Evaluate the Interactions between Transportation-Related Particulate Matter, Ozone, Air Toxics, Climate Change, and Other Air-Pollutant Control Strategies

NCHRP 25-25, Task 59

Requested by:

American Association of State Highway
and Transportation Officials (AASHTO)

Standing Committee on Environment

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SPECIAL NOTE: This report **IS NOT** an official publication of the National Cooperative Highway Research Program, Transportation Research Board, National Research Council, or The National Academies.

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DISCLAIMER

final report

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List of Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASM	Acceleration Simulation Mode
B20	Biodiesel (20 percent blend with diesel)
BEV	Battery-electric vehicle
CAFE	Corporate average fuel economy
CARB	California Air Resources Board
CCV	Closed crankcase ventilation
CDPF	Catalytic diesel particulate filter
CE	Cost-effectiveness
CH_4	Methane
CMAQ	Congestion Mitigation and Air Quality Improvement Program
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DOC	Diesel oxidation catalyst
DOT	Department of Transportation
DPF	Diesel particulate filter
E85	Ethanol (85 percent blend with gasoline)
EGR	Exhaust gas recirculation
EGU	Electrical generating unit
EMFAC	Emission Factor Model (CARB)
EPA	Environmental Protection Agency
FBC	Fuel borne catalyst
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GPS	Global positioning system
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (U.S. Department of Energy)
HC	Hydrocarbon
HD	Heavy-duty
HDDV	Heavy-duty diesel vehicle
HEV	Hybrid-electric vehicle
HGAC	Houston-Galveston Area Council
HOT	High occupancy/toll
HOV	High-occupancy vehicle
I/M	Inspection and maintenance
ITS	Intelligent Transportation Systems
LD	Light-duty
LNC	Lean NO_x catalyst
LNG	Liquefied natural gas
LNT	Lean NO_x trap

LPG	Liquid propane gas
MAG	Maricopa Association of Governments
MOVES	Motor Vehicle Emission Simulator model (U.S. EPA)
MPO	Metropolitan Planning Organization
MWCOG	Metropolitan Washington Council of Governments
NCHRP	National Cooperative Highway Research Program
NCTCOG	North Central Texas Council of Governments
NEPA	National Environmental Policy Act
NH_3	Ammonia
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
NYMTC	New York Metropolitan Transportation Council
OBD	On-board diagnostics
PAG	Pima Association of Governments
PHEV	Plug-in hybrid-electric vehicle
PM ($PM_{2.5}$, PM_{10})	Particulate matter (smaller than 2.5 or 10 microns)
ppm	Parts per million
ROG	Reactive organic gases
RSD	Remote sensing diagnostics
SACOG	Sacramento Area Council of Governments
SANDAG	San Diego Association of Governments
SCAG	Southern California Association of Governments
SCR	Selective catalytic reduction
SIP	State Implementation Plan
SNCR	Selective noncatalytic reduction
SO_x	Sulfur oxides
TCM	Transportation control measure
TDM	Transportation demand management
TIP	Transportation Improvement Program
TOG	Total organic gases
TRB	Transportation Research Board
TSE	Truck stop electrification
TSI	Two-speed Idle
TSM	Transportation systems management
ULSD	Ultra-low sulfur diesel
VMT	Vehicle-miles of travel
VOC	Volatile organic compounds
VSP	Vehicle-specific power

Executive Summary

STUDY OVERVIEW

The objectives of this study are to provide transportation officials with information on the effects of different transportation air quality control strategies on a full range of pollutants, and to identify methods for evaluating tradeoffs among different pollutants when selecting control strategies.

The study first assesses the effectiveness and cost-effectiveness of a variety of transportation emission control strategies at reducing emissions of various pollutants, including ozone precursors, particulate matter (PM), air toxics, and greenhouse gases (GHG); and identifies which strategies may reduce some pollutants while increasing others. A total of 34 control strategies are reviewed in three categories – transportation demand management (TDM), transportation systems management (TSM), and vehicle and fuel technology.

The study also includes:

- A review of different pollutant weighting systems used by agencies and researchers in evaluating projects across multiple pollutants;
- A survey of how state and regional transportation and air quality agencies have evaluated cost-effectiveness, considering multiple pollutants, and made tradeoffs among these pollutants when prioritizing control strategies; and
- Information gaps and research needs to assist agencies in selecting the most cost-effective control strategies, considering their potential impact on multiple pollutants.

Key study findings are summarized below.

EFFECTIVENESS AND COST-EFFECTIVENESS OF TRANSPORTATION DEMAND MANAGEMENT AND SYSTEMS MANAGEMENT STRATEGIES

Transportation demand management strategies can be defined as those that seek to reduce vehicle-travel, and particularly travel by single-occupancy vehicles. While these strategies usually reduce all types of emissions in roughly the same proportion, since their primary effect is on total vehicle-travel, some also may show increased emissions from new transit or vanpool service that is provided with the intent of reducing personal vehicle-miles of travel (VMT).

Transportation systems management strategies seek to improve traffic flow and reduce inefficient vehicle operations. These strategies commonly include congestion relief as well as vehicle idling reduction. Some strategies with TDM objectives, such as HOV lanes, also can affect traffic flow characteristics. The emissions impacts of these strategies can be complex, as emissions are affected in different ways by changes in traffic flow, depending upon the specific flow changes (e.g., speed change, reduction in idling) and pollutants being considered.

Key findings regarding these strategies include:[1]

- Commute-focused TDM outreach programs, including employer-based outreach, rideshare, and vanpool programs, often have relatively good cost-effectiveness. However, these projects also show wide variation in cost-effectiveness across individual projects. This suggests that their cost-effectiveness depends strongly upon the specific context of the project and how effectively it is implemented. Telecommuting projects tend to be relatively high-cost, especially when costs for telecommuting facilities and equipment are included.
- Bicycle and pedestrian projects show mixed results. In some studies they perform relatively well, while in others they do not. The overall magnitude of emission reductions from these projects is generally small, although costs also are modest compared to other infrastructure investments.
- Other transportation infrastructure investment to reduce VMT, including transit and freight rail, is generally high-cost (poor cost-effectiveness) compared to most other strategies. Transit service improvements also show high costs per ton of pollutant reduced.
- Pricing strategies can vary significantly in their cost-effectiveness depending upon the method of administration and amount of charge. VMT fees and congestion pricing can have moderate to high costs if fee levels are low, because of the high cost of monitoring and enforcement infrastructure. Higher fee levels result in improved cost-effectiveness. Most of the evidence on pricing strategies is based on GHG studies rather than pollutant emission reduction studies.
- More efficient land use patterns can provide significant GHG benefits over the long term for modest implementation (planning and administrative) costs. However, cost-effectiveness estimates have not considered the full costs or cost savings that may result from changes in infrastructure needs,

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[1] The following conclusions are based primarily on *implementation costs to the public sector*. Therefore, they do not reflect a more complete accounting of costs and benefits which may include additional costs such as business costs (e.g., to implement worksite trip reduction), traveler savings (e.g., lower transit fares), or non-monetary benefits such as time savings and improved mobility.

public services, etc., which are potentially much more significant than implementation costs.

- Traffic signal improvements (timing, synchronization) and incident management usually show good cost-effectiveness, with the exception of NO_x in some cases. However, this may change if induced demand effects are considered.[2] Measurement of induced demand associated with traffic operations is uncertain and it is, therefore, difficult to make definitive statements about the cost-effectiveness of these and other traffic operations strategies.
- Most studies evaluating traffic flow improvements, or regional pricing, transit, and land use strategies that can measurably affect traffic speeds, did not find tradeoffs among pollutants – i.e., all pollutants were consistently reduced. However, as noted, some projects did show increased NO_x levels as a result of higher traffic speeds. Whether there is a tradeoff will depend upon the specific operating conditions, as well as the analysis data and methods used.
- Truck idle reduction can provide modest but cost-effective air pollution and GHG reduction benefits with a low public investment cost.
- Speed limit reductions (evaluated for GHG only) can provide significant benefits at modest cost to the public sector for enforcement.
- Little data was available to evaluate a number of strategies, including intersection geometric improvements, traveler information, ramp metering, pricing effects (except for GHG), and managed lanes.

EFFECTIVENESS AND COST-EFFECTIVENESS OF VEHICLE AND FUEL TECHNOLOGY STRATEGIES

Vehicle and fuel technology strategies include the use of less polluting vehicle technology (e.g., more energy-efficient vehicles, pollution controls), and/or alternative fuels that reduce emissions. Vehicle and fuel technology strategies and their effects tend to be different for light-duty versus heavy-duty vehicles. Heavy-duty vehicle strategies and impacts also differ across different classes of vehicles (e.g., buses, medium trucks, large trucks). The effects and cost-effectiveness of individual strategies vary widely by the specific technology and pollutant of interest, and also can vary significantly depending upon the conditions under which the vehicle is operated (e.g., ambient temperature, load profiles). Key findings include:

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[2] Induced demand can be defined as an increase in travel resulting from improved travel conditions (e.g., reduced travel times or costs).

- In general, most of the control strategies evaluated in this analysis provide emission reductions for one or more pollutants, without notably increasing other pollutants. Key exceptions include certain diesel retrofits, which can increase fuel consumption and carbon dioxide (CO_2) emissions by several percent, and biodiesel, which may increase emissions of oxides of nitrogen (NO_x) up to 10 percent, depending upon the blend percentage.
- Substantial uncertainty also surrounds technologies relying on grid electricity (e.g., truck stop electrification and plug-in hybrids), given the large variation in electrical generating unit (EGU) emissions by region of the country and time of day. EGU emissions also are expected to decrease over time as older units are retired and cleaner units are brought on line, diminishing this particular concern in the future.
- The review of the available literature found a wide range of cost-effectiveness estimates for the different technologies, depending upon assumed mileage, useful life, among other factors. Several strategies evaluated appear to have favorable cost-effectiveness, including idle reduction, vehicle inspection and maintenance, and PM retrofit options.[3] However, depending upon the remaining useful life of the vehicle, accelerated retirement may provide a more favorable cost-effectiveness, especially for NO_x reductions.
- In general, the adoption of alternative fuels does not appear to be as cost-effective at criteria pollutant reduction as many other vehicle and fuel technology strategies. Similarly, strategies primarily targeting fuel consumption and CO_2 reduction do not appear to offer substantial incremental benefits in criteria pollutant reductions, although plug-in hybrid and battery electric vehicle options may prove cost-effective in the long run.

WEIGHTING METHODS

When evaluating the cost-effectiveness of multiple pollutants it often becomes necessary to weight the pollutants to combine them into one composite cost-effectiveness index. This is especially true in areas where there is more than one pollutant of major concern, such as areas in nonattainment for more than one pollutant. While the most appropriate weighting scheme may depend on local conditions, several factors should be considered, including health costs, precursor versus direct emissions, and progress towards attaining national air quality standards.

The issue of pollutant weighting was considered at a national level in a 2002 Transportation Research Board (TRB) special report on the Congestion

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[3] "Favorable" cost-effectiveness is defined based on two state programs, in California and Texas, that employ a cost-effectiveness target of about \$13,000 to \$16,000 per ton of pollutant controlled in order to qualify for funding.

Mitigation and Air Quality Improvement Program (CMAQ). This study explored the option of weighting NO_x versus volatile organic compounds (VOC) in a 1:1, 4:1, or 8:1 ratio, ultimately selecting 4:1 to reflect the fact that NO_x levels limit ozone formation more than VOC in most areas. At that time PM had not been regulated yet, so it was not included in the weighting, and carbon monoxide (CO) was not included due to major progress in regulating CO emissions. Several studies since then have attempted to include PM in a weighting scheme based on health-based research, but there has been a lack of agreement so far in converting the research results into a weighting scheme. A national weighting scheme that includes NO_x, VOC, CO, and PM would be useful and there appears to be data available to support the development of one, although variations might be needed to account for specific local problems.

No weighting schemes were found that incorporated air toxics, likely because of the wide variety of toxic air pollutants, lack of supporting research on the health effects of toxics, and the fact that they are not regulated as criteria pollutants. Also, the few weighting schemes available that include greenhouse gases are not based on quantitative data, such as health costs. Because the impacts of climate change will occur over a long timeframe and are highly uncertain, it is difficult to quantify them in cost terms. If the impacts of climate change were quantified into social costs, it could be possible to incorporate greenhouse gases into a weighting scheme with criteria pollutants.

SURVEY OF PRACTITIONERS

Transportation and air quality agencies in every state perform some evaluation of air quality projects, usually forecasting of emission reduction impacts of potential air pollution control strategies, since such estimates are required as a condition for CMAQ funding and may be needed to demonstrate attainment of a particular pollutant. A survey was conducted to identify agencies that have developed more rigorous cost-effectiveness evaluation procedures and methods for making tradeoffs among different pollutants. The survey was conducted by first distributing a web-based survey to areas in nonattainment for more than one pollutant, and second by conducting follow up in-depth interviews with those that indicated the use of advanced evaluation methods. Responses to the web survey were obtained from 20 agencies and five were reached for more in-depth follow-up.

The survey and interviews found the following:

- Most agencies consider criteria pollutants (VOC, NO_x, CO, PM), but only about half consider greenhouse gases and few consider toxics.
- Less than half of the agencies consider tradeoffs among multiple pollutants.
- Less than half of the agencies use weighting or some type of cost-effectiveness combined for multiple pollutants.

- Outside of metropolitan planning organizations (MPOs) in California that use the California Air Resources Board (CARB) cost-effectiveness database tool, the Phoenix, Arizona MPO was found to be the only agency using a quantitative method of combining cost-effectiveness for multiple pollutants. The New York State Department of Transportation (DOT) also plans to release CMAQ guidance with weighting among multiple pollutants.
- Several other agencies have a qualitative method of combining cost-effectiveness for multiple pollutants, such as through a table ranking priority for different strategies or as agreed upon by a committee.
- Several agencies indicated that they currently are working to incorporate greenhouse gases into their project selection process.
- The Phoenix MPO indicated that they currently are working to incorporate PM emission rate versus speed relationships from the U.S. Environmental Protection Agency's (EPA) MOVES model into their project selection process.

INFORMATION GAPS AND RESEARCH NEEDS

Transportation Demand Management

Measuring and predicting the benefits of TDM strategies has been a research topic of interest for decades, starting with programs enacted in the 1970s in response to the energy crisis, and continuing through air quality efforts in the 1990s to implement the provisions of the 1990 Clean Air Act Amendments. Some types of strategies have been fairly extensively studied, others less so. Due to limited funding for evaluation efforts, however, few evaluation studies have been conducted using robust and consistent methods. The potential of some strategies (such as telecommuting and traveler information) is evolving due to technological changes. Furthermore, better forecasting models are needed for other strategies (such as nonmotorized improvements) to account for specific local conditions.

The following is a list of topic areas where information is particularly lacking and most needed. This list considers the level of certainty or uncertainty in existing knowledge, the importance and potential of the strategy for future emission reductions, and the feasibility of obtaining additional useful information.

- Impacts of TDM programs, such as worksite- or neighborhood-based programs, in auto-centric locations or smaller cities with relatively low levels of transit service and limited traffic congestion; and most effective TDM actions under these circumstances;
- Impacts of nonwork TDM programs such as neighborhood-based marketing and "school pools";
- Potential for additional market penetration of alternative work schedules, including compressed work weeks as well as telework in different markets;

- Impacts of localized parking management policies in different contexts on destination-shifting (i.e., parking management leading people to drive to destinations that are farther away or less transit-accessible);
- Impacts of nonmotorized improvements (including systemwide improvements as well as individual projects) on utilitarian travel under different conditions/contexts;
- Evidence on freight mode-shifting in response to rail and intermodal improvements, and appropriate emission factors for comparing truck and rail goods movement;
- Life-cycle emissions impacts, considering construction and maintenance of highway and transit facilities in addition to emissions from vehicles operating on the facilities; and
- For all measures, robust studies from different contexts compiled into a "library" so that practitioners can look up examples that are similar to their own situation.

Transportation System Management

Assessing the impacts of TSM strategies generally requires some sort of emissions modeling to account for local traffic conditions. The emissions impacts of most TSM strategies can in theory be modeled in some detail, if sufficient resources are available for developing the required traffic simulation models emissions model interfaces. The release of EPA's MOVES model in 2010 has made it possible to model the emissions impacts of TSM strategies with more precision than could previously be done. However, most local agencies that are evaluating TSM strategies are not in a position to do detailed simulation modeling and must use simplified methods such as average speed-based factors in conjunction with assumptions about average speed changes. Additional research activities that will advance capabilities in this area include:

- Incorporate new MOVES emission rates into standardized cost-effectiveness calculations for various strategies and decision-making guides for choosing between these strategies. These will make the most difference for PM and CO_2, where emission rates by speed were not previously available.
- Conduct research on the impact of various TSM strategies on operating mode profiles and the resulting impact on emissions. Use both real-world second-by-second global positioning system (GPS) data and traffic simulation model results. Create generalized vehicle-specific power (VSP) profiles for various traffic and strategy conditions.
- Evaluate the adequacy of the vehicle tests conducted in Kansas City study to produce PM emission rates for MOVES and collect more vehicle testing data if needed.

- Conduct research on the impact of induced demand on the effectiveness of TSM strategies, considering strategies that affect travel-time reliability (e.g., incident management) as well as those that affect average or typical levels of congestion and delay. Some simple experiments could be performed using a range of assumptions on traveler response to travel-time improvements (e.g., using elasticities from the literature) to evaluate how emissions tradeoffs vary for different assumptions regarding induced demand impacts, as well as under different types of traffic conditions.

Vehicle and Fuel Technology

The quality of information on vehicle and fuel technology improvements varies, with some technologies well-documented and others with considerable uncertainty remaining. Cost-effectiveness will also change over time as baseline vehicle emission control technology improves. Areas for further research include:

- Additional VOC speciation is needed to better assess toxic emission impacts, especially for alternative fuels. Once technology and fuel-specific speciation profiles are developed, these factors could be applied to existing modeling tools.
- Additional research and development is needed to more accurately determine emission impacts for NO_x diesel retrofits, as well as for multiple technology and/or fuel combinations (e.g., alternative fuels, retrofits, inspection and maintenance programs).
- More in-use data is needed on the distribution of engine operating profiles at the fleet and subfleet levels for retrofit effectiveness assessments. The use of on-board diagnostics (OBD) data for late model heavy vehicles should be evaluated for this purpose.
- Data is needed regarding the frequency of malmaintenance for retrofit effectiveness assessments.
- Continued evaluation of OBD effectiveness is needed to correlate with actual emission measurements.
- Continued research regarding heavy-duty diesel inspection and maintenance (I/M) methods and effectiveness is needed.
- Improved life-cycle modeling of alternative fuels is required to reduce uncertainties, especially for criteria pollutant emissions.
- Further biodiesel testing is needed for improved NO_x determination, especially for late-model diesel technologies.
- Although the uncertainty associated with fuel prices cannot be eliminated, improved sensitivity analyses and scenario modeling can be developed for vehicle operators to explicitly demonstrate the relationship between payback periods/cost-effectiveness and key variables (e.g., idle hours per year, miles per year, infrastructure and equipment costs).

1.0 Introduction

The objective of this research project is to provide transportation officials with information on the effects of different transportation air quality control strategies on a full range of pollutants, and to identify methods for evaluating tradeoffs among different pollutants when selecting control strategies. The research is intended to identify:

- Which types of control strategies will have beneficial effects on reducing all pollutants, including ozone precursors, particulate matter (PM), air toxics, and greenhouse gases (GHG); as well as which ones may reduce some pollutants while increasing others, and the specific tradeoffs involved;
- Factors and uncertainties that may affect these interactions and tradeoffs, such as specific local air pollution problems, and the future evolution of vehicle emissions control technologies and fuels;
- How transportation and air quality agencies have evaluated cost-effectiveness, considering multiple pollutants, and made tradeoffs among these pollutants when prioritizing control strategies; and
- Additional, more in-depth research that may be needed to assist agencies in selecting the most cost-effective control strategies, considering their potential impact on multiple key pollutants.

The research was conducted in three tasks:

- **Task 1** reviewed and summarized the literature on the cost-effectiveness of different transportation emissions control strategies for the variety of pollutants being considered, and reviewed methods for weighting cost-effectiveness for multiple pollutants.
- **Task 2** identified information gaps on the state of knowledge of cost-effectiveness as well as multipollutant tradeoffs.
- **Task 3** was a survey of practitioners to identify whether and how they make tradeoffs among multiple pollutants in the project selection and prioritization process.

The research findings are presented in the following sections of this report:

- **Section 2.0** identifies three major categories of strategies – demand management, systems management, and vehicle and fuel technology – as well as 34 distinct strategies within these categories;
- **Section 3.0** presents ranges of cost-effectiveness (measured in dollars per ton of pollutant reduced) as well as information on effectiveness (total amount of pollution reduced by a typical project) for demand management and systems

management strategies, and draws conclusions about the relative cost-effectiveness of different types of projects;

- **Section 4.0** presents similar information for vehicle and fuel technology strategies;
- **Section 5.0** discusses different methodologies that have been applied in the literature to weight multiple pollutants in project evaluation and decision-making;
- **Section 6.0** summarizes the findings from the survey of practitioners; and
- **Section 7.0** identifies information gaps and research needs.

The report also contains the following appendices:

- **Appendix A** provides an inventory of literature sources reviewed;
- **Appendix B** presents more detailed figures illustrating ranges of cost-effectiveness for the various strategies discussed in Sections 3.0 and 4.0;
- **Appendices C through G** present the detailed methodology and findings from the practitioner surveys; and
- **Appendix H** presents tables summarizing the effects of each emission reduction strategy on the various pollutants of interest.

2.0 Strategies Considered

The following is a list of transportation emission reduction strategies considered in this project. The focus is on air quality control strategies that can be implemented at a local, regional, or state level.

2.1 TRANSPORTATION DEMAND MANAGEMENT STRATEGIES

Transportation demand management (TDM) strategies can be defined as those that seek to reduce vehicle-travel, and particularly travel by single-occupancy vehicles. Demand management strategies are classified into those that *primarily* reduce VMT (by reducing vehicle-trips, reducing trip lengths, or encouraging travelers to shift modes), and those that include *additional transportation services* (e.g., transit, rail freight) in order to encourage shifting travel to more efficient modes. VMT-reduction strategies should reduce all pollutants roughly in proportion to their VMT reduction effect, although there may be other modest effects from improved traffic flow, if congestion also is reduced. In contrast, strategies that add other transportation services require consideration of emissions from these services, which may offset (to varying degrees) the emissions reductions resulting from passenger vehicle or truck VMT reduction. The amount of the offset will depend upon the relative efficiencies, load factors, and emissions characteristics of the vehicles involved.

VMT Reduction

1. Employer-Based TDM Programs
2. Other TDM Programs (school, community/residential, etc.)
3. Areawide Ridesharing Programs
4. Telework and Alternative Work Schedules
5. Bicycle/Pedestrian Projects and Programs
6. Land Use Strategies
7. General Road/Travel Pricing (VMT fee, fuel tax)
8. Parking Pricing/Management
9. Transit Pricing – Fare Discounts/Incentives
10. Park-and-Ride Facilities
11. Transit Marketing, Information, and Amenities

VMT Reduction and New Transportation Service

1. New/Expanded/Increased Transit Service
2. Vanpool Programs
3. Freight Rail/Intermodal Improvements

2.2 TRANSPORTATION SYSTEM MANAGEMENT STRATEGIES

Transportation system management (TSM) strategies seek to improve traffic flow and reduce inefficient vehicle operations. *Congestion relief* strategies can reduce pollutants by reducing idling and hard acceleration and increasing speeds into more efficient operating ranges. Depending upon the specific operating effects, however, some emissions may increase. For example, NO_x emissions tend to increase above 35 to 40 mph, and fuel consumption and CO_2 emissions also increase at higher speeds. *Other systems management* strategies include speed limit reductions to reduce vehicle speeds into more efficient ranges, and idle reduction programs to reduce unnecessary idling, especially by heavy-duty vehicles (e.g., at truck stops).

Congestion Relief

1. Managed Lanes – High-Occupancy Vehicle (HOV), High-Occupancy/Toll (HOT), Truck-Only
2. Congestion Pricing
3. Signal Timing and Coordination
4. Intersection Improvements
5. Incident Management
6. Ramp Metering
7. Traveler Information

Other Systems Management

1. Speed Limit Enforcement/Reduction
2. Vehicle Idling Restrictions/Programs

2.3 VEHICLE AND FUEL TECHNOLOGY STRATEGIES

Vehicle and fuel technology strategies include the use of less polluting vehicle technology (e.g., more energy-efficient vehicles, pollution controls), and/or alternative fuels that reduce emissions. Vehicle and fuel technology strategies are identified based on whether they are evaluated for light-duty (LD) vehicles, heavy-duty (HD) vehicles, or both. For heavy-duty vehicle strategies, impacts are distinguished within different classes of vehicles (e.g., buses versus trucks, medium versus large trucks) to the extent that significant differences exist for applicable markets.

Vehicle Technologies

1. Diesel Engine Retrofits (HD)
2. Diesel Vehicle Retrofits (Aerodynamics, Rolling Resistance) (HD)
3. Accelerated Retirement (LD and HD)
4. Hybrid Vehicles (LD and HD)
5. Idle Reduction Technologies (HD)
6. Inspection/Maintenance Programs (LD)
7. National Fuel Economy and Emission Standards (LD)

Low-Carbon Fuels

1. Biodiesel (B20)[4] (HD)
2. Compressed/Liquefied Natural Gas (HD)
3. Liquid Propane Gas (HD)
4. Ethanol (E85)[5] (LD)

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[4] B20 is a blend of 20 percent biodiesel and 80 percent petroleum-based diesel.

[5] E85 is a blend of 85 percent ethanol and 15 percent gasoline.

3.0 Transportation Demand and Systems Management

Transportation demand and systems management strategies are considered in the same section of this report. Most of the literature evaluating the cost-effectiveness of strategies includes both types of projects. Combining the discussions, therefore, eliminates the need to have duplicate discussions of the same data source. It also allows for easy comparison of relative cost-effectiveness among the various TDM and TSM strategies reviewed.

3.1 OVERVIEW OF SOURCES REVIEWED

A variety of sources were reviewed, including both comprehensive reports that cover multiple strategies and pollutants and research papers that cover individual strategies or groups of strategies. The review focused on identifying sources that provide information on 1) cost-effectiveness for any of the various pollutants of interest in this project, and/or 2) tradeoffs among the different pollutants for a particular strategy. A few points about the existing literature are noteworthy:

- Most of the relevant literature included here is in the form of cross-cutting studies that evaluate multiple strategies, since the primary interest in evaluating cost-effectiveness has been for the purpose of comparing different types of projects. Other literature has looked at the effectiveness of individual strategies, but not examined cost-effectiveness and, therefore, is not included.
- Most of the focus has been on air pollutants, particularly criteria pollutants and precursors. GHG has only become of widespread interest within the past few years and is covered by a handful of recent synthesis studies. None of the studies reviewed evaluated cost-effectiveness with respect to air toxics, most likely since they have not been regulated. However, since many toxic air pollutants are emitted in the form of volatile organic compounds (VOC), it is expected that they will follow the patterns of VOC cost-effectiveness.
- Most of the research on air pollutant cost-effectiveness is a number of years old, and much of it dates from the 1990s. This points to the need for caution in using the results. In particular, emission factors have declined significantly over time and, therefore, older studies are likely to *overstate* the cost-effectiveness of any particular strategy compared to the application of such a strategy today. Emission factors also vary locally, meaning that the same strategy with the same costs might show different cost-effectiveness results depending upon the location and year for which it is evaluated. Both

costs and effectiveness also may change significantly over time for vehicle and fuel technology strategies, as technology evolves and as the vehicle fleet (to which strategies such as retrofits or replacement are applied) changes.

