding the benefits and costs of these proposals, and a lack of definition regarding how the changes will interact in a larger system in which they will occur and their long-term effects, and who they will affect which has equity implications.

A promising approach, called supply curves, that has been used at a national level for developing abatement strategies for GHG reduction is proposed for use in this paper. Some of the critiques of past use of supply curves are being addressed through the use of the principles of consequential life cycle assessment and life cycle cost analysis. Pilot studies currently underway for a large state road agency and local governments will provide initial feedback on the ability to use this approach at a conceptual level for initial prioritization of alternatives. Initial results indicate that sufficient data can be gathered in a reasonable amount of time to compare alternatives and that the results can be compared on a much more consistent basis than has occurred previously. It is apparent from work to date that a number of important assumptions need to be made, that need to be fully documented, and assessed for quality, for consideration in decision making.

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