- Somewhat counteracting the effect of improving technology (declining emission rates) is the fact that we have not made adjustments for inflation, meaning that absolute values from older studies would slightly understate cost-effectiveness, compared to values stated in today's dollars.
- Treatment of costs and cost-estimation methods can be inconsistent across studies. For example, assumed lifetimes of projects vary, as does the inclusion of full life-cycle annual operating costs. Costs in this review generally include only public-sector implementation costs and, therefore, do not consider other important costs and benefits (monetary or nonmonetary) that may accrue to businesses and travelers.

Relevant sources are summarized in Table A.1 (Appendix a) and described below in reverse chronological order. Table A.1 shows which types of strategies and pollutants are evaluated. It also includes an assessment of the study team's "confidence" in the reliability of the study results. Studies are rated "high" confidence if they are based on *observed* data as much as possible and standardize key calculation methods and assumptions across projects, or if they utilize relatively sophisticated modeling techniques. Studies that utilize sketch-plan modeling techniques or assumptions not directly based on observed data are rated "medium" or "low" confidence. For the most part, this literature review does not include pre-project cost-effectiveness estimates that are based on back-of-the-envelope assumptions, such as are developed for many CMAQ projects for reporting and project selection purposes. The reliability of these estimates is deemed too low to provide substantially useful information on cost-effectiveness for different pollutants.

- U.S. DOT (2010). *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions.* April 2010.
  - This report synthesizes the literature on GHG reductions and cost-effectiveness of about 50 transportation strategies, including vehicle and fuel technology, system efficiency, and travel activity measures. Information on cobenefits, including quantitative information on other pollutant changes where available, also is presented.
- PB Americas, et al. (2009). *Cost-Effectiveness of Transportation Strategies with Respect to Greenhouse Gas Reduction Potential*. Strategic Highway Research Program (SHRP) Project C09, Task 5 Report, unpublished draft, November 2009.
  - This report reviews the literature on the cost-effectiveness and effectiveness (expressed in percent of transportation sector emissions) of a variety of transportation GHG reduction strategies, including VMT reduction, system operations, and vehicle and fuel technologies. The

  information in the report is primarily a synthesis of information from U.S. DOT (2010) and Cambridge Systematics (2009).

- Cambridge Systematics, Inc. (2009). *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions.* Washington, D.C.: Urban Land Institute.
  - This report provides a national-level estimate of the effectiveness (measured in total and percentage GHG reductions from surface transportation) and costs of 49 demand management and operations strategies. Cost-effectiveness is not directly calculated.
- ICF International (2008). *SAFETEA-LU 1808: CMAQ Evaluation and Assessment: Phase I Final Report*, prepared for Federal Highway Administration, FHWA-HEP-08-019.
  - This report evaluates all strategies eligible for funding under the Congestion Mitigation and Air Quality (CMAQ) Program and provides results for HC, CO, NO_x, $PM_{2.5}$, and $PM_{10.}$ The report also includes a section on cost-effectiveness, which includes data on 68 projects from the CMAQ database. Pollutants were analyzed individually in this report without a weighting scheme.
- Ayres, G. (2007). *Bus Emissions versus Passenger Car Emissions*. Volpe National Transportation Systems Center, Memorandum to Roy Chen, Federal Transit Administration, June 26, 2007.
  - This memorandum compares emissions of criteria pollutants for diesel buses with average passenger loads, including both an average bus (as of 2006) and a new (model year 2007) diesel bus, compared with the equivalent emissions from 8.72 displaced passenger cars. While an average bus will increase NO_x and PM emissions compared to an average passenger car (using 2002 emission factors), a new bus meeting EPA regulations for model years 2007-2009 will result in decreases of all pollutants.
- Harrington, W., S. Houde and E. Safirova (2007). *A Simulation of the Effects of Transportation Demand Management Policies on Motor Vehicle Emissions.* ASCE Transportation Land Use Planning, and Air Quality Conference. Orlando, Florida, July 2007.
  - This paper presents percent emissions reductions for VOC, CO, and NO_x from various pricing strategies (cordon toll, freeway toll, comprehensive toll, gas tax) using results from an integrated regional travel demand and land use model applied to the Washington, D.C. region. The study, therefore, evaluates the effects of changes in traffic operational conditions (speeds) across the network as well as VMT reduction. Overall, for any given pricing strategy the study finds relatively consistent effects (percentage reductions) across all three pollutants that are close to the percentage VMT reduction for the strategy. Cordon tolls and freeway

tolls tended to show slightly higher percentage benefits for VOC than for CO and NO_x.

- ICF International (2006). *Multipollutant Emissions Benefits of Transportation Strategies.* Prepared for Federal Highway Administration, FHWA-HEP-07-004.
  - This report evaluates a wide variety of transportation strategies and provides results for HC, CO, NO_x, $PM_{2.5}$, PM_{10}, SO_x, and NH_3. The report does not include cost-effectiveness information, but provides information on emissions increases and decreases by pollutant for each strategy and discusses the tradeoffs involved between pollutants.
- Dowling, Richard, et al. (2005). *Predicting Air Quality Effects of Traffic-Flow Improvements.* NCHRP Report 535.
  - This study created a methodology to model the impacts of traffic-flow improvements on vehicle emissions by considering household trip making, destination choice, time-of-day choice, mode choice, and route choice. The methodology was applied to a number of case studies, which evaluated impacts on total hydrocarbon (THC), CO, and NO_x emissions. No cost-effectiveness information was included in the study.
- Hampton Roads Planning District Commission (2003). *Hampton Roads Congestion Mitigation and Air Quality Improvement Program: Post Evaluation Study.*
  - HRPDC[6] prepared a study to determine the efficiency or cost-effectiveness of CMAQ projects in reducing emissions for VOC and NO_x. This study assessed benefits of a sample of CMAQ projects. The study ranks projects by cost-effectiveness separately for VOC and NO_x.
- Transportation Research Board (2002). *The Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience.* TRB Special Report 264, National Academy Press, Washington, D.C.
  - This report evaluates all strategies eligible for funding under the Congestion Mitigation and Air Quality (CMAQ) Program and provides results for HC, CO, NO_x, and PM_{10}. The report also includes a full section on cost-effectiveness, which includes data on 141 projects collected by literature review. In addition, the report discusses weighting issues and utilizes one main weighting approach and two alternatives.

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[6] Following a reorganization in 2009, the Hampton Roads Transportation Planning Organization (HRTPO) was created as the official MPO for the region (www.hrtpo.org). The organizations are related as the HRPDC provides staff for the HRTPO.

- Johnston, R.; C. Rodier, M. Choy, and J. Abraham (2000). *Air Quality Impacts of Regional Land Use Policies.* Prepared for the U.S. EPA.
  - This study uses two different model systems, including the regional travel-demand model and an integrated transportation-land use model, to assess the emissions impacts of alternative land use, transportation network (HOV lanes, HOT lanes, and light-rail transit), and pricing scenarios in the Sacramento region. Reactive organic gases (ROG), CO, NO_x, and PM_{10} are evaluated. In general, emissions changes roughly track VMT changes, although the magnitude of impact varies somewhat by pollutant and modeling system used, probably reflecting differences in speeds on the transportation networks.
- Hagler Bailly, Inc. (1999). *Costs and Emissions Impacts of CMAQ Project Types.* Prepared for U.S. EPA Office of Policy. http://www.fhwa.dot.gov/environment/cmaq_pt1.htm.
  - This study evaluates, for each of a set of 24 individual CMAQ projects, the total annual costs, estimated annual emissions reductions, and actual project lifetimes. Emission reductions represent estimates obtained from project sponsors, so methodologies and quality may vary. Cost-effectiveness is not calculated although it could be. The study notes inconsistencies in cost methodologies, particularly assumed lifetime of the project, whether ongoing operating costs are included, and inclusion of local match costs, that can reduce the comparability of estimates across projects.
- Pansing, C., and M. Sillings (1998). *Comparative Evaluation of the Cost-Effectiveness of 58 Transportation Control Measures.* Transportation Research Record No. 1641, and presentation at the Transportation Research Board Annual Meeting, January 1998.
  - The authors review the cost-effectiveness of 58 transportation control measure projects of seven different types, standardizing emissions factors, cost assumptions, and cost-effectiveness measures across projects.
- Rowell, M.; F. Buonincontri, and J. Semmens (1997). *The Cost-Effectiveness and Magnitude of Potential Impact of Various Congestion Management Measures.* Prepared for Arizona DOT, Report No. FHWA-AZ97-453.
  - This report includes estimates of effectiveness and cost-effectiveness for a variety of travel and emission reduction measures implemented or proposed for the Phoenix and Tucson metropolitan areas.
- Federal Highway Administration (1995). *Transportation Control Measure Analysis: Transportation Control Measures Analyzed for the Washington Region's 15 Percent Rate of Progress Plan.* Metropolitan Planning Technical Report No. 5.
  - This report develops effectiveness and cost estimates for 48 transportation control measures (TCM) considered for the Washington, D.C. region.

While impacts are projected, rather than observed, a variety of analytical methods, including mode choice models were used to estimate project effectiveness. Cost-effectiveness also is calculated, although the information is not presented in a way that can be readily compared across projects.

- Stewart, J. (1994). *Evaluating the Cost-Effectiveness of Employer-Based Trip Reduction Programs: Reviewed and Reexamined*. Transportation Research Record No. 1433.
  - This study reviews three major studies that have attempted to determine the cost-effectiveness of employer-based trip reduction programs using such measures as cost per employee and cost per one-way trip reduced. The study finds that each study uses slightly different methodologies and assumptions and, as a consequence, arrives at different, noncomparable results. A key focus of the study is on the evaluation of full costs of trip reduction programs, including costs to employers, which are often difficult to estimate.

3.2 DETAILED REVIEW OF KEY SOURCES

Following is a more detailed discussion of the findings of selected studies discussed above. In addition, the project team conducted original analysis of the projects listed in the 2002 and 2008 CMAQ program evaluation reports, which together represent the most comprehensive and consistent source of data on cost-effectiveness for demand management projects.

Federal CMAQ Program Evaluation Reports

Relative Effectiveness

The 2002 TRB report on the CMAQ Program reported daily emissions reductions for a variety of strategies. Table 3.1 presents the emissions reductions by strategy as ratios compared to the average reduction for all TDM and TSM strategies. These results show that employer-based TDM programs provide the highest emissions reductions (about six times the average), with parking pricing/ management, transit pricing, incident management, managed lanes, and road pricing also providing greater-than-average reductions per project. In contrast, new transit service, telework, ridesharing, vanpooling, park-and-ride, and other TDM projects tend to provide relatively low absolute emission reductions.

Table 3.1 Emissions Reductions Number of Times Above or Below Average

Strategy	HC	CO	NO_x	PM_{10}
Employer-Based TDM Programs	6.20	6.36	5.84	5.64
Parking Pricing/Management	2.73	0.00	2.85	2.85
Transit Pricing – Fare Discounts/Incentives	2.49	0.31	2.59	2.95
Incident Management	1.71	1.43	1.24	0.00
Managed Lanes (HOV/HOT/Truck)	1.24	0.00	1.63	1.73
General Road/Travel Pricing	1.18	0.00	1.34	1.33
TDM Average	**1.00**	**1.00**	**1.00**	**1.00**
Congestion Pricing	0.91	0.00	0.98	0.27
Signal Timing and Coordination	0.30	0.36	0.29	0.00
New/Expanded/Increased Transit Service	0.30	0.13	0.33	0.49
Telework and Alternative Work Schedules	0.28	1.15	0.25	0.00
Areawide Ridesharing Programs	0.16	0.28	0.14	0.10
Bicycle/Pedestrian Projects and Programs	0.11	0.48	0.08	0.02
Other TDM Programs	0.11	0.05	0.10	0.02
Park-and-Ride Facilities	0.09	0.17	0.13	0.11
Vanpool Programs	0.05	0.00	0.08	0.02

Source: Cambridge Systematics, Inc. analysis of TRB Special Report 264, *The CMAQ Program: Assessing 10 Years of Experience* (2002).

Cost-Effectiveness

Both the 2002 TRB CMAQ report and the 2008 FHWA CMAQ report examined of the effectiveness of a large number of TDM projects of various types. The 2002 report took projects which were deemed to have relatively reliable post-project evaluation data and applied standardized emission factors to compare these projects on a cost-effectiveness basis. The 2008 report also gathered project evaluation data from individual projects and evaluated cost-effectiveness as well. Costs in both studies included public agency capital and operating costs.

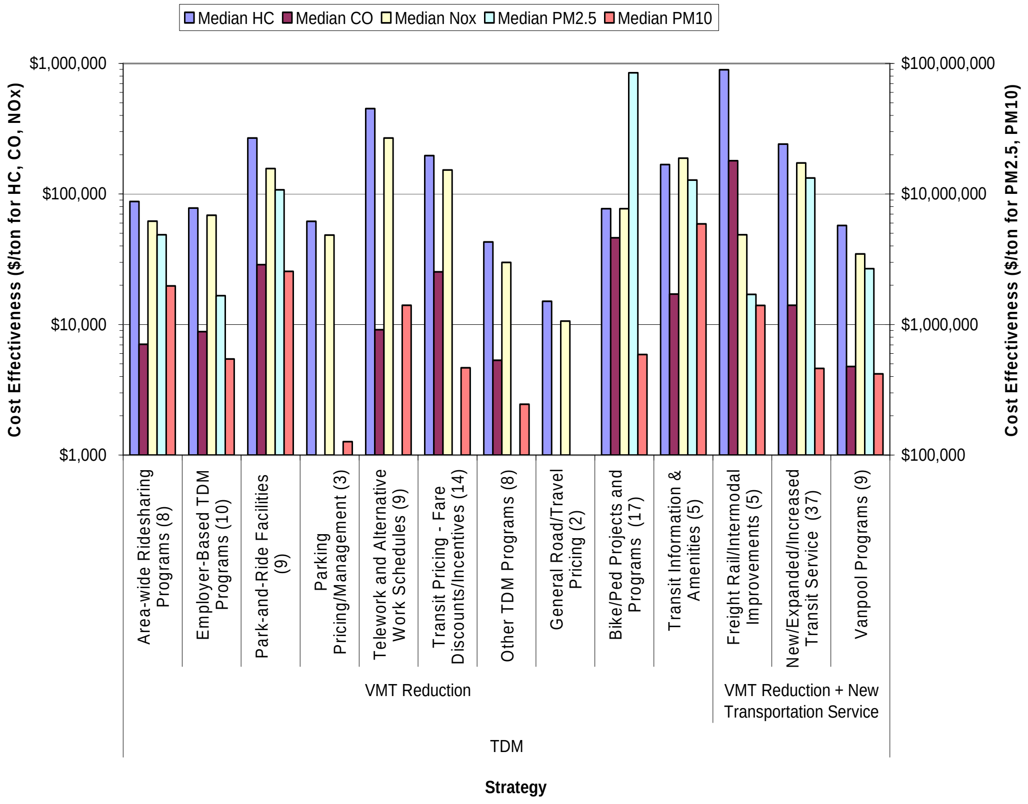
The two reports were used by the project team to build a database of 209 projects with cost-effectiveness data for HC, CO, NO_x, $PM_{2.5}$, and PM_{10}. Seven out of these 209 projects were eliminated as outliers due to these projects plotting at significantly higher values than all of the other projects. It should be noted that the two data sources used to construct this database have costs based on different years and no adjustments were made to account for inflation. This database was used to create Figures 3.1 and 3.2, which present the median cost-effectiveness by strategy for each of the five pollutants. ($PM_{2.5}$ and PM_{10} are plotted on a secondary axis due to the much higher values of results; note that for all pollutants the Y-axis is logarithmic). In addition, Figures B.1 to B.5 in

Appendix B show ranges of cost-effectiveness (minimum, median, maximum) by project type.

The number of strategies included by project type is shown in parentheses on the X-axis of Figures 3.1 and 3.2. However, it should be noted that some projects were not evaluated for all pollutants. For example, few projects had evaluation data for $PM_{2.5}$. Therefore, there may be some outlier values that reflect only a small number of projects, rather than particularly good or poor cost-effectiveness of that project type. Figures B.1 through B.5 identify the number of projects evaluated for each type of pollutant.

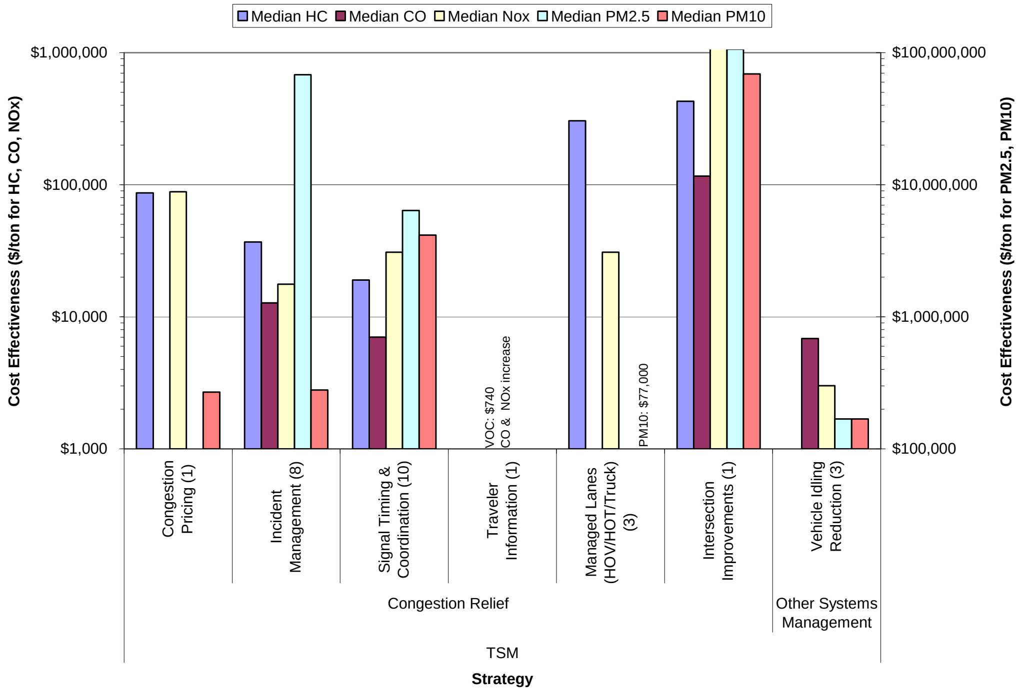
The ability to examine cost-effectiveness for TSM strategies from the CMAQ database is limited by the small number of projects included for some strategies. In particular, congestion pricing, traveler information, and intersection geometric improvements only had one project each. Given the variability of results, cost-effectiveness findings based on only one or two projects may not be representative of that type of project in general.

Figure 3.1 Median Cost-Effectiveness of TDM Strategies



Source: Cambridge Systematics, Inc. analysis of data from TRB (2002) and ICF (2008).

Figure 3.2 Median Cost-Effectiveness of TSM Strategies



Source: Cambridge Systematics, Inc. analysis of data from TRB (2002) and ICF (2008).

Figures B.1 to B.5 show that some strategies for some pollutants have a narrow range of cost-effectiveness, while others have a medium or wide range. This may reflect from two different phenomena: 1) considerable uncertainty or variability in the cost-effectiveness of a strategy (indicated by a wide range of results); and/or 2) the number of projects evaluated (fewer projects means the range of results is likely to be narrower). In general, there is less data on PM and CO than for VOC and NO_x which historically have tended to be of interest in more areas (i.e., those with ozone problems). $PM_{2.5}$ has only become of interest relatively recently with the issuance of EPA nonattainment designations in 2005.

A challenge in comparing cost-effectiveness across pollutants is that cost-effectiveness values will scale differently depending on the relative mass of pollutants emitted. For example, CO emissions are typically an order of magnitude larger than VOC or NO_x emissions, which in turn are perhaps an order of magnitude greater than PM_{10} emissions. One way to address this is by comparing relative cost-effectiveness, e.g., compared to the median for a particular pollutant. Table 3.2 lists TDM strategies by whether they fall above or below the median cost-effectiveness for each pollutant, while Table 3.3 does the same for TSM strategies. Within the table, the strategies are listed in descending order of cost-effectiveness (absolute value). The rankings are compared with median values across *all* types of projects included in the CMAQ database, including TDM, TSM, and alternative fuel projects.

While they are discussed in greater detail in Section 4.0, vehicle and fuel technology strategies also were evaluated in the CMAQ studies and included in the database of projects we analyzed. Table 3.4 shows how these project types compare to the overall median for each pollutant. This table is included here for ease of comparison with TDM and TSM project types from the same database.

When ranked in relative terms, VMT reduction-only strategies should, in general, perform consistently across all pollutants; any outliers would most likely be due to anomalies in the data. In contrast, VMT reduction/new service strategies may be expected to perform differently for some pollutants than others. For example, heavy-duty vehicles (transit, trucks, rail) tend to have relatively higher emission factors for NO_x and PM than for HC and CO. These strategies would be more likely to show strong cost-effectiveness for NO_x and PM if emissions are reduced. On the other hand, they also may be more likely to show net increases in emissions (e.g., if transit vehicle occupancy is too low and net NO_x emissions therefore increase compared to equivalent cars).

Based on the CMAQ study findings, none of the TDM strategies evaluated, including new service strategies, showed a median increase in emissions. Only new/expanded transit service showed a range of results that included an increase, but that was only for one project for PM_{10}. For TSM strategies, one traveler information, one HOV lane, and one incident management project also showed an increase in NO_x emissions.

The results for VOC and NO_x are probably the most reliable, since nearly all projects were evaluated for these pollutants. Some general observations by project type, considering the VOC and NO_x findings most heavily, include:

- Employer-based TDM, regional rideshare, and vanpooling projects tended to perform relatively well, below the median on most pollutants;
- Bicycle/pedestrian projects showed mixed/moderate results;
- Telework, transit (including new service, price incentives, information, and amenities), and park-and-ride projects tended to perform relatively poorly, above the median on most pollutants evaluated;
- Freight rail/intermodal projects tended to perform relatively poorly for VOC and CO, but relatively well for NO_x and PM;
- Signal timing, vehicle idle reduction, and incident management were TSM project types that were among the best-performing of all projects; and
- For vehicle and fuel technology projects, alternative fuels, inspection and maintenance, and diesel retrofit projects generally performed well.

For comparison, the 2002 CMAQ evaluation report cites a cost-effectiveness threshold of roughly $10,000 per ton (presumably for ozone precursors) as used in many regulatory studies as a cutoff for selecting non-CMAQ measures such as stationary source controls (p. 129). While most CMAQ projects fall above this threshold, it should be noted that most TDM and TSM projects have significant other benefits (particularly mobility). In contrast, non-transportation strategies, as well as transportation vehicle and fuel technology strategies, are usually intended largely if not solely for the purposes of emissions control.

Table 3.2 Relative Ranking of TDM Strategies by Pollutant Based on Median Cost-Effectiveness

Dollars per Ton

Range	HC	CO	NO_x	$PM_{2.5}$	PM_{10}
Above Median					Transit Information and Amenities ($5,911,468)
	Freight Rail/Intermodal Improvements ($893,459)				Park-and-Ride Facilities ($2,554,342)
	Telework and Alternative Work Schedules ($452,704)	Freight Rail/Intermodal Improvements ($180,259)	Telework and Alternative Work Schedules ($268,961)		Areawide Ridesharing Programs ($1,976,153)
	Park-and-Ride Facilities ($268,460)	Bicycle/Pedestrian Projects and Programs ($46,278)	Transit Information and Amenities ($188,430)	Bicycle/Pedestrian Projects and Programs ($84,823,991)	Telework and Alternative Work Schedules ($1,403,555)
	New/Expanded/Increased Transit Service ($241,528)	Park-and-Ride Facilities ($28,791)	New/Expanded/Increased Transit Service ($172,977)	New/Expanded/Increased Transit Service ($13,287,023)	Freight Rail/Intermodal Improvements ($1,402,472)
	Transit Pricing – Fare Discounts/ Incentives ($196,551)	Transit Pricing – Fare Discounts/ Incentives ($25,345)	Park-and-Ride Facilities ($156,997)	Transit Information and Amenities ($12,797,808)	Bicycle/Pedestrian Projects and Programs ($589,800)
	Transit Information and Amenities ($168,276)	Transit Information and Amenities ($17,081)	Transit Pricing – Fare Discounts/ Incentives ($152,617)	Park-and-Ride Facilities ($10,800,387)	Employer-Based TDM Programs ($545,213)
Median – All Strategies	**$145,450**	**$16,511**	**$88,426**	**$4,910,989**	**$526,528**
Below Median	Areawide Ridesharing Programs ($87,626)	New/Expanded/Increased Transit Service ($14,076)	Bicycle/Pedestrian Projects and Programs ($77,096)	Areawide Ridesharing Programs ($4,867,780)	Transit Pricing – Fare Discounts/ Incentives ($465,795)
	Employer-Based TDM Programs ($78,078)	Telework and Alternative Work Schedules ($9,128)	Employer-Based TDM Programs ($68,801)	Vanpool Programs ($2,685,195)	New/Expanded/Increased Transit Service ($460,792)
	Bicycle/Pedestrian Projects and Programs ($77,096)	Employer-Based TDM Programs ($8,826)	Areawide Ridesharing Programs ($62,065)	Freight Rail/Intermodal Improvements ($1,707,043)	Vanpool Programs ($419,202)
	Parking Pricing/Management ($61,713)	Areawide Ridesharing Programs ($7,074)	Freight Rail/Intermodal Improvements ($48,784)	Employer-Based TDM Programs ($1,668,784)	Other TDM Programs ($245,442)
	Vanpool Programs ($57,315)	Other TDM Programs ($5,341)	Parking Pricing/Management ($48,604)		Parking Pricing/Management ($126,802)
	Other TDM Programs ($42,876)	Vanpool Programs ($4,773)	Vanpool Programs ($34,735)		General Road/Travel Pricing ($26,629)[a]
	General Road/Travel Pricing ($15,060)[a]		Other TDM Programs ($29,941)		
			General Road/Travel Pricing ($10,623)[a]		

Source: Cambridge Systematics, Inc. analysis of data from TRB (2002) and ICF (2008).

[a] Results based on only one or two projects and may not be representative of this type of project in general.

Table 3.3 Relative Ranking of TSM Strategies by Pollutant Based on Median Cost-Effectiveness

Dollars per Ton

Range	HC	CO	NO_x	$PM_{2.5}$	PM_{10}
Above Median				Intersection Improvements ($106,166,167)[a]	
	Intersection Improvements ($428,247)[a]	Traveler Information (increase)[a]	Traveler Information (increase)[a]	Incident Management ($68,168,367)	Intersection Improvements ($68,974,198)[a]
	Managed Lanes (HOV/HOT/ Truck) ($305,180)	Intersection Improvements ($116,390)[a]	Intersection Improvements ($1,264,080)[a]	Signal Timing and Coordination ($6,394,106)	Signal Timing and Coordination ($4,154,132)
Median – All Strategies	**$145,450**	**$16,511**	**$88,426**	**$4,910,989**	**$526,528**
Below Median	Congestion Pricing ($86,838)	Incident Management ($12,752)	Incident Management ($17,708)	Vehicle Idling Reduction ($168,232)	Incident Management ($279,456)
	Incident Management ($36,907)	Signal Timing and Coordination ($7,010)	Signal Timing and Coordination ($30,850)		Congestion Pricing ($268,554)
	Signal Timing and Coordination ($18,985)	Vehicle Idling Reduction ($6,833)	Incident Management ($17,708)		Vehicle Idling Reduction ($168,232)
	Traveler Information ($737)[a]		Vehicle Idling Reduction ($3,007)		Managed Lanes (HOV/HOT/Truck) ($77,001)

Source: Cambridge Systematics, Inc. analysis of data from TRB (2002) and ICF (2008).

[a] Results based on only one or two projects and may not be representative of this type of project in general.

Table 3.4 Relative Ranking of Vehicle and Fuel Technology Strategies by Pollutant Based on Median Cost-Effectiveness

Dollars per Ton

	HC	CO	NO_x	$PM_{2.5}$	PM_{10}
Above Median	Accelerated Retirement ($753,425)				
	Diesel Engine Retrofits ($225,175)	Accelerated Retirement ($705,551)			
	Alternative Fuels ($206,474)	Alternative Fuels ($124,241)	Alternative Fuels ($96,829)		Accelerated Retirement ($753,425)
Median – All Strategies	**$145,450**	**$16,511**	**$88,426**	**$4,910,989**	**$526,528**
Below Median	Inspection/Maintenance Programs ($5,509)		Accelerated Retirement ($37,671)	Alternative Fuels ($676,227)	Diesel Engine Retrofits ($180,781)
			Diesel Engine Retrofits ($21,063)	Diesel Engine Retrofits ($426,947)	Alternative Fuels ($148,914)
			Inspection/Maintenance Programs ($7,902)		

Source: Cambridge Systematics, Inc. analysis of data from TRB (2002) and ICF (2008).

Dowling, et al. (2005)

This study is useful for examining potential tradeoffs among pollutants for strategies affecting traffic flow. The study applied the Puget Sound regional travel model data set as a basis for case studies of eight hypothetical projects. Bureau of Public Roads (BPR) speed-flow equations were replaced with Highway Capacity Manual (HCM) equations and other parameters added to better capture the impact of traffic flow improvements. The results for each case study on the three pollutants evaluated are shown in Table 3.5.

Table 3.5 Emissions Impacts of Case Study Projects
Percent of Puget Sound Regional Emissions

Case Study	THC	CO	NO_x
Add Freeway Lane – Rural	0.00%	0.00%	0.00%
Close Freeway Lane – Urban	-0.19%	-0.28%	-0.37%
Remove Freeway HOV Lane (two Cases)	-0.02% -0.06%	-0.04% -0.08%	-0.03% -0.08%
Narrow Street	0.00%	0.00%	0.00%
Access Management	-0.04%	-0.03%	-0.02%
Intersection Channelization	0.00%	0.00%	0.00%
Signal Coordination	-0.04%	-0.03%	-0.02%
Transit Improvement (Double Bus Frequency on Route)	0.00%	0.00%	0.00%
Remove Park-and-Ride Lot	0.09%	0.09%	0.08%

Source: Dowling, et al. (2005).

The key observation for the purposes of the current study is that all three emissions move in the same direction and generally show similar percentage changes. This suggests that there are not any significant tradeoffs with these types of projects (i.e., increasing one pollutant while decreasing others).

Hampton Roads Planning District Commission (2002)

The Hampton Roads Planning District Commission (HRPDC) prepared a study to determine the efficiency or cost-effectiveness of CMAQ projects in reducing emissions for VOC and NO_x. This study assessed benefits of a sample of CMAQ projects, using observed data such as actual transit ridership and bikeway usage. The study ranks projects by cost-effectiveness separately for VOC and NO_x. Table 3.6 shows the effectiveness and cost-effectiveness of projects ranked by VOC reduction, while Table 3.7 shows effectiveness and cost-effectiveness ranked by NO_x reduction.

Table 3.6 Hampton Roads Project Effectiveness and Cost-Effectiveness *VOC*

Project Type	Total VOC Reductions (Tons per Year)	Cost-Effectiveness (Dollars per Ton VOC)
Intersection Geometric	6.82	$1,569
Signal Retiming	7.6	$5,461
Signal System Retiming	3.59	$6,966
Intersection Geometric	4.1	$7,142
Signal System Retiming	11	$20,823
Intersection Geometric	9.24	$21,587
Ridesharing and TDM	25	$44,000
Intersection Geometric	0.37	$49,315
Intersection Geometric	1.15	$56,012
Transit (New Service)	2.5	$60,000
Transit (New Service)	1.95	$85,470
ITS-ATMS	8.03	$99,626
Transit (New Service)	3.42	$137,255
Signal System Retiming	0.95	$174,921
Transit (New Service)	1.56	$215,812
Transit (New Service)	1.5	$281,709
Transit (New Service)	2.56	$496,659
Transit (New Service – Ferry)	0.3	$1,248,889
ITS-Roadway Information (two Projects)	No Impact	Not Measurable
Bikeway (3 Projects)	No Impact	Not Measurable
Transit (Park-and-Ride)	No Impact	Not Measurable

Source: Hampton Roads Planning District Commission, 2002.

Table 3.7 Hampton Roads Project Effectiveness and Cost-Effectiveness *NO_X*

Project Type	Total NO_X Reductions (Tons per Year)	Cost-Effectiveness (Dollars per Ton NO_X)
Intersection Geometric	2.73	$3,914
Signal Retiming	3.06	$13,584
Intersection Geometric	1.64	$17,894
Ridesharing and TDM	37.5	$29,333
Transit (New Service)	3.5	$42,857

Project Type	Total NO_x Reductions (Tons per Year)	Cost-Effectiveness (Dollars per Ton NO_x)
Intersection Geometric	3.48	$57,257
ITS-ATMS	12.05	$66,418
Transit (New Service)	1.65	$101,010
Transit (New Service)	3.52	$133,276
Intersection Geometric	0.13	$136,986
Intersection Geometric	0.45	$144,622
Transit (New Service)	1.39	$303,379
Transit (New Service)	3.29	$386,291
Transit (New Service – Ferry)	0.9	$416,296
Transit (New Service)	0.62	$539,530
Signal System Retiming	0.08	$2,165,688
Signal System Retiming	-0.37	($67,815)
Signal System Retiming	-0.47	($486,354)
ITS-Roadway Information (two Projects)	No Impact	Not Measurable
Bikeway (3 Projects)	No Impact	Not Measurable
Transit (Park-and-Ride)	No Impact	Not Measurable

Source: Hampton Roads Planning District Commission, 2002.

Some conclusions that can be drawn from this assessment include:

- Traffic operations improvements, notably signal timing and intersection geometry reconfiguration, tend to perform very well on cost-effectiveness for VOC reduction. However, this is not the case for NO_x reduction, since they may increase speeds to the point where NO_x reduction is minimal or even an increase in emissions is observed.
- Transit projects, which primarily included new shuttles, circulators, and express routes, tend to perform relatively poorly on both VOC and NO_x cost-effectiveness; however, most still result in net reductions in emissions.
- Only one ridesharing/TDM project (a vanpool and park-and-ride program) was evaluated; this project performed moderately compared to other projects.
- Measurable impacts could not be identified for three bikeway and two traveler information projects.

Pansing and Sillings (1998)

Pansing and Sillings (1998) conducted a review of the cost-effectiveness of 58 transportation control measure projects, standardizing emissions factors, cost assumptions, and cost-effectiveness measures across projects. These projects were funded by three different agencies and grouped into seven project categories. Many of these projects are the same as those included in the 2002 CMAQ program evaluation study. Therefore, the Pansing and Sillings review is presented as an alternative interpretation of these findings, rather than a source of additional data on cost-effectiveness.

At the 1998 Transportation Research Board meeting the authors presented their findings in the form of plots of cost-effectiveness (cost per pound of emissions reduced) versus effectiveness (total emissions reductions) on a logarithmic scale. Total costs are defined as the costs (amortized capital and operating, including net farebox revenue) to the project sponsor and funding agencies. Emissions are the gross sum of HC, CO, NO_x, and PM_{10} emissions (and, therefore, would tend to be dominated by CO emissions). Projects falling in the quadrant with low costs (less than $10 per pound, equivalent to about $2,000 per ton) and high emissions reductions (greater than 10,000 pounds per day, or about five tons per day) were characterized as "best," and those in the high-cost/low-reductions quadrant characterized as "worst." The upper limit of costs was in the range of $1,000 per pound (about $2 million per ton). Cost-effectiveness was evaluated for vehicle-trips and VMT as well as emissions. The authors examined the plots for commonalities by type of project. Some of their key findings (as interpreted by the authors of this report) are described below.

- **Bicycle Facilities (6 projects) –** Bicycle projects were among the lowest-cost projects and had moderate total effectiveness.
- **Financial Incentives and Disincentives (4) –** These were consistently the most cost-effective projects as well as having the greatest total effectiveness.
- **Organizational TDM (2) –** These (which included Transportation Management Associations) were noted as "surprisingly" cost-effective.
- **Telecommunications (9) –** These (which included telecenters) were generally not cost-effective at reducing *vehicle-trips*, since many people simply drove shorter distances to a telecenter, but some were cost-effective at reducing VMT because of long trip distances for telecommuters.
- **Vanpools (4) –** These were noted as having variable cost-effectiveness, but with more success than shuttles at reducing VMT.
- **Line-Haul Transit/Shuttles/Ferries (22) –** These were "moderately effective" at reducing trips and VMT, although effectiveness was highly variable, also depending upon time of day and type of trip. Peak-period transit/feeder shuttles and line-haul transit were found to be far more cost-effective than midday shuttles.
- **Alternative Fuel (11) –** Cost-effectiveness was variable, but most projects had high costs and relatively low effectiveness ($100-$1,000 per pound) and were not as cost-effective as demand management strategies. Two "line-haul" alternative fuel transit services had high emission reductions with lower costs.

Overall, the authors concluded that "TDM other than telecommunications is more effective and cost-effective than alternative fuel and fixed-route transit/ shuttle projects"; and of the TDM projects, financial incentives and disincentives were the most consistently effective and cost-effective. Table 3.8 summarizes their findings regarding strategy effectiveness.

Table 3.8 Summary of Key Findings by Category

I – WORST **(Low Effectiveness and Low-Cost Effectiveness)**	**II – TRADEOFF** **(High Effectiveness and Low-Cost Effectiveness**
Alternative Fuels Telebusiness Centers (select) Midday Shuttles	Peak-Period Shuttles (select) Telebusiness Centers (select)
III – TRADEOFF **(Low Effectiveness and High-Cost Effectiveness)**	**IV – BEST** **(High Effectiveness and High-Cost Effectiveness)**
Bicycle Facilities	Financial Incentives and Disincentives Organizational TDM Telecommunications (select) Vanpools Line-Haul Transit/Alternative Fuels

Source: Pansing and Sillings (1998).

Rowell, et al. (1997)

This report for the Arizona DOT includes estimates of effectiveness and cost-effectiveness for a variety of travel and emission reduction measures implemented or proposed for the Phoenix and Tucson metropolitan areas. The estimation methods generally rely on "sketch-level" or back of the envelope calculations of effectiveness (e.g., assumed percent mode shift from ridesharing programs) based on review of the literature. However, it is interesting to compare the general magnitude of results with those found in other studies. These results are shown in Table 3.9, which presents strategies by the four categories used by Pansing and Sillings. In this table, the cost-effectiveness cut-off is $2,000 per ton and the effectiveness cut-off is arbitrarily set at 1,000 tons per year (Phoenix results). Cost estimates ranged over $10,000 per ton for about 40 percent of all project types. While not explicitly stated, the emissions appear to be the sum of HC, CO, NO_x, and PM_{10} emissions, and costs are public agency costs.

Infrastructure, alternative fuel, congestion pricing, and service expansion projects had some of the highest costs, while a number of TDM project types had some of the lowest costs. Signal synchronization and congestion pricing had the greatest overall effectiveness.

Table 3.9 Phoenix Assessment – Summary of Key Findings by Category
Ranked Approximately by Descending Cost
(Worst to Best Cost-Effectiveness)

I – WORST **(Low Effectiveness and Low-Cost Effectiveness)**	**II – TRADEOFF** **(High Effectiveness and Low-Cost Effectiveness)**
Park and Ride	Rail Transit
	Congestion Pricing
	Natural Gas Bus Service
	Bus Service and Expansion
	Parking Management
	HOV Lanes
	Parking and Transportation Allowance
III – TRADEOFF **(Low Effectiveness and High-Cost Effectiveness)**	**IV – BEST** **(High Effectiveness and High-Cost Effectiveness)**
Vanpooling	Telecommuting
Ridematching Programs	Countywide TDM Program
	Signal Synchronization
	Guaranteed Ride Home
	Flextime
	Compressed Work Week

Source: Cambridge Systematics, Inc. analysis of data in Rowell, Buonincontri, and Semmens (1997).

Greenhouse Gas Emission Reduction Measures

The literature on transportation greenhouse gas (GHG) reduction strategy effectiveness and cost-effectiveness is largely distinct from the literature on cost-effectiveness of other air pollutants. Most of the literature on transportation GHG strategies has focused on vehicle and fuel technology strategies. The literature on the cost-effectiveness of VMT reduction and system efficiency strategies is quite limited in its extent and, for the most, part relatively new, published within the past five years.

While some of this literature represents original research and analysis, other literature provides valuable summary and synthesis of other sources, including research and evaluation results for individual strategies. Studies dating as far back as the 1970s have evaluated VMT and congestion reduction strategies for energy and/or air quality purposes. Some of this literature contains information useful to GHG assessment as well, but it generally requires some additional analysis to infer GHG impacts from reported VMT, energy, and/or air pollutant reductions. This type of estimation was done, for example, for the U.S. DOT Report to Congress (2010).

The cost-effectiveness of a variety of GHG reduction measures, including TDM, TSM/operations, and vehicle and fuel technologies, was recently summarized for a Strategic Highway Research Program (SHRP) report prepared for Project C09, Incorporating GHG Into the Collaborative Decision-Making Process. This summary draws from material developed for the U.S. DOT Report to Congress prepared by the current project team, which estimates ranges (low/high) of cost-effectiveness based on a review of existing literature. It also draws from the *Moving Cooler* study (Cambridge Systematics, 2009), as well as other relevant literature. As such, it represents summary judgment on the likely range of cost-effectiveness for each strategy, considering the existing literature.

Table 3.10 shows the ranges of cost-effectiveness (in dollars per metric ton of CO_2-equivalent educed) for the demand-focused emissions control measures reviewed in this study. In the source studies, cost-effectiveness is reported for both *direct* costs (implementation costs only – usually borne by the public agency) and *net* costs (including other costs and cost savings, typically vehicle operating costs). Only direct costs are shown here, since none of the other cost-effectiveness estimates reviewed in this section consider net social costs. Note that some literature sources have cited $50 per metric ton (tonne) as a reasonable threshold for determining whether a project is cost-effective when evaluated in terms of GHG reductions.[7]

Table 3.10 GHG Cost-Effectiveness of TDM Strategies

Strategy	Direct Cost-Effectiveness (Dollars per Tonne)[a]	Comments
VMT Reduction		
Employer-Based TDM Programs	$30-$180	
Other TDM Programs (School, Community/Residential, etc.)	$90	Individualized marketing
Areawide Ridesharing Programs	$80	
Telework and Alternative Work Schedules	$1,200-$2,300	Telework
	$0	Alternative work schedules
Bicycle/Pedestrian Projects and Programs	$80-$210	Comprehensive infrastructure investments
Land Use Strategies	$10	Planning/administrative costs only

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[7] For example, nearly all strategies analyzed in a recent McKinsey report examining GHG strategy impacts and costs across all sectors show abatement costs of less than $50 per ton. See: McKinsey & Company (2009), *Pathways to a Low-Carbon Economy.* The $50 per ton figure is also cited in the NCHRP Project 20-24, Task 59 Report (Burbank, C., and H. Kassoff, 2009: *Strategies for Reducing the Impacts of Surface Transportation on Global Climate Change: A Synthesis of Policy Research and State and Local Mitigation Strategies*).

Strategy	Direct Cost-Effectiveness (Dollars per Tonne)[a]	Comments
General Road/Travel Pricing	$60-$150	VMT fee (2-5 cents per mile)
(VMT Fee, Fuel Tax)	$30-$90	Pay-as-you-drive insurance
Transit Pricing – Fare Discounts/Incentives	$1,300	25-50% fare reductions
VMT Reduction and New Transportation Service		
New/Expanded/Increased Transit Service	$1,200-$3,300	Bus service expansion, frequency increase, urban rail
Vanpool Programs	$80	Included in areawide ridesharing estimate
Freight Rail/Intermodal Improvements	$370-$450	Rail freight
	$730-$1,500	Ports/marine

Source: SHRP Project C09, Task 5 Memorandum.

[a] Greenhouse gas reductions are commonly cited in metric tons (tonnes), and all GHG cost-effectiveness estimates in this report are presented as such.

Table 3.11 shows cost-effectiveness for systems management strategies. Of particular note, the operations strategies (except for managed lanes and congestion pricing) include estimates of induced demand, i.e., the additional GHG emissions produced by traffic growth in response to improved travel conditions, which offset the benefits of congestion reduction. This means that these project types perform relatively more poorly on cost-effectiveness than they would if induced demand effects were not considered. There is considerable uncertainty over the magnitude of induced demand, particularly with respect to traffic operations strategies and, therefore, these findings should be viewed with caution.

Table 3.11 GHG Cost-Effectiveness of TSM Strategies

Strategy	Direct Cost-Effectiveness (Dollars per Tonne)	Comments
Congestion Relief		
Managed Lanes (HOV/HOT/Truck-Only)	$1,200	New HOV lanes
	$700	Truck-only toll lanes
Congestion Pricing	$340-$700	Congestion pricing to maintain LOS D, or CBD cordon pricing
Signal Timing and Coordination[1]	$340-$830	Adaptive control systems
Incident Management[a]	$80-$170	
Ramp Metering[a]	$40-$90	
Traveler Information[a]	$160-$500	

Strategy	Direct Cost-Effectiveness (Dollars per Tonne)	Comments
Other Systems Management		
Speed Limit Enforcement/Reduction	$10	
Vehicle Idling Restrictions/Programs	$20-$50	Truck idle reduction technology

Source: SHRP Project C09, Task 5 Memorandum.

[a] These operations strategies include estimates of induced demand.

An issue that is especially important for GHG emissions, although it may affect emissions of other pollutants as well, is that of life-cycle impacts. Life-cycle impacts include emissions from the construction, maintenance, and operations of transportation facilities, the manufacture and disposal of vehicles, and the production and transport of fuels, in addition to direct fuel combustion in the vehicle. While full fuel-cycle emissions are well-documented (and important mostly for alternative fuel strategies as discussed in the next section), evidence on vehicle and infrastructure emissions is much more limited. The only published estimates are provided by Chester.[8] His results suggest that together fuel, vehicle, and infrastructure-cycle emissions increase emissions by one-half beyond operating emissions alone for light-duty vehicles and buses, double emissions for rail transit, and increase emissions around a quarter for aircraft.

3.3 SUMMARY OF FINDINGS

Some conclusions that can be drawn from this review with respect to emission reduction cost-effectiveness and pollutant tradeoffs are drawn below. These conclusions are based primarily on *implementation costs to the public sector*. Therefore, they do not reflect a more complete accounting of costs and benefits which may include additional costs such as business costs (e.g., to implement worksite trip reduction), traveler savings (e.g., lower transit fares), or nonmonetary benefits such as time savings and improved mobility.

- Travel demand management projects, including employer-based outreach, rideshare, and vanpool programs often have relatively good cost-effectiveness. However, these projects also show wide variation in cost-effectiveness across individual projects. This suggests that their cost-effectiveness depends strongly upon the specific context of the project and how effectively it is implemented. Telecommuting projects tend to be relatively high-cost, especially when costs for telecommuting facilities and equipment are included.

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[8] Chester, Mikhail Vin (2008). *Life-cycle Environmental Inventory of Passenger Transportation Modes in the United States.* Institute of Transportation Studies, University of California, Berkeley.

- Bicycle and pedestrian projects show mixed results. In some studies they perform relatively well, while in others they do not. The overall magnitude of emission reductions from these projects is generally small, although costs also are modest compared to other infrastructure investments.
- Other transportation infrastructure investment to reduce VMT, including transit and freight rail, is generally high-cost (poor cost-effectiveness) compared to most other strategies. Transit service improvements also show high costs per ton of pollutant reduced.
- Pricing strategies can vary significantly in their cost-effectiveness depending upon the method of administration and amount of charge. VMT fees and congestion pricing can have moderate to high costs if fee levels are low, because of the high cost of monitoring and enforcement infrastructure. Higher fee levels result in improved cost-effectiveness. Most of the evidence on pricing strategies is based on GHG studies rather than pollutant emission reduction studies.
- More efficient land use patterns can provide significant GHG benefits over the long term for modest implementation (planning and administrative) costs. However, cost-effectiveness estimates have not considered the full costs or cost savings that may result from changes in infrastructure needs, public services, etc., which are potentially much more significant than implementation costs.
- Traffic signal improvements (timing, synchronization) and incident management usually show good cost-effectiveness, with the exception of NO_x in some cases. However, this may change if induced demand effects are considered. Measurement of induced demand associated with traffic operations is uncertain and it is, therefore, difficult to make definitive statements about the cost-effectiveness of these and other traffic operations strategies.
- Most studies evaluating traffic flow improvements, or regional pricing, transit, and land use strategies that can measurably affect traffic speeds, did not find tradeoffs among pollutants – i.e., all pollutants were reduced. However, as noted, some projects did show increased NO_x levels as a result of higher traffic speeds. Whether there is a tradeoff will depend upon the specific operating conditions, as well as the analysis data and methods used.
- Truck idle reduction can provide air pollution and GHG reduction benefits with a low public investment cost.
- Speed limit reductions (evaluated for GHG only) can provide significant benefits at modest cost to the public sector for enforcement.
- Little data was available to evaluate a number of strategies, including intersection geometric improvements, traveler information, ramp metering, pricing effects (except for GHG), and managed lanes. Little data also is available to evaluate the life-cycle emissions impacts of construction and maintenance associated with transportation infrastructure.

4.0 Vehicle and Fuel Technology

The general approach taken in this report to vehicle and fuel technology projects is somewhat different than for TDM and TSM projects. This is because the body of literature on these strategies is rather different. There are many more studies focusing on the relative effectiveness and tradeoffs for a specific control technology for specific pollutants. Many of the control technologies involve tradeoffs (e.g., air pollutant versus GHG reduction) which are of interest.

Some of the same summary studies that review TDM and TSM strategies also are included (most notably the CMAQ evaluation studies). In comparison to many of the individual technology studies, which focus only on effectiveness, these summary studies have the advantage of reviewing cost-effectiveness. On the other hand, they report effectiveness and cost-effectiveness only for aggregate technology categories (e.g., diesel retrofits, alternative fuels) rather than for specific technologies.

4.1 SOURCES REVIEWED

The body of literature reviewed for this effort is listed in Table A.2 of Appendix A. The table also indicates which emission reduction strategy each source addresses, along with a rating of confidence in the findings. A ranking of "High" was given to those sources that met one or more of the following criteria: the calculation methodology was clearly presented, an adequate number of projects were evaluated, the source of the numbers is well-known and highly trusted (such as the EPA verification web site summary). A ranking of "Medium" was given to those sources that presented informative information, but lacked detailed calculation methodology or had a low number of projects that were evaluated. A ranking of "Low" was assigned to sources that presented informative supporting information, but lacked detail in the study descriptions, the calculation methodology, and had a low number of projects that were evaluated.

Following this table, Section 4.2 reviews the general availability and quality of literature by each type of technology strategy. Then, Section 4.3 summarizes findings regarding cost-effectiveness and tradeoffs for each type of strategy.

Table A.3 of Appendix A identifies what approach or method was used in the analysis, as well as which pollutants were addressed by each source.

4.2 AVAILABILITY AND QUALITY OF LITERATURE BY STRATEGY

Diesel Engine Retrofits

Information on diesel engine retrofits is by far the most abundant and comprehensive of the strategies evaluated for this task. Both California and the U.S. EPA maintain databases of verified/certified retrofits. These sources were given the highest confidence ranking as the information presented in these databases are tested by the respective agencies and certified to specific standards.

Diesel engine retrofit technologies reviewed in the course of this literature search include:

- **Diesel Particulate Filters (Catalytic and Noncatalytic: CDPFs and DPFs) –** A device which captures diesel particulates and prevents their discharge from the tailpipe. DPFs are normally coated with precious metal catalysts such as platinum or palladium. These catalysts enable the DPF to burn the particulates it has collected. The device's recurring process of burning captured material is called "regeneration."
- **Diesel Oxidation Catalysts (DOC) –** A catalyst for that promotes the oxidation of diesel exhaust gases. DOC's are only capable of reducing the soluble organic fraction emissions (gas-phase hydrocarbons and carbon monoxide), not the solid inorganic fraction emissions.
- **Lean NO_x Catalysts (LNC) –** Catalyst designed to reduce nitrogen oxides from diesel or spark-ignited engines in the presence of excess amounts of oxygen (i.e., lean combustion conditions).
- **NO_x Adsorbers –** NO_x adsorber or NO_x trap (also called Lean NO_x trap, or LNT) is a device that is used to reduce oxides of nitrogen (NO and NO_2) emissions from a lean burn internal combustion engine. Adsorbers function somewhat like a DPF in that nitrogen is actually stored within the device and must be periodically regenerated (i.e., purged).
- **Exhaust Gas Recirculation (EGR) –** An emission control method that involves recirculating exhaust gases from an engine back into the intake and combustion chambers. This lowers combustion temperatures and reduces NO_x.
- **Selective Catalytic Reduction (SCR) –** Selective catalytic reduction (SCR) is a means of converting NO_x with the aid of a catalyst into N_2 and water, H_2O. A gaseous reductant, typically anhydrous ammonia, aqueous ammonia or urea, is added to a stream of flue or exhaust gas and is absorbed onto a catalyst. Carbon dioxide, CO_2 is a reaction product when urea is used as the reductant.
- **Selective Noncatalytic Reduction (SNCR) –** Selective Noncatalytic Reduction (SNCR) is a method to lessen nitrogen oxide emissions by injecting

either ammonia or urea into the combustion chamber to react with the nitrogen oxides formed in the combustion process. The resulting product of the chemical redox reaction is N_2, CO_2, and water.

- **Closed Crankcase Ventilation (CCV) –** An encasement and filter system used with the exhaust and crankcase components of an engine to reduce emissions (including in-cab emissions).
- **Engine Reflash –** Software modification on electronically controlled engines (typically model years from the 1990s) to reduce NO_x emissions.
- **Fuel Borne Catalysts (FBC) –** An organo-metallic fuel soluble catalyst, typically platinum and/or cerium or iron, used to reduce engine-out PM, HC and CO emissions.

Many of these retrofit systems can be used in varying combinations to achieve emission reductions for a broad spectrum of pollutants.

It was often difficult to find information on emissions impacts and cost-effectiveness within the same document. For analyzing diesel engine retrofit impacts on pollutants, two studies emerged as key references for this category: *Diesel Retrofit Technology and Program Experience*" by Emissions Advantage, LLC in a study conducted for the U.S. EPA and *Diesel Retrofit Technology Verification* in a study conducted by the U.S. EPA. The most comprehensive information for the cost-effectiveness of diesel engine retrofits comes from the CMAQ reviews and is largely restricted to studies using diesel oxidation catalyst and/or diesel particulate filter technologies.

Accelerated Retirement

The most comprehensive information found for both the impacts and cost-effectiveness of accelerated retirement of heavy-duty vehicles came from CMAQ program reviews. Accelerated retirement of heavy-duty diesel vehicles reduces emissions across all pollutants because of the advancements in technology and new emission standards for newer engines, but cost-effectiveness can vary greatly, primarily depending upon vehicle-mile traveled and engine age.

For light-duty vehicles, much of the available literature comes from programs conducted in California. As a result, the data included may not be completely applicable to a wider geographic area due to differences in vehicle age distributions and emission standards. The only program types evaluated in the literature were voluntary programs with a financial incentive based on the criteria for candidate and replacement vehicles. The studies generally used factors from the U.S. Department of Energy's GREET model or CARB's EMFAC model to calculate the emissions impacts of vehicle replacement. The emissions considered were primarily HC and NO_x, which were usually summed in a 1:1 weighting. There was mention of CO and CO_2 as well; however, this was less prevalent and rarely included analysis of fleetwide effects on total emission levels. There was no mention of effects on toxic emissions in the literature reviewed.

The economic analyses conducted for the different studies had a wide range in terms of level of detail. For some analyses, the costs were calculated in a very simple fashion, only taking into consideration the costs of the incentive and vehicle scrappage. Other sources include detailed effects such as the loss of the economic utility of the vehicle, the effects of increased vehicle migration into the region, and the effect on fleetwide vehicle resale values.

The most significant work reviewed concerning accelerated retirement was a study by the RAND Corporation entitled, *Fighting Air Pollution in Southern California by Scrapping Old Vehicles*. This study included an extremely detailed economic analysis of the implications of these types of programs in an attempt to ensure that any far-reaching effects would be taken into consideration. The one drawback of this study is its age (2001), limiting the ability to extrapolate emission benefit and cost-effectiveness estimates to account for today's fleet technology mix.

Idle Reduction

There are several studies that evaluated idle reduction as a means of reducing emissions. Technologies for idle reduction reviewed during the course of this literature search included: auxiliary power units, heat recovery systems, heater and air conditioning units, automatic start/stop technology, single system truck stop electrification, and dual system truck stop electrification. A particularly detailed study on the emissions impacts of idle reduction reviewed under this effort was led by the Center for Air Quality Studies at the Texas Transportation Institute and was conducted under a $3 million grant from the U.S. EPA. The study was presented at the TRB 2009 Annual Meeting. Argonne National Laboratories conducted many smaller studies on idling reduction.

Cost impacts vary with the price of diesel fuel, adding uncertainty to cost-effectiveness estimates. Once again, the most comprehensive sources for cost-effectiveness estimates were reviews of CMAQ programs.

Alternative Fuels

The literature review for alternative fuels focused on biodiesel, liquid propane gas (LPG), compressed/liquefied natural gas (CNG/LNG), and ethanol (E85). Two sources key to the literature review for determining emissions impact for alternative fuels were a draft U.S. DOT Report to Congress on Transportation's Impact on Climate Change and Solutions and several reports from the National Renewable Energy Laboratory's Alternative Fuels Data Center. The primary study evaluating biodiesel impacts was performed by the U.S. EPA Office of Transportation and Air Quality (OTAQ). Alternative fuel costs vary substantially over time and with the region of the country, creating substantial uncertainty in cost-effectiveness estimates. Cost-effectiveness information was obtained from reviews of CMAQ programs. The U.S. EPA's March 2010 Renewable Fuel Standard Program Final Rule, released after the literature review for this study was conducted, contains a highly detailed assessment of the impacts associated with expanding biofuel use (e.g., ethanol and biodiesel) under the 2007 Energy Independence and Security Act (EISA) requirements.

Inspection/Maintenance Programs

Inspection and Maintenance (I/M) programs are generally aimed at light-duty vehicles, and are designed to reduce emissions that result from vehicle mechanical malfunctions or emission control system deterioration. The literature available only evaluates those areas that actually have I/M programs. However, these programs exist in urban areas throughout the country and the data should have widespread applicability. The literature included analysis of programs using the following types of I/M tests:

- **Two-Speed Idle (TSI) –** An emissions test performed at low and high idle, without applying a load to the engine. The lowest cost testing option; also the least accurate.
- **Acceleration Simulation Mode (ASM) –** A steady-state chassis dynamometer emissions test applying constant loads to the engine.
- **I/M240 –** A more elaborate (and expensive) transient chassis dynamometer emissions test applying varying engine loads and speeds over time.
- **On-Board Diagnostic (OBDII) –** A test that only checks for OBDII fault codes and readiness, with no emissions test.
- **Remote Sensing (RSD) –** A system that remotely measures vehicle emissions in use during normal travel; can be used in conjunction with other types of test programs. For example, RSD measurements can be used to provide automatic pass or fail test results for the (respectively) cleanest and highest polluting vehicles in the fleet without the vehicle needing to go to an I/M facility, thereby improving program cost-effectiveness.

Most of the available sources do not discuss the differences in cost-effectiveness among the different types of I/M testing programs. One source, the report by ERG entitled, *Technical Note: Emission Control Strategy Evaluation in the Austin/San Marcos MSA*, was used to rank I/M programs in terms of cost-effectiveness, and this source listed a range of much higher costs than was found in the rest of the literature.

The focus of the literature was on reduction of the criteria pollutants HC, CO, and NO_x. There was some mention of effects of I/M programs on CO_2 emissions; however, this appeared to have significant uncertainty, especially with regards to cost-effectiveness. There was no mention in the literature regarding toxic or PM emissions. The programs often provide a direct way of calculating emission benefits, because an emissions test is a part of many I/M programs. OBD testing, however, does not specifically include an emissions test.

Some OBD test areas do conduct an IM240 test of a random sampling of OBD vehicles in order to gather information about the general effectiveness of OBD testing.

Hybrid Vehicles

The literature available for the discussion of hybrid-electric vehicles (HEV) is largely focused on fuel and energy consumption, with battery technology being the most significant driver of those characteristics. Much of the advanced literature on the subject is focused more toward development of the battery technology, with less focus on exhaust emissions of the vehicle system as a whole. Because of the engineering tradeoffs with these vehicles and the uncertainty regarding the degree of future vehicle electrification, there is a broad discussion of HEVs, plug-in hybrid-electric vehicles (PHEV), and battery-electric vehicles (BEV) available in literature. The tradeoffs involve a balance between vehicle tailpipe CO_2 emissions and the CO_2 emissions associated with grid electricity generation, and the total energy consumption involved in each.

There is no discussion of hybrid vehicles having difficulty meeting current criteria or toxic emissions standards, suggesting that the focus of engineering efforts in the field is on fuel economy and drivability. Additionally, there is little in the literature to suggest any significant relationship between vehicle hybridization and emissions of criteria pollutants. These effects are not perceived to be instrumental in guiding the progression of hybrid technology.

The cost analysis of vehicle hybridization is fairly straightforward compared to the other strategies that were investigated. The hybrid vehicle has a marginal cost compared to a conventional light-duty vehicle, associated primarily with battery costs and fuel prices. The economic analysis then balances the increased upfront battery costs with the lifetime fuel savings, with the uncertainties stemming from future changes in both battery and fuel costs.

The most significant study evaluated was written by Matthew Kromer and John Heywood, entitled, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*. This document includes a relatively comprehensive study of previous literature, identifying the significant benefits and challenges for HEV, PHEV, and BEV technology. The study also includes an economic analysis, including a number of specific cost-effectiveness calculations for the three electrification technologies, such as a well-to-tank and tank-to-wheels analysis, a cost of operation analysis based on fuel and maintenance costs, and calculations of the cost per ton of associated greenhouse gas reduction.

National Fuel Economy and Efficiency Incentives

There are a wide range of strategies available for the promotion of vehicle efficiency, each with advantages and disadvantages. These strategies can be implemented by targeting either manufacturers or vehicle owners. National fuel economy standards, such as the corporate average fuel economy (CAFE) standard, are intended to promote technological advancements that contribute to increased vehicle fuel economy. The current CAFE strategy focuses on vehicle manufacturers, requiring that they meet average requirements for each of their car and truck fleets in order to avoid fines. This affects vehicle costs, which in turn impacts buyer choices. An example of a program that would directly affect consumers would be an increased gasoline tax. This would affect buyers' perception of operating costs and would cause them to alter their buying habits. Manufacturers would then tend to change their vehicle designs to satisfy the altered purchasing patterns. The discussion of fuel economy standards places most of the available options into one of the above two strategies.

The discussion of these strategies in the literature is focused primarily on implementation and the uncertain effects on vehicle purchases. There is little mention of information on the cost-effectiveness of the complete programs, or the effects on criteria pollutant emissions. The U.S. DOT's Report to Congress on Transportation's Role in Reducing U.S. Greenhouse Gas Emissions (U.S. DOT, April 2010) evaluated a broad range of near-term vehicle efficiency improvement options, many of which will likely be used to meet new fuel economy and GHG reduction standards, although no clear relationship between fuel consumption reductions and criteria/toxic emissions were identified. U.S. EPA's April 2010 final rulemaking on GHG emission and fuel economy standards, published after the literature review for this study was conducted, provides a detailed evaluation of impacts of these standards on CO_2 as well as other pollutant emissions.[9]

Heavy-Duty Vehicle Efficiency Improvements

The efficiency of heavy-duty vehicles may be improved through powertrain or vehicle/trailer improvements. Potential powertrain advancements currently being considered for deployment include friction reduction, turbo-compounding, and auxiliary electrification, among others. Vehicle and trailer improvements primarily focus on retrofits to improve aerodynamics, as well as weight reduction and low rolling resistance tires. Future heavy-duty vehicle efficiency standards currently are being evaluated for consideration under EISA, and will likely involve multiple technology strategies in order to comply. The California ARB already has adopted an aggressive retrofit requirement for Class 8 trucks operating within the state, mandating use of certain SmartWay-certified retrofits.

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[9] U.S. Environmental Protection Agency (2010). *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards: Regulatory Impact Analysis.* EPA-420-R-10-009, http://www.epa.gov/oms/climate/regulations/420r10009.pdf, pp. ES 5-6.

4.3 FINDINGS BY STRATEGY

Diesel Engine Retrofits

Diesel retrofits typically target on-road engines prior to the 2007 model year, as later model years already are equipped with highly effective NO_x and PM controls. As such, diesel retrofits may be applied to a substantial portion of today's on-road fleet, but will become continually less important in the long run due to natural fleet turnover.[10]

Emission reductions from diesel particulate filters depend on the type, age, and emissions profile of the vehicle receiving the retrofit, as well as the miles traveled and remaining useful life of the vehicle. Catalyzed DPFs are very effective at reducing $PM_{2.5}$, but must be used with low-sulfur diesel. Catalyzed DPFs used with higher sulfur diesel fuel result in sulfate emissions due to the nature of the catalyst (Wescott, 2005). However, as ultra low-sulfur fuel will be fully phased in by 2010, high-sulfur diesel will not be available for use, eliminating this potential side effect. One evaluation of DPF retrofit performance cited the most common problem with DPFs is the plugging of the filter (Emissions Advantage LLC, 2005).

Use of DPFs can result in a fuel (and CO_2) penalty from two to 4 percent due to increased energy requirements for system operation (EPA, 2007). Catalyzed DPFs require a minimum exhaust temperature in order for the catalyst to be regenerated (Emissions Advantage LLC, 2005). For this reason, vehicles operating at low engine loads for long periods may not be appropriate candidates for this technology. DPFs are especially effective at reducing PM emissions, including $PM_{2.5}$. DPFs can be used in conjunction with several retrofit technologies such as CCVs to achieve even greater emission reductions. When DPFs are used in conjunction with LNC technology, a fuel penalty of four to seven percent can result (EPA, 2007). This larger fuel penalty results because LNC systems require an exhaust $HC:NO_x$ ratio of 6:1 to be effective, and this is typically achieved by additional fuel injected into the exhaust after the primary combustion (Emissions Advantage LLC, 2005).

As with DPFs, emission reductions realized by diesel oxidation catalysts also depend on the type, age, and emissions profile of the vehicle receiving the retrofit, as well as the mileage accumulation rate and remaining useful life of the vehicle. DOCs are very effective at reducing VOC and CO emissions and moderately effective at reducing PM emissions, but can result in a fuel penalty of

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[10] There is additional uncertainty with the long-run emission reduction benefits associated with the 2007 and later HDDV emission standards. The OEM DPF, EGR, and SCR systems used to meet these standards may be subject to performance deterioration, which could continue unchecked in the absence of a HDV I/M program (yet to be developed).

up to two percent (EPA, 2007). DOCs also are substantially lower in cost than DPFs (roughly $1,000 for DOCs versus up to $10,000 for DPFs–EPA420-R-07-005. When DOCs are used with FBCs, there is the possibility of producing fine metallic emissions, which although not explicitly defined as toxic, are a potential concern and can be controlled with an exhaust filter. In fact, some providers will not sell a DOC/FBC system unless it is used in conjunction with a PM filter (EPA, 2007).

Other common control technologies, though not as widely evaluated, include selective catalytic reduction, selective noncatalytic reduction, fuel-borne catalysts, lean NO_x catalysts, closed crankcase ventilation, exhaust gas recirculation, NO_x adsorbers, and engine reflash. Selective catalytic reduction (SCR) systems are highly effective at NO_x reduction (up to about 90 percent), but are very complex and costly to retrofit, estimated between $12,000 and $20,000 (EPA420-R-07-005). SCR also requires regular replenishments of urea, and can result in ammonia slip. A fuel use penalty of approximately three to six percent also is anticipated (NAS, 2009; EPA, 2007). Selective noncatalytic reduction systems have a narrow window of operating temperatures, which can limit their use and their effectiveness, although they have shown promise in combination with SCR systems (Emissions Advantage LLC, 2005).

Lean NO_x catalyst (LNC) systems are relatively costly, roughly $15,000-$20,000, and provide NO_x reductions between 10 and 25 percent (Emissions Advantage LLC, 2005; EPA, 2007). In addition, these systems can result in a fuel penalty of three to seven percent and can produce NO_2 (EPA, 2007).

Low-pressure exhaust gas recirculation (EGR) systems can be retrofit on older engines to reduce NO_x by upwards of 40 percent, but also can result in a fuel penalty of up to five percent and are almost always used in conjunction with a PM filter as they can cause higher PM emissions (EPA, 2007). In addition, these systems are generally used in conjunction with a PM filter, to limit reintroduction of PM back into the combustion chamber, which would impede system performance. Capital costs for an EGR/DPF package are estimated between $15,000 and $18,000 (WRAP, 2005).

Closed crankcase ventilation (CCV) controls drastically reduce *crankcase* PM and related emissions (e.g., HC and CO) by 90 percent or more.[11] CCVs require replacement of the filter at regular intervals, or the effectiveness of the system will suffer. CCV operation does not impact fuel consumption or vehicle performance. CCV system costs are relatively quite low, at approximately $450, or up to $2,000 when combined with a DOC (WRAP, 2005).

Engine reflash software can be applied to 1993 to 1998 engines, and is estimated to result in NO_x reductions up to 25 percent, although the creditability of these

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[11] Net emission reductions for CCVs are about 33 percent for PM, 23 percent for CO, and 66 percent for HC (WRAP, 2005).

reductions vary. Reflash systems can have a fuel penalty of less than 1 percent, but the application is engine manufacturer-specific (Emissions Advantage LLC, 2005). Reflash costs are often covered entirely by engine manufacturers, and are generally limited to approximately one hour or less of labor (WRAP, 2005).

Key factors impacting the cost-effectiveness of retrofits are:

- Cost of the retrofit;
- Engine year and type (mechanical versus electronic);
- Horsepower rating;
- Exhaust system type (single versus dual);
- Application and duty cycle (urban stop and go, short-haul, or long-haul);
- Annual and lifetime mileage;
- Engine operating characteristics (temperature ranges, fuel, etc.);
- The location of the operations (urban versus rural);
- Emission certification levels;
- The number, age, and emissions profile of the existing vehicle;
- Remaining useful life of the vehicle; and
- Maintenance procedures (e.g., active regeneration frequency for DPFs and urea replenishment for SCR).

A summary of the relative emissions impacts of various diesel engine retrofits is presented in Table 4.1, with quantitative ranges provided where available.

Table 4.1 Relative Emissions Impacts for Diesel Engine Retrofits[a]

Technology	VOC	CO	NO_x	PM	CO_2	Toxics
DPF	Decrease 60%-90%	Decrease 60%-90%	–	Decrease 90%	Increase 2%-4%	Decrease in PAH, Benzene, ethylene, propylene, and toluene Increase in NO_2
CDPF	Decrease 20%-90%	Decrease 20%-90%	Decrease 0%-5%	Decrease 90%	Increase 1%-4%	N/A
LNC/DPF	Decrease 60%-90%	Decrease 60%-90%	Decrease 20%-25%	Decrease Up to 90%	Increase 4%-7%	N/A
EGR/DPF	Decrease 60%-90%	Decrease 60%-90%	Decrease Up to 50%	Decrease Up to 90%	Increase Up to 5%	N/A
FBC/CDPF	Decrease 80%	Decrease 80%	Decrease < 10%	Decrease 85%	Increase Up to 2%	N/A
DOC	Decrease 20%-90%	Decrease 20%-90%	–	Decrease Up to 50%	Increase Up to 2%	N/A
FBC/DOC	Decrease Up to 50%	Decrease Up to 50%	Decrease Up to 10%	Decrease 30%-60%	Increase 4%-6%	Potential for increase in fine metallic emissions

Technology	VOC	CO	NO$_x$	PM	CO$_2$	Toxics
SCR	Decrease 50%-90%	Decrease 50%-90%	Decrease Up to 90%	Decrease Up to 50%	Increase 3%-6%	N/A
SNCR	N/A	N/A	Decrease	N/A	N/A	N/A
FBC	Decrease Up to 50%	Decrease Up to 50%	Decrease Up to 10%	Decrease Up to 33%	N/A	Fine metallic emissions
LNC	–	–	Decrease 10%-25%	–	Increase 3%-7%	N/A
CCV	Decrease 30%-40%	Decrease 30%-35%	–	Decrease 10%-25%	–	Decrease
EGR	–	–	Up to 40-50%	Increase	Increase Up to 5%	N/A
Reflash	Decrease	Decrease	Decrease Up to 25%	Decrease	Increase < 1%	N/A
NO$_x$ Adsorber	Decrease Up to 90%	Decrease Up to 90%	Decrease > 90%	Decrease 10%-30%	N/A	N/A

[a] Percentage of decrease/increase presented where that information was available.

Information on cost-effectiveness (Table 4.2) was obtained mostly from reviews of CMAQ projects. The cost-effectiveness of retrofits varies by vehicle type, mileage, engine age, and other factors for any given retrofit technology. Cost-effectiveness estimates also can vary substantially depending upon the calculation methodology employed, including the timeframe used for calculating benefits and costs, cost categories included (e.g., capital, operation and maintenance, equipment resale/scrap values, among others), and discount rates. In many instances details regarding cost-effectiveness calculation methodologies were lacking, and definitive conclusions regarding the subsequent impacts on calculated ranges could not be made. Information for CMAQ program participants was particularly inconsistent.

The cost-effectiveness data also has significant data gaps. For example, even though the literature indicated that DPFs affect multiple pollutants, limited cost-effectiveness data was found only for PM$_{10}$, VOC, and NO$_x$.

Table 4.2 Cost-Effectiveness of Diesel Engine Retrofits

Dollars per Ton

Technology	Vehicle Type	VOC	CO	PM$_{2.5}$	PM$_{10}$	NO$_x$	NO$_x$, VOC Combined[a]
CDPF	School Bus				$12,400-$50,500		
CDPF	Class 6 and 7 Truck				$28,400-$69,900		
CDPF	Class 8b Truck				$12,100-$44,100		
DOC/CDPF	HDDVs						$1,900-$19,000 (Median: $5,950)

Technology	Vehicle Type	VOC	CO	$PM_{2.5}$	PM_{10}	NO_x	NO_x, VOC Combined[a]
DOC	School Bus				\$12,000-\$49,100		
DOC	Class 6 and 7 Truck				\$27,600-\$67,900		
DOC	Class 8b Truck				\$11,100-\$40,600		

[a] CMAQ cost-effectiveness evaluations use the weighted value 1 VOC to 4 NO_x.

As the table shows, there is a wide range of cost-effectiveness for various diesel engine retrofits. In the CMAQ program alone, diesel retrofits for buses and HDDVs were reported to have cost-effectiveness ranges of \$7,000-\$677,000 for VOC, \$1,000-\$174,000 for CO, \$8,000-\$2,100,000 for $PM_{2.5}$, \$7,000-\$1,700,000 for PM_{10}, and \$21,000 for NO_x. However, the CMAQ summary report did not go into detail about what types of retrofits were chosen in each of the projects, making it impossible to characterize the cost-effectiveness of specific retrofit technologies.

An evaluation was recently performed assessing the aggregate cost-effectiveness of the various NCDC-funded programs, predominantly characterized by DPF and DOC retrofits (U.S. EPA 2009, ref. 56). The estimated PM control cost-effectiveness for these programs was \$33,300 per ton, well within the ranges reported above. Estimates for HC and CO control were \$16,900 and \$5,000 per ton, respectively.

Accelerated Retirement

In general, the literature found accelerated retirement programs to be moderately cost-effective options for the reduction of criteria pollutant emissions from light-duty vehicles, and to a lesser extent for heavy-duty trucks. The cost-effectiveness for buses, however, was concluded to be prohibitively high, although no precise threshold for judging cost-effectiveness was provided by the authors. In one study, the fleetwide reduction in HC and NO_x taken together was 3.8 percent as a result of the program. Accelerated retirement programs can, to some extent, be tailored to specific regions based on the required criteria for candidate vehicles and their replacements. For example, areas with older fleets may be able to set their candidate selection criteria relatively loosely and still obtain substantial benefits.

Only one program, entitled, *Abating Greenhouse Gas Emissions through Cash-for-Clunker Programs*, evaluated program benefits in terms of CO_2 emissions, however, and did not find them to be cost-effective. The authors' discussion suggests that the level of uncertainty associated with program costs and the actual energy requirements of vehicle scrappage and replacement were relatively high. The conclusion reached was that programs can be created that will successfully reduce CO_2 emissions, but they would not be cost-effective compared to other GHG mitigation options.

The most significant cost associated with these programs is the retirement incentive, although there also is a real cost associated with the retiring a vehicle before the end of its useful life. In addition, these programs have an unintended side effect of artificially inflating used (replacement) car values, they are sometimes singled out as having a disproportionately negative effect on low-income individuals.

The key factors affecting the effectiveness of these programs are:

- The incentive value;
- The criteria for candidate and replacement vehicles;[12]
- The amount of migration of older vehicles into the region;
- Remaining useful life of the replaced vehicle;
- The foregone value of the lost transportation;
- For CO_2-based programs, the energy required to scrap the vehicle and manufacture its replacement;
- The fuel type and emission standard level of the replacement vehicle;
- Annual miles traveled (for both candidate and replacement vehicle); and
- Travel mode shifts (e.g., transit ridership increase).

The costs of these programs are generally borne entirely by the government entity conducting the program. The range of cost-effectiveness encountered in literature was fairly wide. Variation in the program design factors above contribute to the size of the range, as each program can be designed in a wide variety of ways depending on exactly what is to be achieved.

Tables 4.3 and 4.4 show the direction of emissions impacts and range of cost-effectiveness for accelerated retirement/replacement strategies.

Using the estimates developed for EPA's regulatory rulemakings, the cost-effectiveness associated with replacing older engines with those meeting Tier 2 standards is about $2,000 per ton, substantially lower than for PM retrofits. Similarly, the cost-effectiveness of adopting the Tier 4 standards for NO_x reduction was estimated at $1,010 per ton, again, drastically lower than retrofit options such as SCR (U.S. EPA 2009, ref. 56).

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[12] As older vehicles with less stringent emission standards are naturally retired from the fleet, the baseline fleet as a whole becomes cleaner. Accordingly, the emission benefits available from accelerated retirement programs are likely to become less substantial with time.

Table 4.3 Emissions Impacts of Accelerated Retirement/Replacement

Vehicle Type	VOC	CO	NO_x	PM	CO_2[a]	Toxics
HDDV	Decrease	Decrease	Decrease	Decrease	Equivocal/ Decrease	Decrease
Buses	Decrease	Decrease	Decrease	Decrease	Equivocal/ Decrease	Decrease
Light-duty	Decrease	Decrease	Decrease	Decrease	Equivocal/ Decrease	Decrease

[a] Programs will only result in a decrease in CO_2 if they are based on the fuel economy requirements of replacement vehicles.

Table 4.4 Cost-Effectiveness of Accelerated Retirement/Replacement

Vehicle Type	VOC	CO	NO_x	PM_{10}	CO_2/GHG	NO_x, VOC Combined
Transit Buses	\$852,000-\$1,500,000	\$706,000	\$25,100-\$231,000	\$753,400		\$6,700-\$569,000
HDDV						\$4,000-\$31,600
Light-Duty					\$50/tonne	\$4,500-\$22,200

Idle Reduction

According to the information from the literature review, idle reduction strategies are effective at reducing emissions across all pollutants. Idle reduction strategies include truck stop electrification, both single and dual system, to auxiliary power units and alternative heating and cooling options.[13] Idle reduction technologies also include automatic start/stop technology which will automatically shut the engine off if the truck is at idle for a given amount of time, which generally ranges anywhere from three to 15 minutes before shut-off occurs.

High fuel prices provide truck operators with relatively quick cost recovery periods for many on-board idle reduction options, roughly two to three years for a typical long-haul truck assuming \$6,000 in retrofit costs (ATRI, 2006). Truck stop electrification also can be particularly cost-effective for truck operators, as the cost of the infrastructure is amortized by the hosting entity over a longer period than would generally be deemed acceptable for truck owners. However,

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[13] Single-system truck stop electrification refers to stand-alone, off-board equipment located at the truck stop used to provide heating and air-conditioning. Dual-system truck stop electrification uses both on-board and off-board equipment and requires that modifications be made to the truck itself.

emissions impact analyses must take into consideration the potential for increases in upstream emissions at electrical generation facilities.

There are regional variations in the effectiveness of idle reduction technologies and strategies. Regional variations in climate, for example, can affect technology choices. If a vehicle operates primarily in cooler climates, more benefit is realized from direct-fired heaters than from air-conditioners, and the opposite is true for vehicles operating in warmer climates. Emissions from upstream electrical generation plants also vary from region to region, and are largely dependent on the type of electrical generation facility. Idle reduction in urban areas will often have a relatively larger benefit than those in rural areas as the number of people impacted will be greater (Gaines, 2009).

Key factors in the effectiveness of idle reduction strategies are:

- The number of truck parking spaces equipped with idle reduction technology;
- Average number of hours of idling each day per truck;
- Cost of idle reduction technology;
- Emissions associated with electrical power generation upstream;
- Utilization by truckers; and
- Fuel prices.

Table 4.5 shows the range of cost-effectiveness for accelerated idle reduction technologies.

Table 4.5 Cost-Effectiveness of Idle Reduction Technologies
Dollars per Ton

Technology	VOC	CO	PM	NO_x	NO_x, VOC Combined[a]	CO_2[b]
APU		$6,800	$110,300-$173,600	$2,900-$4,600	$2,700-$3,500	$20
Truck Stop Electrification					$1,400-$2,000	$50-$60

[a] 4:1 NO_x to VOC weighting applied (9).

[b] Dollars per metric ton, direct (capital) costs only. Net savings are expected when fuel cost savings are included.

Unlike many other control strategies, idle reduction measure effectiveness may not decline significantly with fleet turnover. This is because many idle emission rates are expected to be relatively insensitive to advanced emission controls, which rely on relatively high engine loads and/or exhaust temperatures to function properly (e.g., EGR and CDPFs), although CCVs will provide significant benefits even at idle.

The recent evaluation of idle reduction projects funded under the NCDC estimated NO_x reduction cost-effectiveness at $1,600 per ton, although this aggregated figure includes multiple types of idle reduction technologies (U.S. EPA 2009, ref. 56).

Alternative Fuels

Alternative fuels provide yet another means for achieving emissions reductions, though there can be significant tradeoffs between pollutants depending upon fuel type. For natural gas, while emissions in VOC, NO_x, PM, and CO are decreased, there is an increase in methane, a greenhouse gas, unless catalysts are designed for additional methane control. Although natural gas is frequently less expensive on an equivalent-gallon basis than gasoline, light-duty natural gas vehicle costs vary dramatically depending upon whether they are original equipment manufacturer (OEM) (~$3,000-$6,000) or gasoline vehicle conversions (~$15,000), substantially impacting cost-effectiveness estimates.

Ethanol results in the reduction of criteria pollutants such as HCs, NO_x, PM, and CO, but results in increases in aldehyde and greenhouse gas emissions.[14] Flex fuel vehicles which can use any blend of ethanol in gasoline up to 85 percent (E85) are commonly available at low incremental cost (about $150 per vehicle– DOT 2009). However, without considering subsidies, current E85 fuel prices are substantially higher than gasoline, leading to poor cost-effectiveness values for CO_2 reduction ($250-$575 per ton; Fulton, 2004; Lutsey and Sperling, 2009; IPCC, 2007 McKinsey, 2009; Lutsey, 2008). Increased evaporative emissions from ethanol are primarily a concern for E5 and E10 blends rather than for E85. For exhaust emissions, there is either a decrease or no statistically significant difference between E85 and gasoline exhaust emissions, except for those of formaldehyde, acetaldehyde, and methane, which all increase with ethanol (U.S. DOE).

Biodiesel has been the focus of particular study regarding criteria emission impacts. The presence of oxygen in biodiesel helps decrease VOC, CO, PM and toxic emissions substantially, but may increase NO_x emissions. The potential for increased NO_x becomes greater with increasing blend percentages. EPA estimates an increase of approximately two percent in NO_x emissions associated with B20, although a more recent study by NREL found no significant change in NO_x levels associated with late model on-road diesel engines. California ARB currently is investigating NO_x impacts in more detail using the latest EGR-equipped engines.

Biodiesel may be used in volumes up to 20 percent without requiring significant engine/fuel system modifications. However, biodiesel is typically more expensive than petroleum diesel, although the cost differential varies in time and by area of the country. Biodiesel cost-effectiveness estimates are sparse, possibly

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[14] While tailpipe CO_2 emissions will increase with ethanol use relative to gasoline, lifecycle ethanol emissions may be lower than gasoline, depending upon the feedstock, manufacture, and delivery methods used.

due to the large variation and uncertainty in fuel price differentials. One study estimated \$240 per tonne of CO_2 reduction, assuming a \$1.50 per gallon price differential between petroleum diesel and B100 (Rabl, 2007).

Key factors in the effectiveness of alternative fuels are:

- The price of the baseline and alternative fuels (including fueling delivery and infrastructure costs);
- Alternative fuel vehicle incremental costs (OEM or conversion); and
- Bi/dual-fuel versus dedicated vehicle configuration (with dedicated vehicles obtaining greater emission reductions in general).

Tables 4.6 and 4.7 show the direction of emissions impacts and range of cost-effectiveness for alternative fuels.

Table 4.6 Emissions Impacts of Alternative Fuels

Fuel Type	VOC	CO	NO_x	PM	Toxics	Other
Biodiesel (B20)	-12%	-17%	Equivocal/ Increase (~2%)	-16%	Decrease	N/A
Additives	N/A	N/A	Decrease Up to 5%	Decrease	N/A	N/A
CNG	Decrease	Decrease	Decrease	Decrease	N/A	Increase in CH_4
E85	Decrease	Decrease	Decrease	Decrease	Decrease in 1,3 Butadiene Increase in Formaldehyde, Acetaldehyde	Possible increase in CH_4
Propane	Unchanged	Decrease	Unchanged	Decrease	N/A	Increase in CH_4

Table 4.7 Cost-Effectiveness of Alternative Fuels[a]

Alternative Fuel Strategy	Vehicle Type	VOC	CO	$PM_{2.5}$	PM_{10}	NO_x	GHG (Life Cycle)	NO_x, VOC Combined [a]
CNG	Transit Buses	\$152,000-\$2,900,000	\$124,000-\$734,000	\$676,000		\$82,000-\$316,000		\$7,800-\$665,800 (Median: \$148,000)
CNG	HDDV						\$130	
LPG	HDDV						\$130	
E85	LDV						\$30-\$90	
Biodiesel	On-Road HDD Trucks						\$240	

[a] GHG cost-effectiveness estimates reflect fuel cost savings. Other pollutant cost-effectiveness estimates from some sources (such as the CMAQ evaluations) do not. Since fuel costs are highly variable, the information added by considering this factor tends to be of limited value.

As with most other control strategies, the emission reductions resulting from alternative fuels will likely become less significant with time (in absolute terms) as the baseline gasoline and diesel vehicle fleets become cleaner due to the introduction of more stringent emission standards.

The 2002 CMAQ analysis also estimated the cost-effectiveness of "alternative fuel nontransit vehicles," aggregated across several options, including CNG and LPG fuels, between $4,700 and $37,000, with a median value of $20,800, assuming a 4:1 NO_x to VOC weighting (9). The U.S. EPA's March 2010 Regulatory Impact Analysis for the renewable fuel standard final rule features an analysis of non-GHG emissions impacts, estimating increases between -1 and +10 percent in 2022.

Inspection/Maintenance Programs

The literature suggests that I/M programs are often cost-effective ways to reduce emissions of criteria pollutants when compared to their costs to motorists and taxpayers. Programs are shown to reduce emissions of HC and CO by up to 15 percent fleetwide. For NO_x, the reductions are shown to be up to approximately eight percent for the fleet of vehicles in an I/M area. For CO_2 reductions, fleetwide reductions are estimated at approximately one percent due to fuel economy improvements after repair, but these benefits are not shown to be cost-effective if CO_2 reduction is the only goal.

The costs associated with I/M programs include the cost of implementing the program and motorist costs and inconvenience. Test fees are commonly in the $20-$50 per vehicle range, although repairs can cost several hundred dollars, depending upon the reason for test failure. Program efficiency suffers when motorists are required to conduct repairs that may not contribute to decreased vehicle emissions. Some OBD failures in particular may not contribute in any measurable way to exhaust emission reductions.

Key factors that affect I/M program effectiveness estimates include:

- Uncertainty with regards to actual repair costs, as data is difficult to collect and can have a wide range of costs, even for a specific repair type;
- Some OBD repairs do not have associated emissions reductions;
- Pass/fail cutpoints for emissions tests have a strong effect on cost-effectiveness;
- Inability to quantify the success or failure of evaporative system repairs;
- The cost savings to motorists due to fuel savings after repairs may be significant but is highly uncertain; and
- If RSD systems are used, there is substantial flexibility in how they are employed, and the cutpoints used have a large effect on effectiveness.

Many of the sources of literature have a relatively narrow cost-effectiveness range considering the amount of variation in the design of these programs. The study by ERG mentioned above, however, estimated much higher costs than the others. The studies employed different weightings for HC, CO, and NO_x, and this increases the cost-effectiveness range. The values over various weightings of HC, CO, and NO_x ranged from $2,100 to $9,000 per ton of emissions reduced for many of the studies. For CO_2, the single source identified for cost-effectiveness reported a value of $8,399 per ton of CO_2 reduced by the program, clearly showing that it was not effective for reduction of CO_2.

Only one source was found that ranked the different types of I/M programs by their relative cost-effectiveness. Table 4.8 shows the different types of program along with the cost-effectiveness values, relative to OBD-only programs.

Table 4.8 Relative Cost-Effectiveness of Different I/M Programs

I/M Test Type	Cost-Effectiveness Relative to OBD Only (NO_x and VOC/2)
ASM	3.1
ASM with RSD	2.5
TSI	2.3
OBD and ASM	1.4
OBD only	1.0

Source: ERG for Capital Area Planning Council (2003).

It can be seen that a program that only includes OBD testing of 1996 and later vehicles has the best cost-effectiveness rating. This is most likely due to the low cost of this type of testing as each vehicle can be tested in a short amount of time without the hardware and maintenance costs of dynamometer systems. Unfortunately, these systems do not test pre-1996 vehicles, which are responsible for a significant amount of air pollution due to their higher emission rates, although this portion of the fleet is become less and less of a concern over time due to natural fleet turnover. Accordingly, standard tailpipe testing may become less cost-effective over time relative to OBD programs. Nevertheless, in the long-run OBD programs themselves may eventually become less cost-effective than today, as more stringent emission standards applied in 2004 and subsequent model years come to dominate the fleet.

Hybrid Vehicles

The literature included a range of cost-effectiveness in CO_2 reduction for hybrid vehicles that extended from negative to positive values. In the best case, hybrid vehicles will offer CO_2 reduction along with lower overall cost than conventional vehicles. However, the range presented extends to positive values that exceed those typically considered cost-effective for CO_2 reduction. The available data suggest that for hybrid technologies in the near term, HEVs will be the most cost-effective in terms of CO_2 reduction, with BEVs being the least cost-effective. PHEV cost-effectiveness is likely to be only slightly higher than HEVs, and this will be strongly dependent on the vehicle's all-electric range as compared to its usage. For single-vehicle tailpipe emissions of CO_2, HEVs offer the potential to reduce emissions by 17 to 65 percent depending on design.

For emissions of criteria pollutants, only anecdotal links were found between hybridization and emissions. The decreased engine running time and decreased requirements for transient loads tend to decrease emissions, while the increased number of engine starts and stops act to increase emissions. Because of this, it is suggested that hybrid fuel economy and criteria emissions are not clearly related. As a result, there was no discussion of emission reductions or cost-effectiveness for criteria pollutants.

The primary tradeoffs discussed in the literature included the increased upfront cost of HEVs compared to long-term fuel savings. Historically, automobile customers have been unwilling to pay significant upfront costs in pursuit of long-term savings, with this slowing the market penetration of these vehicles. Other tradeoffs that may be less significant include concerns over the safety of batteries and high-voltage systems, along with concerns over battery longevity and the cost of replacement during the vehicle's useful life. Another tradeoff concerns the ability of hybridization to enter the light-truck market, as these powertrains may not be able to meet gradeability demands in towing applications. While heavier vehicles such as trucks can benefit greatly from hybrid powertrains, the inability to satisfy towing demands may prevent hybridization from making significant inroads into this market, which is made up of vehicles that consume a relatively large amount of fuel.

The greatest uncertainties impacting the effectiveness of hybridization include the cost and performance characteristics of batteries, along with vehicle lifetime fuel costs. For PHEVs, the design all-electric range has a significant effect of energy efficiency and cost-effectiveness, and this range needs to be well matched to a vehicles intended usage. There also are substantial uncertainties associated with the long-term market demand for hybrid technologies; since baseline conventional gasoline and diesel technologies will become continually more efficient with time, there may be a decrease in the relative benefit associated with hybridization, considering the incremental costs of these technologies. On the other hand, some of the advances in conventional technologies are likely to involve limited hybridization techniques, to some extent blurring the distinction between conventional and hybrid systems in the future.

There also are uncertainties about the future makeup of grid power sources, and which marginal sources of generation will be used for PHEV charging. One study by the Electric Power Research Institute (EPRI) estimated small changes in nationwide VOC (-0.6 percent), NO_x (-1.7 percent), and PM_{10} (+0.2 percent) associated with broad adoption of PHEV technology by 2030 (EPRI, 2007). However, net emission impacts are likely to vary substantially by geographic location and over time.

The cost-effectiveness range encountered for hybridization is fairly wide, extending from negative values, in which the vehicle offers both CO_2 reduction and cost savings (due to fuel savings), to positive values. These values are presented in Table 4.9. The uncertainties listed above create the fairly large amount of uncertainty in calculations of cost-effectiveness, especially for the PHEVs and BEVs, which have increased uncertainties due to the design choice of all-electric range and the carbon dioxide intensity of grid power generation.

Table 4.9 CO_2 Cost-Effectiveness Ranges for Vehicle Hybridization

Vehicle Type	Cost-Effectiveness Range
HEV	-$60 to +$270
PHEV	-$150 to +$590
BEV	$710 to $1,050

National Fuel Economy and Emissions Standards

There is little data in the literature to suggest a significant relationship between standards for fuel economy and emissions of criteria and toxic pollutants. Because of this and the lack of cost data concerning the standards, no cost-effectiveness data is presented. EPA's analysis for its April 2010 rulemaking on GHG and fuel economy standards, which will increase average passenger car fuel economy to 35.5 miles per gallon by 2016, found a measurable but modest impact of these standards on other pollutants. EPA estimates that on a nationwide basis, the new standards will reduce vehicle NO_x, PM and SO_x emissions between 0.1 and 0.8 percent, VOC emissions by 1.0 percent, and will increase CO emissions by 0.6 percent. Toxic impacts were also assessed, with reductions anticipated for benzene (0.1 percent) and 1,3 butadiene (0.3 percent), and increases expected for acrolein and formaldehyde (0.1 percent) and acetaldehyde (2.2 percent).

Heavy-Duty Vehicle Efficiency Improvements

While a great deal of information is available regarding the emission reduction potential and (to a lesser extent) the cost-effectiveness of CO_2 reductions associated with these strategies, very little has been published regarding the associated criteria and toxic impacts of these approaches. A recent analysis performed for the National Academy of Sciences provided a qualitative assessment of the criteria pollutant impacts associated with specific powertrain strategies. One study performed by TIAX LLC for the Union of Concerned Scientists conducted simulation modeling of the engine load and associated NO_x and PM impacts of various aerodynamic, weight reduction, and rolling resistance strategies. While the focus on this study was on CO_2 reductions, NO_x reductions for long-haul truck operation was assumed to follow fuel consumption reductions by 1.22:1.0.

The ratio for short-haul was estimated to be 0.58:1.0. PM impacts were estimated to be too variable for reliable generalization.

No sources were found for the emission reduction or cost-effectiveness for criteria or toxic emission impacts.

4.4 CONCLUSIONS

In general, most of the control strategies evaluated in this analysis provide emission reductions for one or more pollutants, without notably increasing other pollutants. Key exceptions include certain diesel retrofits, which can increase fuel consumption and CO_2 emissions by several percent, and biodiesel, which may increase NO_x emissions up to 10 percent, depending upon the blend percentage (although this effect has not been definitively demonstrated for advanced diesel engines as of yet). Finally, aldehyde emissions are projected to increase associated with ethanol use, as well methane emissions associated with natural gas use. Substantial uncertainty also surrounds technologies relying on grid electricity (e.g., truck stop electrification and plug-in hybrids), given the large variation in electrical generating unit (EGU) emissions by region of the country and time of day. EGU emissions also are expected to decrease over time as older units are retired and cleaner units are brought on line, diminishing this particular concern in the future.

The review of the available literature found a wide range of cost-effectiveness estimates for the different technologies, depending upon assumed mileage, useful life, among other factors. The U.S. EPA acknowledges that the determination of "acceptable" cost-effectiveness levels will vary dramatically depending upon a region's attainment status, its source mix, and the baseline level of controls in place. Accordingly, EPA does not provide specific guidelines for determining reasonable cost-effectiveness ranges. However, two regional programs, California's Carl Moyer program and the Texas Emission Reduction Program (TERP), employ a cost-effectiveness target of about $13,000 to $16,000 per ton of pollutant controlled in order to qualify for funding.[15]

Based on these criteria, several of the strategies evaluated in the previous section appear to have favorable cost-effectiveness, including idle reduction, vehicle inspection and maintenance, and PM retrofit options. However, depending upon the remaining useful life of the vehicle, accelerated retirement may provide a more favorable cost-effectiveness, especially for NO_x reductions. In general, the adoption of alternative fuels does not appear to be as cost-effective at criteria

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[15] The Carl Moyer program calculates emissions as NOx + ROG + PM10. The cap has been revised over time to account for inflation, with a most recent value of $16,000 (CARB, Carl Moyer Program Guidelines, approved revision April 2008). The TERP program only includes NO_x reductions (Texas Council on Environmental Quality, Texas Emission Reduction Plan, http://www.epa.gov/oar/caaac/pdfs/TERP-06-04.pdf).

pollutant reduction as many other vehicle and fuel technology strategies. Similarly, strategies primarily targeting fuel consumption and CO_2 reduction do not appear to offer substantial incremental benefits in criteria pollutant reductions, although plug-in hybrid and battery electric vehicle options may prove cost-effective in this regard in the long run, depending upon a number of factors as discussed above.

5.0 Weighting Methods

When evaluating the cost-effectiveness of multiple pollutants it often becomes necessary to weight the pollutants to combine them into one composite cost-effectiveness. This is especially true in areas where there is more than one pollutant of major concern (such as areas in nonattainment for more than one pollutant). While weighting schemes often depend on these local conditions there are several factors to be considered that are common across all areas of the country, such as health costs, precursor versus direct emissions, and progress towards attaining national air quality standards.

The 2002 TRB report used a weighting of VOC:NO_x:PM_{10} of 1:4:0. This weighting, which was decided by the report committee, attempted to consider a number of factors, such as "the health impacts of particular pollutants, which pollutants currently are most crucial in attaining ozone standards, and even secondary effects, in which one pollutant contributes to the level of another that may not be well estimated." At the time of the report, particulate matter had not been regulated yet; therefore, the committee decided on a weighting of zero for PM. Also, while the study chose a zero weight for CO based on major progress towards eliminating CO problems, it notes that "air quality agencies have typically directed that CO emissions be weighted at one-seventh the value of the other pollutants when assessing strategy impacts on total emissions." The TRB study also used alternative weighting schemes of 1:1 and 1:8 for VOC:NO_x to evaluate the sensitivity of the results to weighting. Several other studies reference the weightings from the TRB study, such as the EPA's 2007 report on heavy-duty diesel retrofits, which cited the TRB report and the fact that "ozone levels in many nonattainment areas are more dependent on NO_x than on VOCs" as its reasoning for choosing the VOC:NO_x ratio of 1:4. The ratio values for these studies are shown in Table 5.1.

The California Air Resources Board (CARB) has for many years provided standardized methodologies for calculating the cost-effectiveness of transportation emission reduction projects funded by state motor vehicle fees, the CMAQ program, and other sources. CARB defines cost-effectiveness as dollar per ton of pollutant reduced, where pollutants are the sum of NO_x, ROG, and PM_{10} (unweighted).[16] California's Carl Moyer program, which funds

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[16] California Air Resources Board (2005). *Methods to Find the Cost-Effectiveness of Funding Air Quality Projects.*

incremental costs for cleaner vehicles and equipment (primarily diesel engines) also calculates cost-effectiveness based on emissions of NO_x + ROG + PM_{10}.[17]

Health-related medical expenses of exposure to pollutants are often used to quantify the value of damages prevented by emission reduction strategy. McCubbin and Delucchi (1999) authored an authoritative and often cited study of the health costs of $PM_{2.5}$, NO_x, VOC, and CO. Kaiser and d'Abadie (2008) interpreted the McCubbin and Delucchi data to show the health costs associated with one ton of VOC, NO_x, and $PM_{2.5}$ emissions to be in an approximate ratio of 1:16:152. Westcott (2005) uses a combination of the TRB (2002) study and the McCubbin and Delucchi data, for which he presented a different interpretation that makes the conservative assumption that all CMAQ projects remove the more damaging pollutant NO_x. Kaiser and d'Abadie (2008) interpret this as a weighting scheme for VOC, NO_x, and $PM_{2.5}$ to be 1:4:9.45. The ratio values for these studies are shown in the second section of Table 5.1.

The New York State DOT's draft CMAQ program guidance[18] also uses health effects as the basis for a proposed weighting system. An "emission score" is proposed to determine the eligibility of, and potentially to rank, CMAQ projects in multiple pollutant nonattainment areas. The score is based on health costs from McCubbin and Delucchi (1999). The guidance cites estimated health care costs of $109,000 for a ton of $PM_{2.5}$, $91,272 for a ton of PM_{10} $11,332 for a ton of NO_x, $718 for a ton of VOCs, and $50 for a ton of CO. The weighting factors for CO, VOC, NO_x, PM_{10} and $PM_{2.5}$ are therefore 0.07:1:16:127:152, respectively.

There are a number of studies on local projects, such as inspection and maintenance programs, that provide weighting ratios used to calculate cost-effectiveness of that particular project. It should be noted that these are based on judgment of local conditions, and should be used with caution when applying them on a national basis. The ratio values for these studies are found in the third section of Table 5.1.

None of the studies available on vehicle emissions reduction strategies provided weighting ratios for greenhouse gas emissions versus other pollutants. However, two sources were found that provide weighting between conventional air pollutants and greenhouse gases for the purpose of evaluating the environmental performance of passenger vehicles to inform consumers when purchasing a vehicle. The American Council for an Energy Efficient Economy (ACEEE) assumed that "approximately half of the overall environmental harm [of passenger vehicles] is associated with global warming risks and the other half is associated with the health effects of conventional air pollutants." The

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[17] California Air Resources Board (2008). *Carl Moyer Program Guidelines*, approved revision April 2008.

[18] New York State Department of Transportation (2010). NYSDOT CMAQ Guidance. Unpublished draft, still undergoing review.

Batterman article made a similar assumption based upon "the potential magnitude and consequence of (but also great uncertainties) of impacts related to energy consumption and greenhouse gas (GHG) emissions," but chose 40 percent for greenhouse gases, 50 percent for conventional pollutants, and assigned the remaining 10 percent to solid waste generation, which are taken out of the calculation for this study's purpose. The ratio values for these two studies are found in the last section of Table 5.1.

Table 5.1 Weighting Ratios from Literature Sources

Source	Based on	VOC	NO_x	$PM_{2.5}$	PM_{10}	CO	CO_2e	Toxics
Committee (Multiple Factors Considered)								
TRB, 2002 (Standard Case)	Committee deliberations on multiple factors	1	4	–	0	0	–	–
TRB, 2002 (Alternative 1)	Chosen to evaluate sensitivity of results to weights	1	1	–	–	0	–	–
TRB, 2002 (Alternative 2)	Chosen to evaluate sensitivity of results to weights	1	8	–	–	0	–	–
U.S. EPA, 2007	TRB (2002) and author judgment on ozone formation	1	4	–	–	–	–	–
Health Costs								
d'Abadie and Kaiser, 2008	McCubbin and Delucchi, 1999	1	16	152		–	–	–
d'Abadie and Kaiser, 2008 citing Westcott, 2005	McCubbin and Delucchi, 1999 and TRB (2002)	1	4	9.45	–	–	–	–
Local Projects								
CARB Guidelines for California Air Quality Projects	Staff Judgment	1	1	–	1	–	–	–
SBCAPCD, 2006	Judgment on Local Project	1	1	–	–	–	–	–
RAND, 2001	Judgment on Local Project	1	1	–	–	–	–	–
Harrington, 1999: A Weights	Judgment on Local Project	1	2.5	–	–	0.1	–	–
Harrington, 1999: B Weights	Judgment on Local Project	1	1	–	–	0.1	–	–
NAS, 2001	Judgment on Local Project Found in IMRC (1993)	1	1	–	–	0.14	–	–
NYSDOT, 2010 (Draft)	McCubbin and Delucchi, 1999	1	16	152	127	0.07	–	–
Greenhouse Gases								
ACEEE, 2009	Author Judgment	1					1	–
Batterman, et al., 2001	Author Judgment	5					4	–

6.0 Survey of Practitioners

Transportation and air quality agencies in every state perform some evaluation of air quality projects, usually forecasting of emission reduction impacts of potential air pollution control strategies, since such estimates are required as a condition for CMAQ funding and may be needed to demonstrate attainment of a particular pollutant. A survey was conducted to identify agencies that have developed more rigorous cost-effectiveness evaluation procedures and methods for making tradeoffs among different pollutants. The survey was conducted in two stages. The first stage was a basic web-based survey that was distributed to CMAQ program managers and transportation air quality conformity specialists at state DOTs and MPOs. Since it was difficult to obtain a single e-mail list of these individuals, specific states and regions that are in nonattainment for multiple pollutants were targeted. In depth follow up interviews were conducted for a handful of respondents that indicated their use of advanced evaluation procedures.

6.1 WEB-BASED SURVEY METHODOLOGY

Several steps were followed to conduct the web-based survey.

- A list of nonattainment areas for ozone, $PM_{2.5}$, and CO was compiled. Information on the corresponding MPO,[19] whether the MPO has conducted a GHG inventory,[20] and state level GHG planning[21] was added to the list. Areas in nonattainment for more than one pollutant or in nonattainment for one pollutant and with an MPO GHG inventory were selected for the survey. These selected areas are found in Appendix C.
- Contacts were found for the MPO and state DOT for the selected areas. Air quality and planning staff were located using lists from the Federal Highway Administration (FHWA),[22] U.S. DOT,[23] and American Association of State

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[19] Association of Metropolitan Planning Organizations, http://www.AMPO.org, accessed November 2009.

[20] Federal Highway Administration, Highways and Climate Change Report. Lists transportation-related GHG inventories either completed or underway. http://www.fhwa.dot.gov/HEP/climatechange/chapter_five.htm, accessed November 2009.

[21] Center for Climate Strategies (CCS) listing of state climate action plans that are completed or underway. http://www.climatestrategies.us/, accessed November 2009.

[22] http://www.fhwa.dot.gov/environment/cmaqpgs/safetealu1808/appendix_a.htm.

[23] http://www.planning.dot.gov/mpo.asp.

Highway and Transportation Officials (AASHTO)[24] and supplemented through visits to agency web sites and phone calls. E-mail addresses for each contact were collected from these resources. The list of contacts to which e-mails were sent is found in Appendix C.

- A brief list of questions was composed to help determine which agencies make tradeoffs among pollutants or have a unique method of weighting pollutants for emissions evaluations. The questions were posted on a web site survey tool. They are listed in Appendix D.
- A brief e-mail to introduce the project and request the recipients to complete the survey on-line was composed, and can be found in Appendix E. The e-mail was sent to 43 recipients on December 1, 2009 and they were asked to respond within two weeks.

6.2 WEB-BASED SURVEY RESULTS

Eighteen responses were received from the 43 individuals that were contacted to fill out the web-based survey, which yields a response rate of about 42 percent. Additionally, the North Central Texas Council of Governments (NCTCOG, the MPO for Dallas-Fort Worth, Texas) and the Pima Association of Governments (Tucson, Arizona) provided responses once they were contacted separately due to their known advanced transportation planning methods. This yielded a total of 20 responses. The following summarizes the responses; but detailed responses by agency can be found in Appendix E.

Figure 6.1 shows responses about the pollutants that an agency considers in their transportation plan, program, or project evaluation. Eleven of the respondents replied that they consider the following four criteria pollutants: HC, CO, NO_x, and PM. Eight respondents said that their agency considers greenhouse gases. Seven out of these eight that consider greenhouse gases are MPOs, and they are from a variety of geographic locations, including New York, California, Illinois, Connecticut, Texas, and Washington, D.C. Only three agencies said that they consider air toxics, including the Virginia DOT, Connecticut DOT, and NCTCOG.

As shown in Figure 6.2, only seven of the 20 respondents said that they consider tradeoffs among pollutants when evaluating transportation control strategies. One respondent said they were not sure, but went on to answer the corresponding Question 2a.

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[24] http://planning.transportation.org/Pages/Members.aspx.

Figure 6.1 Pollutants Considered

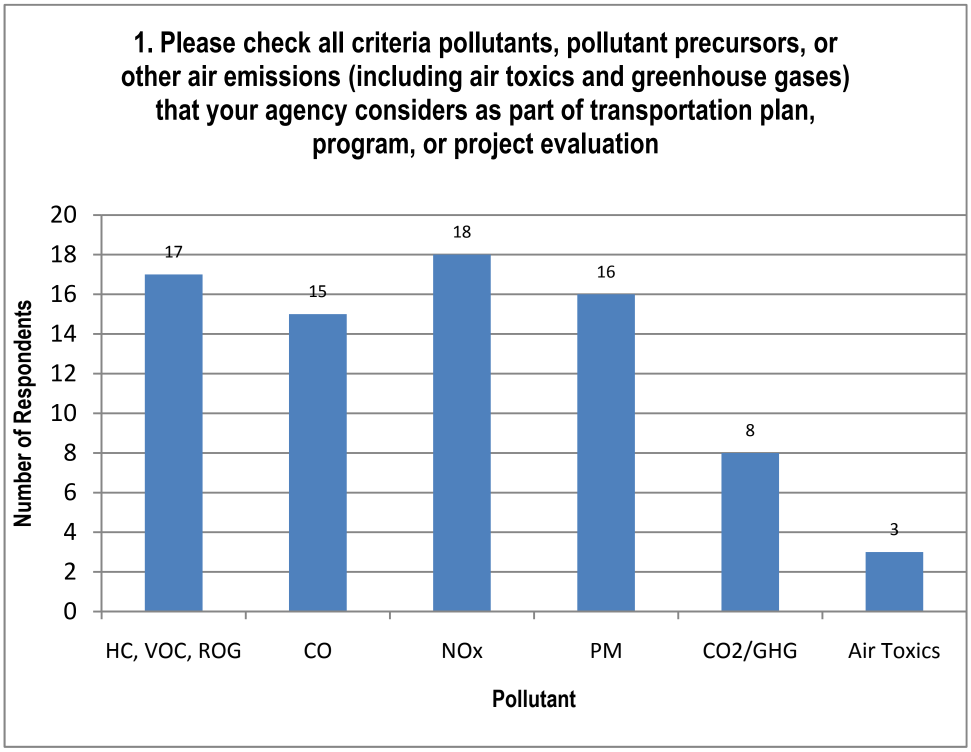


Figure 6.2 Consideration of Tradeoffs

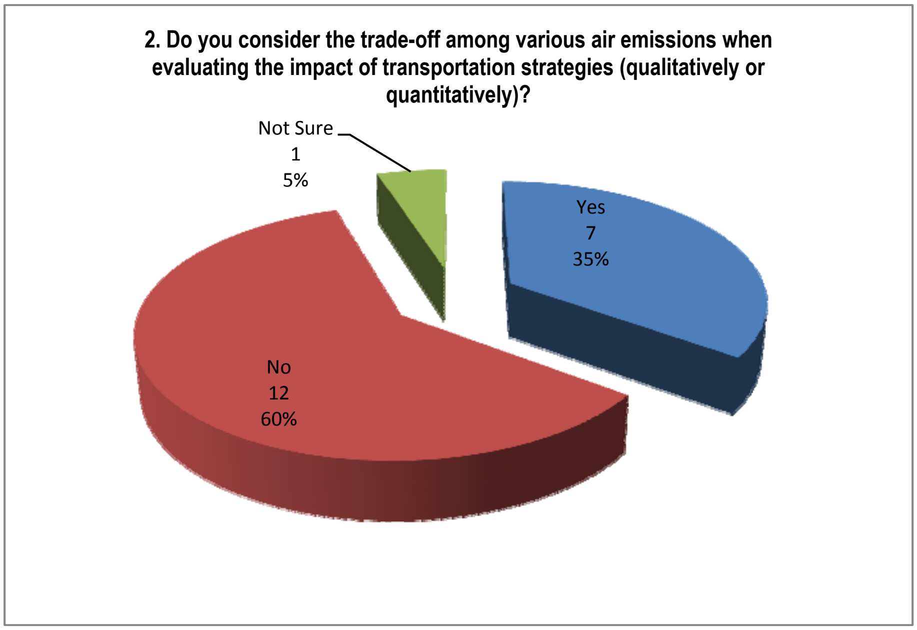


Figure 6.3 shows the type of activity supported by the emission reduction strategy evaluation. All but one of the respondents that said they consider tradeoffs among various air emissions said that this evaluation supports their CMAQ program. For several it also supported another program, such as Transportation Improvement Program (TIP) project selection, conformity analysis, State Implementation Plan (SIP) Transportation Control Measure (TCM) analysis, or a GHG inventory. The "other" responses received were National Environmental Policy Act (NEPA) documentation and clean vehicle/alternative fuel project selection.

Figure 6.3 Activity Supported by Emission Reduction Strategy Evaluation

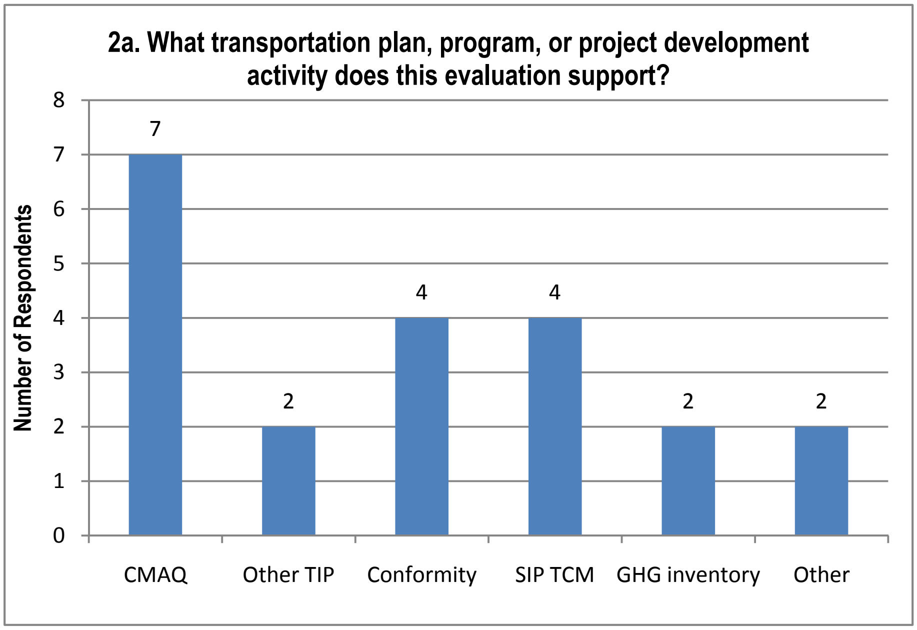
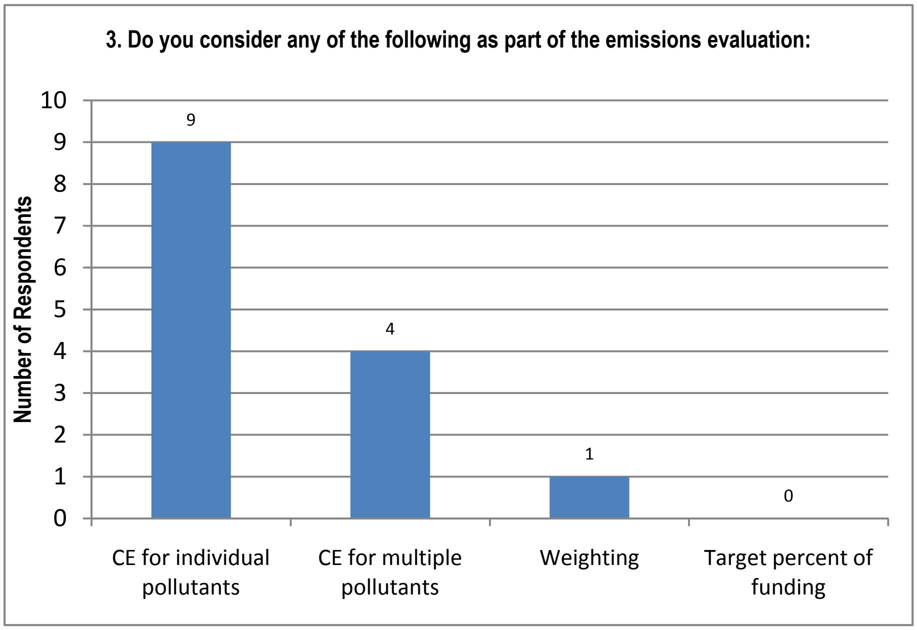


Figure 6.4 shows methods used to consider multiple pollutants, either separately or combined. Almost half of the respondents said they consider cost-effectiveness (CE) separately for individual pollutants, but only five said that they some way of considering multiple pollutants together through a combined cost-effectiveness or weighting. The agencies that have a combined CE for multiple pollutants include MPOs in Sacramento, California; San Diego, California; and Phoenix, Arizona. The Georgia DOT indicated in the survey that they used a combined CE, but during a follow up call it was discovered that they do not. The New York metropolitan area uses a weighting methodology from the New York State DOT, which is not publicly available yet.

Figure 6.4 Methods of Incorporating Multiple Pollutants into Emission Evaluation



6.3 IN-DEPTH INTERVIEWS

After conducting the web-based survey the following respondents were identified as having conducted relevant work on multipollutant evaluation and were contacted to inquire further about their methods.

- Georgia DOT – Phil Peevy;
- New York Metropolitan Transportation Council (NYMTC) – Angelina Foster;
- Southern California Association of Governments (SCAG) – Rongsheng Luo;
- Virginia DOT – Kanathur Srikanth;
- Sacramento Area Council of Governments (SACOG) – Jason Crow;
- Maricopa Association of Governments (MAG) – Cathy Arthur;
- Missoula Office of Planning and Grants – Ann Cundy;
- San Diego Association of Governments (SANDAG) – Elisa Arias; and
- Poughkeepsie-Dutchess County Transportation Council – Eoin Wrafter.

Staff from other agencies that were identified as leaders in the field also were contacted for an in-depth phone interview whether or not they had responded to the survey:

- North Central Texas Council of Governments (NCTCOG) (Dallas-Fort Worth, Texas) – Carrie Reese;
- Houston-Galveston Area Council (HGAC) – Shelley Whitworth;
- Pima Association of Governments (PAG) (Tucson, Arizona) – Lee Comrie; and
- Metropolitan Washington Council of Governments (MWCOG) – Daivamani Sivasailam.

Five of these 13 contacts were ultimately reached. The following questions were asked during the in-depth interviews:

- What **procedures or methods** do you use for evaluating the effectiveness and **cost-effectiveness** of transportation air quality control projects? What pollutants do you evaluate, and why?
- How do you prioritize or make **tradeoffs** among different pollutants? (For example, do you **weight** them in a certain way? **Prioritize** one particular pollutant of concern? Why did you arrive at this system?
- Have there been any particular emission reduction **strategies** where it has been difficult to make tradeoffs compared to other strategies?
- How are you incorporating the consideration of **greenhouse gas** impacts into the evaluation of projects that have traditionally been focused on air pollutant reductions?
- What additional information (data, analytical tools, procedures, etc.) **would help you** better understand the tradeoffs among various pollutants and prioritize/make decisions about projects?

Information gathered from each of the in-depth interviews along with the web-based survey, documents linked from the web-based survey, and other research is summarized in the following profiles of individual metropolitan areas.

Sacramento, California

The six-county Sacramento metropolitan area is in nonattainment for ozone and PM_{10} (one county). They expect to reach attainment and become a maintenance area for PM_{10} soon. Part of the area also is a CO maintenance area. To calculate the cost-effectiveness of ozone, PM_{10}, and CO emissions reductions strategies funded under CMAQ, SACOG uses the California Air Resources Board (CARB) cost-effectiveness analysis tool database.[25] This tool automatically calculates a combined cost-effectiveness for ROG, NO_x, $PM_{2.5}$ or 10, and CO using equal weights for the first three pollutants and 1/7th weight for CO. Appendix F shows a screenshot of the Microsoft Access-based tool and lists the inputs required by

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[25] http://www.arb.ca.gov/planning/tsaq/eval/eval.htm.

strategy, which typically include funding dollars, number of operating days per year, VMT of new and replaced service, and other operational parameters, such as speed.

In addition, California Senate Bill 375 requires the evaluation of greenhouse gas benefits of several strategies, but this analysis occurs as part of the regional transportation plan separately from the CMAQ process. SACOG is evaluating packages of greenhouse gas reduction strategies, such as land use, TSM, TDM, and pricing. They are using their travel demand model, which was recently upgraded to be activity-based, to evaluate the emission reduction benefits of these strategies. They are overall very pleased with the improved model's analytical abilities, which may suggest that such an activity-based travel demand model would improve the analytical abilities of other areas.

San Diego, California

The San Diego metropolitan area is in nonattainment for ozone and is a CO maintenance area. Like SACOG, SANDAG uses the CARB cost-effectiveness analysis tool database to calculate the cost-effectiveness of ozone and CO emission reduction strategies funded under CMAQ. In addition, due to California Senate Bill 375, greenhouse gases will be considered in the next regional transportation plan, which will be completed in 2011. SANDAG is awaiting state guidance on evaluation methods for greenhouse gases. They currently have a Climate Action Strategy, which essentially provides a menu of different greenhouse gas reduction strategies, but does not quantify emission reduction benefits or cost-effectiveness.

SANDAG mentioned a few strategies for which it is particularly difficult to estimate emission reductions using the currently available modeling tools. In particular, the Safe Routes to School Program, Last Mile Bike Share Program, and Bike Facilities/Infrastructure Programs are difficult to estimate because of the lack of inclusion of a nonmotorized mode in the trip assignment portion of the travel demand model. They find it difficult to estimate how many vehicular trips are diverted by these bike and pedestrian trips.

Phoenix, Arizona[26,27]

MAG serves as the MPO for the Phoenix, Arizona metropolitan area, which currently is in nonattainment for both ozone and PM_{10}. MAG is somewhat unique because in addition to air quality conformity and CMAQ funding, it also is responsible for SIP planning. In 2005 MAG began using a weighting methodology to calculate emissions reductions and cost-effectiveness for CMAQ

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[26] Maricopa Association of Governments. *Methodologies for Evaluating Congestion Mitigation and Air Quality Improvement Projects*. April 16, 2009.

[27] Interview with Cathy Arthur. Maricopa Association of Governments. February 12, 2010.

projects. At the time when attainment of the 0.08 parts per million (ppm) ozone standard seemed imminent, ozone precursors (NO_x and total organic gases, or TOG) were weighted at half of PM_{10}. Later, in 2009 when a proposed lower ozone standard of 0.075 ppm (which is now proposed at 0.060-0.070 ppm) threatened to keep Phoenix in nonattainment for ozone, the weightings were revised to be equal for NO_x, TOG, and PM_{10}. These equal weights are assigned by setting the weighted emission rates for NO_x and TOG equal to that of PM_{10} and calculating the priority weighting to achieve that as shown in Table 6.1. During both time periods CO and $PM_{2.5}$ received a weight of zero since Phoenix attains the standards for those pollutants. Emission rates for ozone precursors (TOG and NO_x) have always been seasonally adjusted by dividing by two to account for the six-month ozone season.

Table 6.1 Phoenix Area Weighting

Pollutant	2008 Light-Duty Vehicle Emission Rates	Priority Weight	Weighted Emission Rates
CO	8.47 grams/VMT	0.00	0.00 grams/VMT
TOG	0.76 grams/VMT	0.89	0.68 grams/VMT
NO_x	0.66 grams/VMT	1.03	0.68 grams/VMT
PM_{10}	0.68 grams/VMT	1.00	0.68 grams/VMT

While this weighting is used in cost-effectiveness calculations, which directly ranks the projects, modal committees consider this ranking along with other qualitative criteria for the final allocation of CMAQ funds. It also should be noted that due to the requirements from a half-cent sales tax for transportation approved by voters, CMAQ funding is split into categories, such as bike/ped and freeway management, based on percent allocations in the voter referendum. Therefore, emission reduction projects seeking CMAQ funding in the Phoenix area only compete against other projects in the same category, except during the closeout funding period when all CMAQ eligible projects compete against each other for funds leftover at the end of a funding cycle.

MAG has no immediate plans to incorporate greenhouse gases or air toxics into their evaluation procedure, although they may consider it in the future. Overall, MAG is confident in their evaluation procedures, but they would like to improve their evaluation of intelligent transportation systems (ITS) projects. They realize that their current method for estimating emissions from these projects is weak because they do not consider how speed increases could possibly increase emissions. They currently are contracting with Texas Transportation Institute (TTI) to create a sketch-planning type of methodology to improve their ITS emissions estimate method. In addition, they plan to study in-house the new speed versus emission rate curves from MOVES2010, especially for particulate matter, which was not dependent on speed in MOBILE6. They also are interested in the results for CO and NO_x since some projects that increase speed increase CO and NO_x, which results in a negative cost-effectiveness. They plan to incorporate their findings from this into their evaluation methods for a number of emission reduction strategies that affect speed.

Atlanta, Georgia

The Atlanta metropolitan area currently is in nonattainment for both ozone and $PM_{2.5}$. In the past, CMAQ funding has been allocated for ozone and PM reduction projects separately due to the area's specific nonattainment history. In 2008 there was a call for projects with $PM_{2.5}$ reduction benefits to address the 2004 $PM_{2.5}$ nonattainment designation and to take advantage of evidence from the Federal government of diesel retrofits being a very cost-effective strategy for particulate matter. Before that time all CMAQ funding went to projects that reduced ozone. Responsibility for the CMAQ program in the Atlanta area has been transferred from the MPO for the region, the Atlanta Regional Commission (ARC), to the Georgia Department of Transportation (GDOT), which conducted the 2008 call. In the future, GDOT plans to combine ozone and particulate matter CMAQ calls for projects.

GDOT does not use a weighting scheme, but instead has developed a project selection matrix in coordination with a number of other regional agencies (see Appendix G). This matrix has five categories of project types, each with a group of high-, medium- and low-priority strategies based on the anticipated emission benefit and cost-effectiveness. For the 2008 call for $PM_{2.5}$ reduction projects TDM and Bike/Ped projects were excluded (therefore shown in grey on the matrix) because they were believed to have a lesser effect on reducing $PM_{2.5}$ compared to the remaining categories of traffic flow/ITS, alternative fuel/diesel retrofits, and transit/diesel retrofits. This matrix has been especially helpful for projects that do not submit any emission reduction or cost-effectiveness estimates. It is meant to serve as a guide to assist the project selection committee, but is not the sole determinant.

When asked about additional information that would help the ARC better understand the tradeoffs among various pollutants, staff responded that they were trying to understand the effects of inspection/maintenance (I/M) programs on greenhouse gases. In particular, they had read that the production of nitrous oxide (N_2O) emissions can increase by a factor of up to 10 to 16 times due to aging of the catalytic converter.[28] They investigated both the MOBILE6 and MOVES model to see if the EPA had modeled any of these types of effects in the I/M portion of the program, but found that it only included I/M effects on criteria pollutants. More research into the impact of I/M programs on greenhouse gases may be warranted to inform local agencies in the future.

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[28] http://www.arb.ca.gov/cc/non-co2-clearinghouse/technology/b-2-1.pdf.

Missoula, Montana

Missoula, Montana is a PM_{10} nonattainment area and CO maintenance area. Therefore, more emphasis is placed on PM_{10} emission reduction strategies, such as street sweepers and paving unpaved roads. The Missoula Office of Planning and Grants provides some analysis of the benefits of strategies, but there are not enough resources to provide a rigorous quantitative method. Generally, the three entities eligible for CMAQ funding (city, county, transit agency) meet and match the available funding to proposed emission reductions projects for the area. The three entities generally agree on the relative benefits of each emission reduction strategy.

Summary of Other Cities

Several other cities offered some interesting perspectives through their web-based survey or by brief e-mail correspondence, but could not be reached for an in-depth telephone interview. The following contains the facts learned about these:

- New York, New York (NYMTC) – The MPO's CMAQ solicitations have always considered dollars per ton or dollars per kilogram for project selection. New weighting is proposed in the MPO's draft NYSDOT CMAQ guidance, but this has not been formally adopted by the MPO.
- Washington, D.C. (MWCOG) – Cost-effectiveness is estimated for individual pollutants and the most cost-effective measures selected based on the pollutants that most need reduction.
- Tucson, Arizona (PAG) – The MPO evaluated the cost-effectiveness of various measures in the late 1990s in anticipation of potential ozone nonattainment status. The area is likely to be designated nonattainment in the future with strengthened ozone standards. They will need to look at both VOCs, and NO_x given the regional atmospheric chemistry, but are not sure what method they will use. They have made regional estimates of on-road mobile emissions for CO, VOCs, and NO_x using MOBILE6.2.
- Houston-Galveston, Texas (HGAC) – The agency constantly analyses the cost-effectiveness of projects. Primary interest is in NO_x, with secondary interest in VOC. The agency prioritizes NO_x because the region is NO_x limited in photochemical modeling of ozone formation. It is difficult to make tradeoffs for Transit Pilot Projects because they must balance congestion mitigation and emission reductions. They are in the early stages of studying greenhouse gas emissions.

7.0 Information Gaps

7.1 INTRODUCTION

Sections 3.0 and 4.0 of this report documented emission benefits and cost-effectiveness estimates for a variety of multipollutant emission reduction strategies as found in available literature sources. In this section we compile this information into a matrix of transportation emission control strategies to identify uncertainties in benefit and cost information for these strategies. For each emission reduction strategy we characterize:

- The direction of impact on emissions;
- The magnitude of impact on emissions where available; and
- The level of confidence in cost-effectiveness estimates available.

Then we explain the key uncertainties that led to low or moderate levels of confidence in emissions impacts and cost estimates. The uncertainties fall into three general categories:

- **Technological Uncertainties –** A lack of certainty on the extent to which the vehicle or fuel technology reduces emissions of a given pollutant. For example, some advanced engine emission control technologies have not be fully researched, and some pollutants (such as $PM_{2.5}$) have seen less focus in data collection and modeling.
- **Strategy Implementation Uncertainties –** The impacts are highly dependent upon travel behavior impacts or the system operating context. For example, HOV or HOT lane conversions may increase or decrease emissions, depending upon how congested the general-purpose lanes are before and after the conversion, as well as the extent to which the strategies effect a mode shift to higher occupancy vehicles.
- **Time-Dimension Uncertainties –** The magnitude of impact on emissions and costs may change over time for some strategies. This is especially true for vehicle and fuel technology strategies, as technology costs decrease over time and benefit from economies of scale as the technologies gain larger market shares. On the other hand, strategies that target the current fleet of vehicles, such as diesel engine retrofits, become less effective over time as improved emissions control technologies are incorporated into new vehicles that slowly become part of the on-road fleet. Most TDM and TSM strategies also are likely to become less cost-effective over time, as technology improves and per-mile emission rates decrease. For GHG emissions, which are a cumulative (rather than episodic) pollutant, the magnitude of construction emissions also is a factor. Actions that require infrastructure construction,

which can involve a considerable amount of energy consumption, may have payback periods of years or even decades before the operational or VMT improvements are sufficient to offset the construction emissions associated with the action.

The matrix of transportation control strategies with this information is provided in Tables H.1, H.2, and H.3 in Appendix H. For TDM and TSM strategies (Tables H.1 and H.2), an assessment of uncertainty is provided only for cost-effectiveness, since the total effectiveness and total cost will depend upon the scale at which the strategy is implemented. For vehicle and fuel technology strategies (Table G.3), confidence ratings also are assigned for effectiveness and costs, where these are measured on a per-vehicle basis (i.e., percent emission reduction per vehicle, cost per vehicle). Level of confidence is assessed as follows:

- **Low –** Directionality uncertain (positive or negative impact);
- **Moderate –** Known within an order of magnitude; and
- **High –** Known within perhaps +/- 25-35 percent.

The remainder of this document provides explanations and discussions of the key uncertainties. We end by recommending methods for filling data gaps and/or reducing the uncertainty associated with the existing information.

7.2 TRANSPORTATION DEMAND MANAGEMENT STRATEGIES

VMT Reduction

Technological Uncertainties

There are few technological uncertainties associated with VMT reduction strategies, as the primary effect of these strategies is to reduce travel demand rather than changing emissions per vehicle. A few are worth noting, however.

Land use strategies have uncertainties associated with changes in local congestion due to higher densities in certain areas. Overall, land use strategies that aim to increase density and provide mixed uses should decrease emissions on a regional level due to shorter vehicular trips and the elimination of some trips all together. However, some areas that experience a great increase in density of development may experience local traffic congestion that reduces speeds. As discussed in the TSM Strategies section below, a change in vehicular speed may or may not increase emission rates. Therefore, while land use strategies should result in regional emission reductions for all pollutants, there may be some localized increases.

Park-and-ride facilities present an uncertainty in total emissions reduction due to the fact that a significant portion of total trip emissions from short vehicular trips are from start emissions. If a person goes out of their way (significantly increases their total trip distance) to reach a park-and-ride lot or if the transit portion of their trip is relatively short it is possible that the total emissions attributed to that person's total trip would only go down slightly or possibly even increase. In contrast, if the transit portion makes up a large part of their trip and the park-and-ride lot is not far off of their normal route, their total trip emissions could be significantly reduced.

Telework strategies have uncertainties surrounding the current and future costs of these strategies. Some studies have found to be telework to have low cost-effectiveness based on the capital costs required for telecommunication equipment and services. These costs are declining over time, however, and are likely to further decrease in the future, especially as broadband services experience more widespread market penetration. For some workers, costs may be minimal, while for others, they may be significant, depending upon their particular needs for computer and telecommunications equipment.

Strategy Implementation Uncertainties

As demonstrated in Section 3.0, many TDM strategies show a wide variation in reported cost-effectiveness depending upon the effectiveness and costs associated with the specific project or program. This is despite the fact that many TDM programs, such as areawide ridesharing, vanpooling, and employer-based trip reduction, have been around for decades and have therefore had much opportunity for evaluation.

TDM strategies that rely on marketing, outreach, and incentives may have very different impacts depending upon the size of the population reached, how effectively the information is provided, and the type or size of incentive provided. The impacts also will differ greatly depending upon contextual factors such as the availability and quality of alternative modes relative to driving, workplace characteristics (e.g., how conducive jobs are to alternative work schedules), and other influencing factors (e.g., cost of gasoline or parking). These factors all affect the response (participation) rate of the population reached. More generally, the effectiveness of several strategies whose main purpose is to reduce travel, such as employer-based and other TDM programs, general road pricing, and parking pricing, depend strongly on the availability of alternative transportation modes, such as transit infrastructure, as well as land use conditions in the area that support transit and nonmotorized travel. Finally, some TDM strategies (such as nonwork trip reduction) are fairly new and have not been extensively studied, while the effects of others (such as transit marketing and amenities) are nearly impossible to measure because they make a small incremental impact spread over a large population.

Because of all these factors, it can be difficult to safely generalize about any of these strategies. There are likely to be examples of cost-effective implementation of nearly every type of TDM strategy, as well as examples of ineffective implementation.

Travelers' responses to price signals are, in general, fairly well understood. However, the cost-effectiveness of TDM programs that rely on price signals, such as VMT fees, congestion pricing, and, parking pricing, depend on the method of administration and the amount of the fees or incentives. The more automated the implementation in terms of fee collection and enforcement, the lower the costs. Also, the fee level will greatly affect people's travel choices. Since the administrative cost is nearly independent of the fee level, programs with higher charges will result in greater cost-effectiveness per unit of administrative cost. This it is difficult to generalize about the cost-effectiveness of pricing strategies that have significant administrative costs.

Pricing strategies that are applied only to certain geographic areas or times of day can have very uncertain effects, because they could simply shift trips to other locations or times rather than reducing overall VMT. For example, parking pricing applied in one business district may have the effect of causing some people to go to a different location (perhaps farther away) to shop where parking is free.

There has been little research on the cost-effectiveness of land use strategies. It is generally agreed that direct costs (for planning, code enforcement, etc.) are small compared to the magnitude of travel and emissions affected. However, there is disagreement over what other costs and cost savings should be quantified, and how (e.g., reduced infrastructure costs from compact development, higher brownfields cleanup costs). On the effectiveness side, land use strategies have two general types of uncertainties. One of these is the effect of land use policies on development patterns. This can depend upon a variety of factors such as the strength of any land use policies adopted, legal and regulatory ability of the local government to enforce them, and whether there is a market for alternative forms of development. The second is the effect of development patterns on travel patterns. This depends upon factors such as the specific characteristics of the land use changes (density, mixing of uses, street connectivity, etc.); regional context of the land use changes (a single isolated high-density or mixed-use development in the midst of an auto-oriented suburb is likely to have little impact); and existence of supporting transit and nonmotorized infrastructure.

Pedestrian/bicycle programs and projects also have shown a very wide range of cost-effectiveness in practice. Their effects are highly dependent on the land use patterns surrounding the pedestrian/bicycle infrastructure. For example, people are unlikely to bike or walk to destinations further than a certain comfortable distance or through areas where they feel unsafe or even find unattractive.[29] Therefore, low-density land use with destinations far apart or where there are

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[29] A 2002 survey found that over 80 percent of bike trips are less than five miles in length and over 85 percent of walk trips were less than two miles in length. (Source: National Survey of Pedestrian and Bicyclist Attitudes and Behaviors, National Highway Traffic Safety Administration and Bureau of Transportation Statistics.)

not many other people around to provide a safe feeling are less likely to encourage walking and biking than high-density/mixed use areas. The quality of the facility also influences its usage. For example, multiuse trails with their own right-of-way are higher quality and would attract more users than bicycle lanes next to vehicular traffic on general roadways. Some facilities that are attractive for recreation, however, may serve few utilitarian trips (if they do not effectively connect people with key destinations) and therefore results in few emission reductions. Network effects also are important – the impact of a single bicycle lane, for example, may be proportionately much less than the collective impact of a citywide network of bicycle lanes. The most cost-effective pedestrian and bicycle improvements are likely to be in higher-density areas where there are significant gaps or deficiencies in existing nonmotorized infrastructure.

VMT Reduction Plus New Service

Technological Uncertainties

Some transportation demand management strategies shift travel to a different mode, such as from personal vehicles to transit vehicles or truck to rail freight, through the provision of additional alternative mode services. These include new or expanded transit service, vanpool programs, and freight rail/intermodal improvements. There is some uncertainty in predicting the emissions changes from these strategies due to the technological emission rate characteristics of the vehicles and fuels used before and after the strategy implementation. For example, when implementing transit strategies, the emission rate may vary for the transit vehicles depending on if diesel, natural gas, or hybrid-electric buses are used. Emissions from freight rail will depend upon the technology of the locomotive. If new vehicle technologies such as hybrid-electric buses are used, the emission rates and costs may be uncertain (see Vehicle and Fuel Technology Strategies section below).

For major capital investments (HOV lanes, transit facilities), life-cycle emissions, including facility construction and maintenance, have rarely been evaluated. Construction and maintenance emissions may, in some cases, significantly offset the savings in emissions from vehicle operations over the life of the project.

Strategy Implementation Uncertainties

For strategies involving new transit service as well as vanpooling, the greatest uncertainty is probably associated with the ridership or load factors on the transit or vanpool vehicles. Since transit vehicles have a higher emission rate than light-duty vehicles, it is important that the transit vehicles have a certain number of people riding so that the average emission rate per person is less than that of a single-occupancy light-duty vehicle. In underutilized transit routes it is very possible that more emissions could be produced by a few people riding a transit vehicle than if those few people each drove in a separate car. The specific load factors achieved will be highly dependent upon factors relating to the service provided and its context. Another source of uncertainty for transit and vanpooling strategies is the previous mode taken by the new riders. If a person moves from a single occupant vehicle to transit, it is likely that they helped reduce emissions, but if vanpoolers are formerly transit riders, or transit riders are diverted from another transit service, no emissions benefit is achieved. The prior mode of travel of transit riders also has been found to vary greatly depending upon the project context. Because of these factors it is hard to generalize regarding cost-effectiveness for new transit service.

There is little empirical evidence on the freight mode-shifting impacts of rail or intermodal improvements, and therefore very little evidence on which to judge cost-effectiveness. The ability to shift freight from truck to rail may vary widely depending upon the local economy and origins and destinations of goods moved, as well as the extent to which the existing rail infrastructure is deficient. Furthermore, the logistics and system efficiencies also must be considered when comparing rail to trucking. Rail systems cannot provide the door-to-door service that trucking can and often must send goods to central processing facilities/ warehousing locations first, increasing the total distance traveled by the goods. A truck trip is often required to access a rail terminal, and there are handling costs at each interchange point. Movement by rail is therefore typically cost-effective to the shipper only for longer-haul, lower-value, non-time-sensitive goods. Intermodal improvements are likely to be cost-effective from an emission reduction standpoint only if there is a significant untapped local market for rail-based goods movement "at the margin" – i.e., that can be affected by a public investment in rail or intermodal facilities.

7.3 TRANSPORTATION SYSTEM MANAGEMENT STRATEGIES

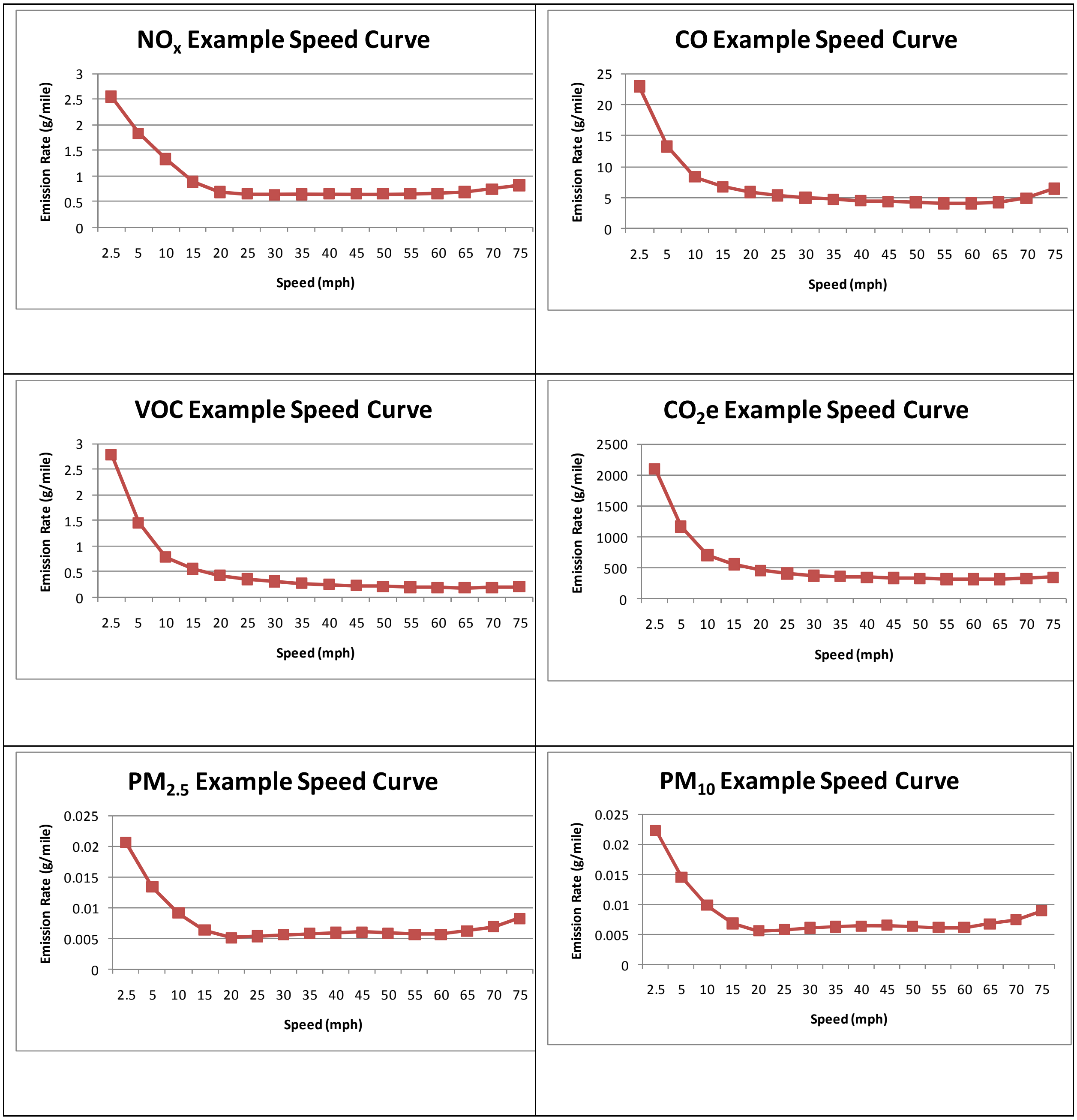
Congestion Relief

Technological Uncertainties

Congestion relief strategies impact emissions by changing speeds and acceleration/deceleration patterns. Emissions models such as the U.S. EPA MOBILE and MOVES models, and the California Air Resources Board's EMFAC model, use relationships between average speed and emission rate for each pollutant. Speed-emissions relationships usually resemble a U shape or L shape with higher emission rates at low speeds, lower emission rates at middle speeds, and steady or higher emission rates at high speeds depending on the pollutant. Examples from EPA's new MOVES model (2010 release) are shown in Figures 7.1 and 7.2 for six pollutants, for urban restricted access roadways (freeways and expressways). Figure 7.1 shows emission rates for light-duty vehicles while Figure 7.2 shows emission rates for heavy-duty vehicles.

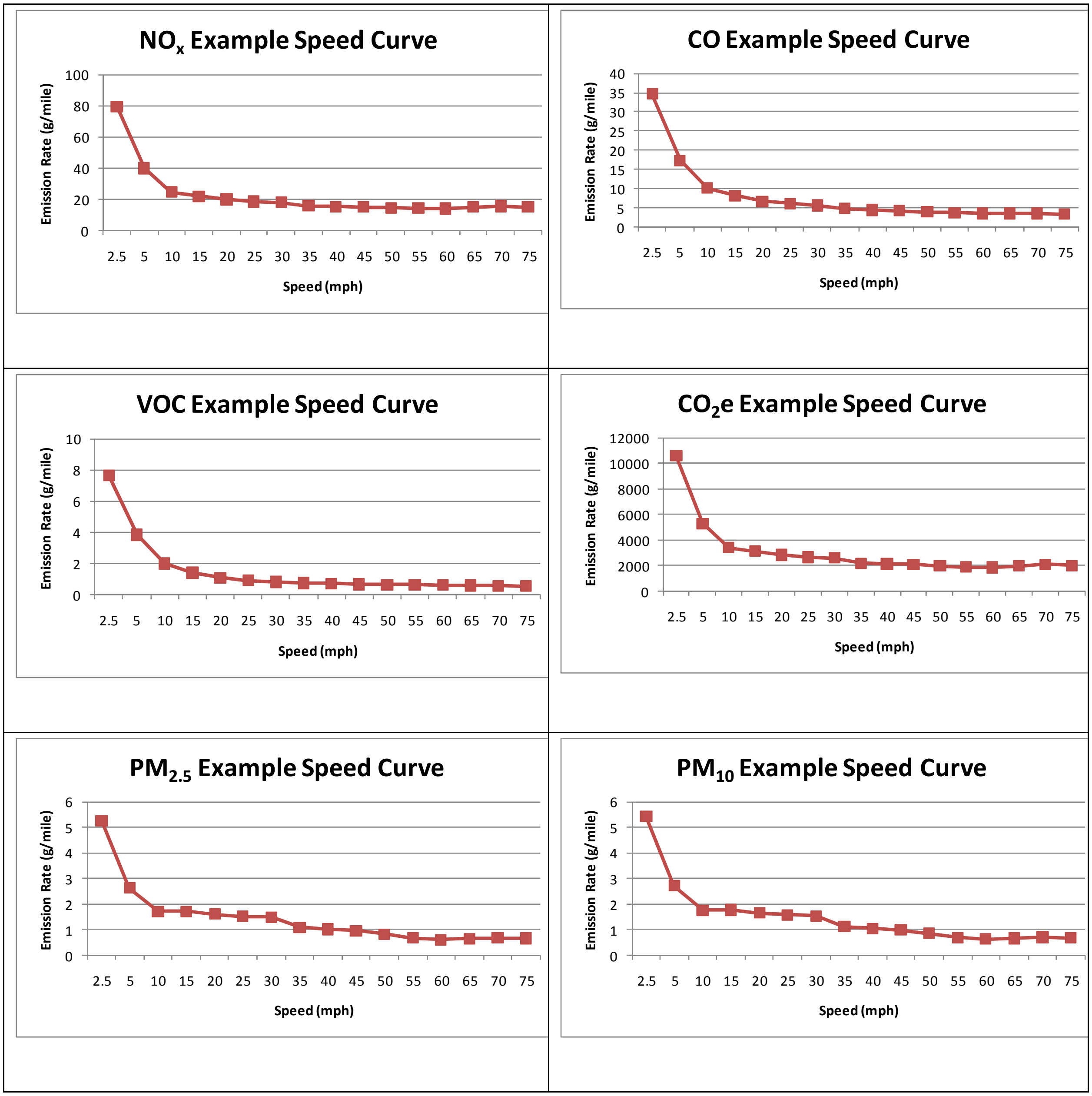
Figure 7.1 Example MOVES Speed versus Emission Rate Curves

Light-Duty Vehicles



Source: Emission rates taken from MOVES2010 run for Hillsborough County, Florida for passenger cars on urban restricted access roadways.

Figure 7.2 Example MOVES Speed versus Emission Rate Curves
Heavy-Duty Diesel Vehicles



Source: Emission rates taken from MOVES2010 run for Hillsborough County, Florida for combination long-haul trucks on urban restricted access roadways.

These relationships are established using vehicle test procedures conducted by EPA. The MOBILE model (EPA's predecessor to MOVES) included emission rates that vary by speed for VOC, CO, and NO_x, but did not vary the rates by speed for PM or CO_2. Since the vehicle test procedures that produced the emission rates for MOBILE were limited in nature, the emission rates were updated for MOVES using data from inspection and maintenance (I/M) programs around the country for VOC, CO, and NO_x and from a study of 496 light-duty cars and trucks conducted in Kansas City for PM.

Tables 7.1 and 7.2 show the percent difference in emission rate by speed versus the minimum emission rate for each pollutant, for light-duty vehicles. Table 7.1 shows this information for urban restricted access roads (consistent with Figure 7.1) and Table 7.2 shows this information for urban unrestricted access roads. The minimum emission rate for each pollutant is indicated by a bold 0 percent entry. The location of this minimum emission rate at different speeds for different pollutants reinforces the known tradeoff between pollutants for strategies impacting speed.

Table 7.1 Percent Difference versus Minimum Emission Rate
Urban Restricted Access – Passenger Cars

Speed (MPH)	VOC	CO	NO_x	PM_{10} and $PM_{2.5}$	CO_2
2.5	1,407%	470%	304%	301%	578%
5	686%	229%	190%	161%	276%
10	323%	107%	111%	77%	126%
15	199%	68%	40%	23%	78%
20	130%	46%	9%	0%	47%
25	92%	32%	3%	4%	30%
30	67%	23%	0%	9%	19%
35	49%	17%	1%	12%	14%
40	35%	12%	2%	15%	11%
45	24%	8%	3%	17%	8%
50	15%	5%	3%	14%	5%
55	8%	1%	3%	10%	2%
60	2%	0%	4%	11%	**0%**
65	0%	5%	9%	21%	1%
70	2%	21%	18%	34%	5%
75	11%	61%	29%	60%	11%

Source: Emission rates taken from MOVES2010 run for Hillsborough County, Florida for passenger cars. Bold cells (0 percent) indicate speed with minimum emission rate.

Table 7.2 Percent Difference versus Minimum Emission Rate
Urban Unrestricted Access – Passenger Cars

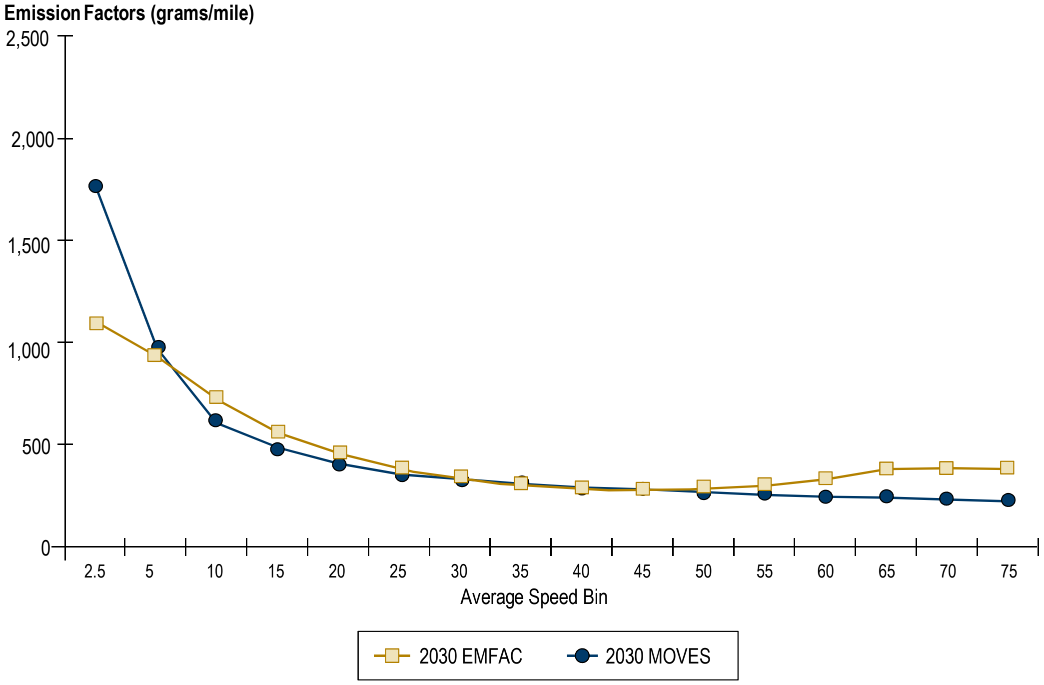
Speed (MPH)	VOC	CO	NO_x	PM_{10} and $PM_{2.5}$	CO_2
2.5	1,372%	434%	297%	250%	565%
5	668%	221%	179%	142%	273%
10	316%	115%	109%	87%	127%
15	199%	80%	75%	69%	78%
20	139%	59%	52%	49%	53%
25	99%	36%	35%	15%	35%
30	71%	27%	15%	8%	21%
35	50%	17%	7%	4%	13%
40	34%	8%	2%	1%	8%
45	22%	2%	0%	0%	5%
50	13%	0%	2%	2%	2%
55	7%	0%	4%	4%	1%
60	3%	3%	6%	6%	0%
65	0%	7%	8%	11%	0%
70	1%	16%	16%	19%	3%
75	8%	50%	27%	40%	9%

Source: Emission rates taken from MOVES2010 run for Hillsborough County, Florida for passenger cars. Bold cells (0 percent) indicate speed with minimum emission rate.

Knowledge of the relationships between speeds and emissions rates, such as those shown in Figures 7.1 and 7.2, can be applied to local conditions for TSM strategies to help understand the effectiveness of these strategies at reducing emissions. It is generally agreed that emissions of all pollutants (including CO_2) decrease fairly substantially as speeds increase up to about 15 to 20 mph. VOC, CO, and CO_2 continue to decrease (albeit more slowly) up to highway speeds (50 to 65 mph), while NO_x remains essentially flat between about 25 and 55 mph. PM shows mixed effects, with a minimum around 20 mph and some variations in the 25 to 60 mph speed range. All pollutants show an upturn at the highest speeds (65 to 70 mph).

The new MOVES data produce significantly different speed versus emission rate curves in some cases, compared with data developed for other models, as shown in Figure 7.3 which compares CO_2 rates predicted by an early version of MOVES versus EMFAC. While the latest version of MOVES has corrected the emissions rates for high speeds to inflect upward slightly, similar to EMFAC, the point remains that different emissions models based on different driving-cycle assumptions can produce different emission rates. These differences emphasize the technological uncertainty inherent in deriving emission rates from vehicle test procedures. There is a greater amount of this technological uncertainty for PM and CO_2 since speed-emission relationships for those pollutants were only recently derived for use in emissions models.

Figure 7.3 Comparison of EMFAC and MOVES CO_2 Emission Rates by Speed



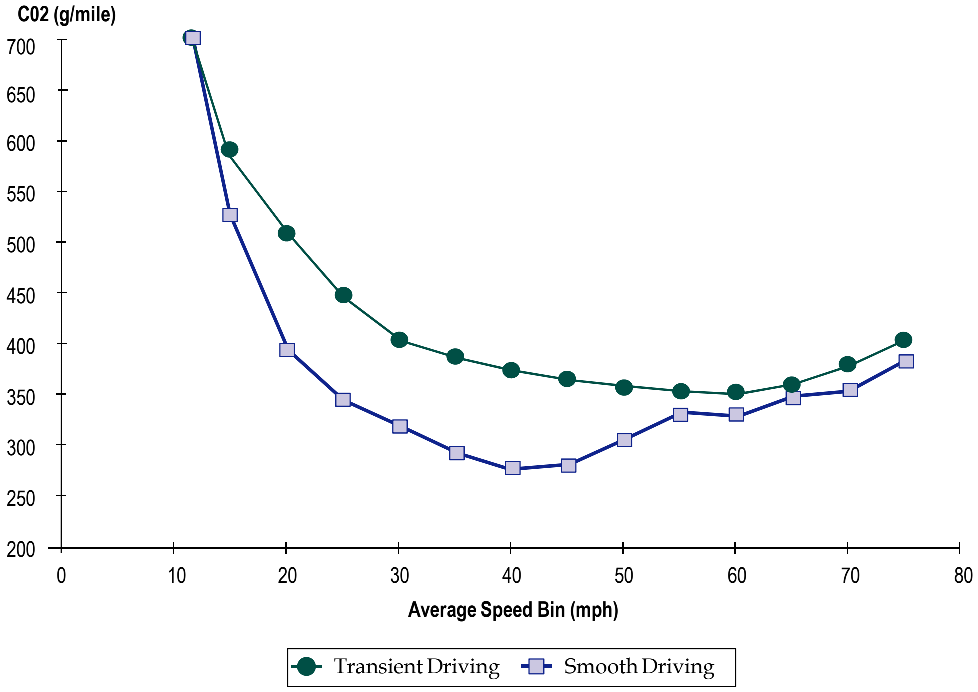
Source: Bai, Song, et al. MOVES versus EMFAC: A Comparative Assessment based on a Los Angeles County Case Study. University of California at Davis.

Note: Based on Draft MOVES 2009 emission rates.

Very few, if any, practitioners have incorporated the new speed-emission relationships from MOVES into their new decision-making processes yet. In fact, in the practitioner survey conducted for this project, the only survey respondent to mention this was the Phoenix MPO, which said they plan to study the new speed versus emission rate relationships for PM in-house and later incorporate them into their evaluation methods for a number of emission reduction strategies that affect speed. As indicated by this response, the first priority for practitioners will likely be to incorporate the PM-speed relationships before updating the relationships for the other pollutants since they did not exist before the MOVES model release.

Furthermore, since the MOVES (and EMFAC) data show little variation in emissions across a wide speed range for some pollutants, it is not clear that the predicted change in emissions will be significant – or rather, it is quite likely that change predicted based on average speeds may be outweighed by changes in operating conditions (speed/acceleration conditions) specific to the project location. While using average speed to approximate an emission rate is a standard industry method, it still has technological uncertainty built into it. This is because while speed is a good predictor of emission rate, a vehicle operating mode measure that incorporates acceleration/deceleration is actually a better predictor. For the MOVES model, the EPA uses vehicle-specific power (VSP), which is based on acceleration to create operating mode bins. The acceleration data needed to calculate VSP would likely have to be acquired from either second-by-second global positioning system (GPS) data for a certain real-world project corridor or from a traffic simulation model of such a corridor. Since both of these options would be costly and time-consuming, it is unlikely that a project would estimate its emissions savings using this detailed approach unless some default operating mode distributions were available for certain strategies. Figure 7.4 illustrates how emissions may vary as a function of different driving patterns, for the same average speeds.

Figure 7.4 Comparison of CO_2 Emission Rates for Transient versus Smooth Driving



Source: Koupal, J. (2009). *Developing Emissions Rates for MOVES*. Presented at 2009 International Workshop of Emissions Models, Beijing China, December 2009.

MOVES does have default operating mode distributions built into the model for use when only average speed is known, but these are a source of uncertainty because it is not possible to know whether vehicle are accelerating or decelerating at a certain speed. For example, when queues are forming and dissipating on freeways, speeds are typically in the 35-45 miles per hour range, but decelerations are dominant for vehicles entering a queue and accelerations are dominant for vehicles exiting a queue. Currently, Cambridge Systematics and E.H. Pechan Associates are conducting a research project for the Federal Highway Administration (FHWA) that will create generic VSP profiles for different roadway types and traffic conditions, such as a freeway on-ramp at different volume to capacity ratios, with and without ramp metering. The use of such profiles in place of the MOVES defaults should reduce uncertainty due to unknown acceleration/deceleration patterns due to traffic conditions. Eastern Research Group also is conducting a project for FHWA that takes the Kansas City data to develop alternate drive cycles for the various roadway types and times of day, to consider the sensitivity associated with driving profiles and emissions.

Finally, some TSM strategies also may involve major capital investment (capacity expansion, bottleneck relief) and may therefore result in initial increases in GHG and other air pollutant emissions that offset savings from more efficient vehicle operations.

Strategy Implementation Uncertainties

Implementing a congestion relief strategy should increase average speeds in almost all cases, but depending on the original and final speed this could increase or decrease emissions. As explained above, the speed versus emission rate relationship for several pollutants is a U shaped curve with downward slope at low speeds and an upward slope at high speeds. If a congestion relief strategy increases speed from a low speed to a medium speed, emissions are likely to go down since the medium speed has a lower emission rate. However, if a congestion relief strategy increases speeds from a medium speed to a high-speed emissions could go up since the high speed has a higher emission rate than the medium speed. To further complicate matters, speed changes may vary by time of day, day of week, etc., depending upon traffic conditions. In addition, some traffic flow improvements (such as signal synchronization or speed harmonization) may “smooth” traffic flow, thus having emissions benefits beyond what might be predicted based on average speed changes. Therefore, due to the uncertain nature of the local conditions that dictate before and after speeds and operating conditions, it can be uncertain whether or not a congestion relief project will increase or decrease emissions, let alone the magnitude of the effect.

Induced demand is another source of uncertainty for TSM strategies. Induced or “latent” demand can be defined as an increase in travel in response to improved travel conditions (e.g., reduced travel times). Induced demand may “fill in” some of the extra capacity created by congestion relief projects and cause congestion to not be decreased as much as expected from a particular strategy. Furthermore, the resulting increases in VMT may partially, or even completely, offset the emission benefits of the congestion reduction. The effects of traffic operations strategies on induced demand, however, have not been well-documented and also are likely to vary according to the project’s context. This creates a source of significant uncertainty for the impact of traffic flow improvements on emissions.

A number of other factors specific to the implementation of individual congestion relief projects can influence the local traffic conditions and, therefore, provide uncertainty in the impacts on emissions.

- **Managed Lanes –** The effects of managed lanes can be complex. First, it is required to know how many travelers are induced to switch from single- to high-occupancy vehicles due to time or cost savings. The mode shift effect is likely to vary based on the expected difference in travel times, but is not likely to be large unless a substantial time savings (at least 10 to 20 minutes) is realized. The impacts of different vehicle operating conditions (speeds and acceleration) also must be considered, both for vehicles that use the managed lanes and those that do not.
- **Congestion Pricing –** The method for collecting tolls can greatly impact the congestion on roadways. For example, electronic toll collection through "fast-pass" type systems would impede traffic less than physical toll collection booths. Also, the amount of the charge to drive on priced roadways, and its variation by time of day or congestion level, will greatly influence congestion levels and also will affect overall travel demand. The administrative costs of congestion pricing can be high if a tolling system is not already in place, and so cost-effectiveness will depend greatly upon the overall benefits that are achieved in any particular application.
- **Ramp Metering –** How the metering pattern/flow rate is set (as well as enforcement affecting the violation of metering by drivers) will affect mainline traffic operations and emissions. Also, if ramp meters create more congestion on the arterial streets connecting to ramps it could offset some of the emission reductions seen on the freeways.

Other System Management Strategies

Technological Uncertainties

Speed limit enforcement/reduction is similar to the congestion relief strategies, but it aims to decrease speeds instead of increasing them. Since this strategy relies on speeds to reduce emissions, all of the same technological uncertainties discussed above for congestion relief strategies also apply to speed limit enforcement/reduction. In particular, the benefits of reducing speeds from 70 to 65 mph or from 65 to 60 mph may be uncertain because of uncertainty over how emissions change at higher speeds. Furthermore, the variability in vehicle speeds may be just as important, if not more so, than the change in average speeds.

Strategy Implementation Uncertainties

There are several strategy implementation uncertainties associated with speed limit enforcement/reduction. The impact of this strategy on emissions will mainly depend on the speed range reduced and compliance of vehicles with the reduced speed limit. This will depend greatly on the method and stringency of enforcement (e.g., automatic speed detection with tickets mailed to the vehicle owner versus tickets given by officers in patrol cars, amount of the fine).

Vehicle idling reduction programs have several strategy implementation uncertainties. These include whether and what type of auxiliary power units (electrification versus small motors) are used when the vehicle is shut off during idling; the emissions associated with the auxiliary power source; how many vehicles participate in the idling reduction; and how strictly idle reduction policies are enforced.

7.4 VEHICLE AND FUEL TECHNOLOGY STRATEGIES

Information Gaps

Three categories of information were commonly missing from the literature sources on vehicle and fuel technologies. First, toxic emission impacts frequently were not evaluated. However, measurement of toxic emissions requires more involved and costly sample collection and laboratory analysis than do criteria pollutants and CO_2. In addition, modeling tools are generally not available for assessing the detailed toxic emission impacts associated with most vehicle and fuel strategies. Accordingly, the lack of toxics data was to be expected. However, given the general correlation between VOCs and toxic emissions, and to a lesser extent, PM and toxics, the general directionality of toxic impacts may be inferred based on other emission impact estimates. For example, the consistent VOC and PM reductions expected from many diesel retrofit strategies would be expected to provide significant toxic reductions as well, although the specific species reduced and the magnitude of the reductions are uncertain. However, by establishing a fixed set of operating cost assumptions (e.g., retail fuel prices, taxes, annual miles traveled, and fuel economy), comparative cost-effectiveness estimates may be developed more easily, highlighting more readily quantifiable cost elements such as capital and installation costs.

Second, while other (nontoxic) emission reduction estimates were frequently identified throughout the literature, actual cost-effectiveness data were less common. The lack of the cost data required for these assessments may be due to the scope limitations of certain studies, or due to the very large uncertainty associated with quantifying incremental costs. For instance, the net cost associated with alternative fuels and vehicle efficiency improvements is highly dependent upon fuel prices, which are themselves highly variable over time and space.

Third, information on the impacts of multiple strategy applications was almost entirely lacking. For example, only minimal discussion was found regarding the emission impacts associated with biodiesel use with PM retrofits. Since interactive effects are likely for many of the vehicle and fuel technologies evaluated, the net emission reductions of such combinations may not be simply additive (or multiplicative). Nevertheless, such interactions may be small in absolute terms, and may have relatively small impacts on net emission reductions or overall cost-effectiveness.

Areas of Uncertainty

The benefit and cost data provided in the literature is still subject to significant uncertainty due to technical, operational, programmatic, and behavioral reasons. The relative effectiveness of many of the technologies also is expected to decrease over time to some degree, as baseline engines become cleaner in the future. The following provides a brief discussion of some of the more important sources of uncertainty in these data.

Diesel Retrofits

While many PM retrofit strategies have been well-demonstrated through EPA and CARB verification protocols, further evaluation and demonstration is needed for NO_x-related retrofits such as SCR and LNC. In addition, the ultimate effectiveness of many diesel retrofit approaches is largely dependent upon the operational profile of the equipment receiving the retrofit. As discussed in Section 4.0, many technologies such as DPFs and SCR rely on high engine loads and exhaust temperatures in order to function properly. To the extent that equipment frequently operate at low loads, spend large periods of time at idle, or have low-horsepower engines with correspondingly low exhaust temperatures, the emission reductions and cost-effectiveness of these retrofits are compromised. Hence the overall effectiveness and value of these measures is uncertain, at the individual equipment level (whose load profile may change over time), and at the fleet level (where the distribution of engine loads across all equipment is uncertain as well). The potential for inconsistent or improper equipment maintenance (e.g., DPF regeneration or SCR reductant recharge) further increases the uncertainty associated with these technologies. Finally, as noted above, the interactive effects of diesel retrofits with alternative fuels such as biodiesel also are uncertain.

The cost, and therefore cost-effectiveness, of diesel retrofits is largely dependent upon the associated equipment costs. While PM strategy costs such as DOCs and DPFs are well-established, the costs for NO_x-related approaches is less certain, but may decrease notably if production volumes increase substantially. Future production volumes themselves are uncertain though, as future market penetration of these technologies will depend upon operator acceptance, as well as the availability of certified systems and program funds. Of these factors, it is particularly critical to reduce the uncertainty associated with load profiles and maintenance before wide-scale investment in these technologies.

Despite the uncertainty associated with the magnitude of emission reductions and ultimate cost-effectiveness, the relative emission reduction benefits across different pollutants (including tradeoffs with GHGs), are reasonably well-established. However, note that all diesel retrofit options should become relatively less important over time as baseline 2007 and 2010 heavy-duty diesel emission standards are introduced, which already include many of these technologies. On the other hand, the need for heavy-duty vehicle I/M will likely increase in order to minimize advanced component degradation.

Accelerated Retirement

The costs and effectiveness of light- and heavy-duty vehicle accelerated retirement programs are largely dependent upon programmatic details, such as the vehicle types and model years eligible for inclusion in the program and the retirement incentives adopted. In addition, often assumptions must be made regarding the age and emission standards of replacement vehicles, and the miles traveled before and after vehicle replacement. Also, if the introduction of a newer, and possibly more reliable, replacement vehicle increases demand for miles traveled, or induces mode shifts away from more efficient transportation (e.g., public transit), then the benefits of these programs will be reduced or even negated. Of these factors, the annual mileage associated with the vehicle being retired and its replacement, along with the relative vehicle emission standards, are most important for determining program effectiveness.

As with diesel retrofits, the relative benefits across pollutants is well-known with reductions anticipated across most pollutants, although GHG impacts will likely be equivocal unless program requirements place specific targets on replacement vehicle efficiency. In addition, the net effectiveness and cost-effectiveness of these programs is expected to decrease with time as the baseline vehicle fleet becomes cleaner and more efficient with time.

Idle Reduction

Most idle reduction technologies are well-demonstrated in their ability to reduce PM, NO_x, and CO_2 emissions. VOC and CO also should be reduced, but these impacts are somewhat less well documented. Key uncertainties surround PM impacts associated with TSE; TSE use is likely to increase PM emissions as the PM rates associated with electricity production are greater than those for vehicles using ULSD, although a large fraction of PM increases are expected to occur in rural areas.

Costs for most idle reduction measures are reasonably well-known, although storage cooling options are not widely deployed at this time. Overall utilization rates for idle reduction measures are particularly uncertain, being largely dependent on fuel prices and associated payback periods. Unless PM levels are of particular concern, however, idle reduction strategies are considered generally cost-effective for a large number of heavy-duty applications.

Unlike many other strategies, idle emissions become relatively more important with time, as many 2007 and later OEM technologies have limited impact at idle. For this reason these strategies are expected to become more important with time.

Alternative Fuels

Unlike most vehicle technology measures, the benefits of alternative fuel options vary significantly depending upon the analysis framework used to estimate those benefits. The end-use pollutant benefits associated with alternative fuels are reasonably well-established, although biodiesel's net impact on NO_x emissions is in need of further evaluation, especially for late model (2007+) vehicles. However, the full life-cycle impacts, including feedstock production, fuel production, and distribution activities are more uncertain. In fact, most life-cycle models such as GREET focus primarily on GHG emissions, and utilize somewhat simplified assumptions regarding criteria emissions. According to GREET, life-cycle emissions from corn ethanol can be substantial, especially for PM and SO_x, so upstream emissions may represent a significant source of uncertainty for certain alternative fuels.

Alternative fuel impacts also will vary, perhaps by a few percent, depending upon fueling system configuration (dedicated versus bifuel/dual-fuel/flex fuel, as well as OEM versus retrofit). The market penetration of the fuels themselves and their associated system configurations will in turn vary depending upon a number of factors, including relative equipment cost, fueling infrastructure availability, performance differences, regulatory mandates, and the relative cost between conventional and alternative fuels. As noted above, the cost differential between baseline conventional fuels and the different alternative fuels is particularly uncertain, varying substantially by region of the country as well as over time, and is generally the single-most important factor determining cost-effectiveness. To the extent that CNG, LNG, and LPG equipment production volumes increase in the future, the cost and cost-effectiveness for these technologies may improve over time.

The relative emission benefits of alternative fuels may diminish over time with the adoption of cleaner baseline vehicles, although alternative fuel emission control technology may continue to advance as well, tending to mitigate this effect.

Inspection and Maintenance Programs

The effectiveness and costs associated with TSI and loaded ASM/IM240 tests have been fairly well-established through direct measurement and validation over many years, although long-term repair effectiveness is still the subject of some debate. The cost-effectiveness of these programs have substantial variability, however, due to program details, such as test fees, vehicle repair costs, model year coverage, waiver limits, etc. In addition, these tests are intended for vehicles without OBDII systems (pre-1996), and are becoming continually less relevant as this portion of the light-duty fleet travels fewer miles and is retired over time.

OBD-based I/M programs are potentially quite cost-effective compared to TSI and loaded emissions tests, requiring significantly less capital investment to operate. However, the emission benefits associated with OBD tests are more uncertain, since they are seldom validated by direct emission measurements. On the other hand, OBD tests are becoming more important with time, as an ever increasing fraction of the fleet becomes OBD-equipped. Accordingly, confirmation of the real-world effectiveness of OBD test programs is critical to confidently assess their cost-effectiveness.

Unlike many of the other technology and fuel strategies evaluated, I/M testing may actually become more important over time, as new vehicles rely on a greater number of increasingly complex technologies to achieve increasingly stringent emission standards. As such, I/M tests become crucial to minimize component failures, which in turn could result in relatively large emission increases. This holds true for late model heavy-duty vehicles as well (2007+) – in fact, EPA has begun the process of developing standards for heavy-duty vehicle OBD systems, which could provide the basis for heavy vehicle I/M programs in the future.

Hybrid and Electric Vehicles

The findings from the literature review did not indicate any reason to suspect light-duty hybrid electric vehicle (HEV) criteria and toxic emissions would vary substantially from their current conventional vehicle counterparts, which must already meet stringent Tier 2 or better emission levels. Incremental GHG benefits for HEVs will depend upon make, model, model year, for both the HEV and the vehicle being replaced. HEVs have reached large production volumes for a limited number of models, so incremental vehicle costs are fairly well-established, although overall cost-effectiveness will depend largely on fuel prices, which can be highly variable.

PHEV and BEV emission impacts are substantially more variable and uncertain than those of HEVs, since battery charging results in emissions from electrical generating units (EGU). First, utilization of EGUs results in a different spatial distribution of emissions, often providing a decrease in urban pollution exposure and an increase in rural emissions. In addition, EGU emissions can vary markedly depending upon the fuel type and associated control technologies used. The EGU mix employed for battery charging will differ substantially depending upon time of day and region of the country. EGU mix and emissions also are likely to change substantially, for all types of emissions, including GHGs, as older, higher polluting units are retired and newer units come on line. While recent modeling of widespread PHEV charging demands in the future found notable net emission reductions on the whole, the magnitude of impacts will vary depending upon all of these factors.

The future costs and cost-effectiveness of PHEVs and BEVs are highly uncertain, given the low production volumes and market penetration of these technologies to date. In addition, battery technology efficiency is still improving, which will in turn lower associated EGU emissions. The ultimate market penetration of these technologies will depend on incremental vehicle costs as well as vehicle range, battery efficiency, and the future availability of public access charging facilities. Overall, the effectiveness and cost of PHEVs and BEVs will remain highly uncertain until market penetrations are high enough to accurately assess battery prices and efficiencies at large production volumes.

Heavy-duty hybrid technology, include hydraulic and electric hybrid systems, is still under development, and further research and demonstration is needed to clearly evaluate its potential benefits and costs. In addition, payload and torque requirements may limit the extent to which these technologies ultimately penetrate the market, which in turn impacts production volumes and system costs. Therefore, the effectiveness and costs associated with heavy-duty hybrids are relatively uncertain at this time.

Vehicle Efficiency Improvements and Standards

As with HEVs, the adoption of other advanced fuel efficiency technologies in light-duty vehicles is not expected to significantly impact non-GHG emissions. Cost projections to meet the future CAFE standards are somewhat uncertain, although the ultimate cost-effectiveness of these standards is primarily dependent on future fuel prices.

Heavy-duty vehicle efficiency improvements, resulting from voluntary measures such as EPA's SmartWay program or from mandated measures such as CARB's heavy-duty vehicle regulations, will rely on improvements to truck and trailer aerodynamics, rolling resistance, and weight reduction. Fuel efficiency improvements and associated GHG impact estimates are fairly well-demonstrated, although performance varies substantially with how the vehicle is driven (e.g., short-haul, urban driving at low speeds with frequent starts and stops, versus long-haul driving at highway speeds with few starts and stops). Limited modeling has been done to estimate the associated NO_x impacts for certain technologies, with NO_x reductions resulting from reduced engine loads. PM, VOC, and CO impacts remain highly uncertain for these measures. While basic aerodynamic retrofit packages appear to be relatively cost-effective for long-haul fleets operating at highway speeds, uncertainties should be significantly reduced through additional on-road measurements and detailed characterization of speed distributions for various fleets.

Costs for retrofit applications are uncertain as well, since most technologies remain at low production volumes to date. Future market penetration and production levels also are uncertain, largely depending upon fuel prices and resulting payback periods. In addition, retrofit strategies may become less effective over time if these technologies are adopted by OEMs to meet potential Federal heavy-duty fuel economy standards.

7.5 FUTURE RESEARCH TOPICS

Many of the data gaps and uncertainties associated with benefits and costs of individual strategies can be addressed through future research and demonstration, as well as through the development of improved emissions modeling tools. One cross-cutting gap is the need for better or more uniformly accepted methods of valuing tradeoffs among different pollutants. This may be addressed in part through additional research into the relative health costs and other social and environmental costs of different pollutants, as well as guidance on how to use the results of this research to develop appropriate weights. Any guidance for practitioners on this topic would need to address how weights could be modified to reflect regional variations in the relative values of each pollutant, depending upon specific local air pollution problems, as well as exposure to population. Assigning relative weights for GHGs versus other pollutants is especially difficult given the long-term and highly uncertain costs associated with climate change.

Other key data needs are summarized below by category of strategies.

Transportation Demand Management

Measuring and predicting the benefits of TDM strategies has been a research topic of interest for decades, starting with programs enacted in the 1970s in response to the energy crisis, and continuing through air quality efforts in the 1990s. Some types of strategies have been fairly extensively studied, others less so. Due to limited funding for evaluation efforts, however, few evaluation studies have been conducted using robust and consistent methods (as documented Section 3.0). The potential of some strategies (such as telecommuting and traveler information) is evolving due to technological changes. Furthermore, better forecasting models are needed for other strategies (such as nonmotorized improvements) to account for specific local conditions.

The following is a list of topic areas where information is particularly lacking and most needed. This list considers the level of certainty or uncertainty in existing knowledge, the importance and potential of the strategy for future emission reductions, and the feasibility of obtaining additional useful information.

- Impacts of TDM programs, such as worksite- or neighborhood-based programs, in auto-centric locations or smaller cities with relatively low levels of transit service and limited traffic congestion; and most effective TDM actions under these circumstances;
- Impacts of nonwork TDM programs such as neighborhood-based marketing and “school pools”;

- Potential for additional market penetration of alternative work schedules, including compressed work weeks as well as telework;
- Impacts of localized parking management policies in different context on destination-shifting and overall VMT;
- Impacts of nonmotorized improvements (including systemwide improvements as well as individual projects) on utilitarian travel under different conditions/contexts;
- Evidence on freight mode-shifting in response to rail and intermodal improvements, and appropriate emission factors for comparing truck and rail goods movement;
- Life-cycle emissions impacts, considering construction and maintenance of highway and transit facilities in addition to emissions from vehicles operating on the facilities; and
- For all measures, robust studies from different contexts compiled into a "library" so that practitioners can look up examples that are similar to their own situation.

Transportation System Management

The emissions impacts of most TSM strategies can in theory be modeled in some detail, if sufficient resources are available for developing the required traffic simulation models emissions model interfaces. The release of EPA's MOVES model this year will make it possible to model the emissions impacts of TSM strategies with more precision than could previously be done. However, most local agencies that are evaluating TSM strategies are not in a position to do detailed simulation modeling and must use simplified methods such as average speed-based factors in conjunction with assumptions about average speed changes. Additional research activities that will advance capabilities in this area include:

- Incorporate new MOVES emission rates into standardized cost-effectiveness calculations for various strategies and decision-making guides for choosing between these strategies. These will make the most difference for PM and CO_2, where emission rates by speed were not previously available.
- Evaluate the adequacy of the vehicle tests conducted in Kansas City study to produce PM emission rates for MOVES and collect more vehicle testing data if needed.
- Conduct research on the impact of various TSM strategies on operating mode profiles and the resulting impact on emissions. Use both real-world second-by-second GPS data and traffic simulation model results. Create generalized VSP profiles for various traffic and strategy conditions.
- Conduct research on the impact of induced demand on the effectiveness of TSM strategies, considering strategies that affect travel-time reliability (e.g.,

incident management) as well as those that affect average or typical levels of congestion and delay. Some simple experiments could be performed using a range of assumptions on traveler response to travel-time improvements (e.g., using elasticities from the literature) to evaluate how emissions tradeoffs vary for different assumptions regarding induced demand impacts, as well as under different types of traffic conditions.

- Evaluate and develop methods for considering life-cycle emissions impacts of capacity expansion projects.

Vehicle and Fuel Technology

The quality of information on vehicle and fuel technology improvements varies, with some technologies well-documented and others with considerable uncertainty remaining. Areas for further research include:

- Additional VOC speciation is needed to better assess toxic emission impacts, especially for alternative fuels. Once technology and fuel-specific speciation profiles are developed, these factors could be applied to existing modeling tools.
- Additional research and development is needed to more accurately determine emission impacts for NO_x diesel retrofits, as well as for multiple technology and/or fuel combinations (alternative fuels + retrofits; I/M + alternative fuels; I/M + retrofits).
- More in-use data is needed on the distribution of engine operating profiles at the fleet and subfleet levels for retrofit effectiveness assessments. The use of OBD data for late model heavy vehicles should be evaluated for this purpose.
- Data is needed regarding the frequency of malmaintenance for retrofit effectiveness assessments.
- Continued evaluation of OBD effectiveness is needed to correlate with actual emission measurements.
- Continued research regarding heavy-duty diesel I/M methods and effectiveness is needed.
- Improved life-cycle modeling of alternative fuels is required to reduce uncertainties, especially for criteria pollutant emissions.
- Further biodiesel testing is needed for improved NO_x determination, especially for late-model diesel technologies.
- Although the uncertainty associated with fuel prices cannot be eliminated, improved sensitivity analyses and scenario modeling can be developed for vehicle operators to explicitly demonstrate the relationship between payback periods/cost-effectiveness and key variables (e.g., idle hours per year, miles per year, infrastructure and equipment costs).

A. Literature Sources and Strategies and Pollutants Addressed

Table A.1 TDM and TSM Strategies-Literature Sources and Strategies Addressed

Title	Author	Date	TDM-VMT Reduction	TDM-VMT Reduction and New Service	TSM-Congestion Relief	TSM-Other	VOC, CO, NO_x	PM	GHG	Confidence Ranking
Transportation's Role in Reducing U.S. Greenhouse Gas Emissions	U.S. DOT	2010	√	√	√	√			√	High
Cost-Effectiveness of Transportation Strategies with Respect to Greenhouse Gas Reduction Potential	PB Americas, et al.	2009	√	√	√	√			√	High
Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions	Cambridge Systematics, Inc.	2009	√	√	√	√			√	High
SAFETEA-LU 1808: CMAQ Evaluation and Assessment: Phase I Final Report	ICF International	2008	√	√	√		√	√		High
Bus Emissions versus Passenger Car Emissions	Ayres	2007		√			√	√		High
A Simulation of the Effects of Transportation Demand Management Policies on Motor Vehicle Emissions	Harrington, et al.	2007	√				√			High
Multipollutant Emissions Benefits of Transportation Strategies	ICF International	2006	√	√	√	√	√	√		N/A
Predicting Air Quality Effects of Traffic-Flow Improvements	Dowling, R., et al.	2005	√	√	√		√			High
Hampton Roads Congestion Mitigation and Air Quality Improvement Program: Post Evaluation Study	Hampton Roads Planning District Commission	2003	√	√	√		√			Moderate
The Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience	Transportation Research Board	2002	√	√	√	√	√			High
Air Quality Impacts of Regional Land Use Policies	Johnston, R., et al.	2002	√	√			√	√		High

Title	Author	Date	TDM-VMT Reduction	TDM-VMT Reduction and New Service	TSM-Congestion Relief	TSM-Other	VOC, CO, NO_x	PM	GHG	Confidence Ranking
Comparative Evaluation of the Cost-Effectiveness of 58 Transportation Control Measures	Pansing and Sillings	1998	√	√			√			High
The Cost-Effectiveness and Magnitude of Potential Impact of Various Congestion Management Measures	Rowell, M.; F. Buonincontri, and J. Semmens	1997	√	√	√		√			Low
Transportation Control Measure Analysis	FHWA	1995	√	√	√	√				Moderate

Table A.2 Vehicle and Fuel Technology Strategies-Literature Sources and Strategies Addressed

	Title	Author	Date	Diesel Engine/ Vehicle Retrofits	Idle Reduction	Accelerated Retirement/ Replacement	Alternative Fuels	Inspection/ Maintenance	Hybrid Technology	Fuel Economy Standards	Confidence Ranking
1	Multipollutant Emissions Benefits of Transportation Strategies	FHWA, ICF	2006	√	√	√	√	√			High
6	TRB Special Report 264. The CMAQ Program. Assessing 10 years of experience.	TRB	2002			√	√	√			Medium
7	SAFETEA-LU 1808: CMAQ Evaluation and Assessment	FHWA	2008	√	√	√	√				Medium
9	The Cost-Effectiveness of Heavy-Duty Diesel Retrofits and Other Mobile Source Emission Reduction Projects and Programs	U.S. EPA	May 2007	√	√	√	√	√			High
10	An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits	U.S. EPA	March 2006	√							High
11	Cleaning the Air: Comparing the Cost-Effectiveness of Diesel Retrofits versus Current CMAQ Projects	Robert F. Wescott, Ph.D. for the Emission Control Technology Association	May 2005	√		√	√	√			Medium
12	Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks	Gaines, Linda L., Christie-Joy Brodrick Hartman, Matthew Solomon, Argonne National Laboratories	January 2009		√						Medium
13	Which Idling Reduction Technologies Are the Best?	L. Gaines, Argonne National Laboratories	August 2008		√						Low
14	Economic Analysis of Commercial Idling Reduction Technologies	Linda Gaines and Danilo Santini, Argonne National Laboratories	2006		√						Low

	Title	Author	Date	Diesel Engine/ Vehicle Retrofits	Idle Reduction	Accelerated Retirement/ Replacement	Alternative Fuels	Inspection/ Maintenance	Hybrid Technology	Fuel Economy Standards	Confidence Ranking
15	Which Idling Reduction System Is Most Economical for Truck Owners?	Linda Gaines, Argonne National Laboratories	October 2008		√						Low
16	Truck Stop Electrification as a Strategy to Reduce Greenhouse Gases, Fuel Consumption and Pollutant Emissions	Zietsman, J. (TTI), P.E., M. Farzaneh (TTI), Ph.D., W.H. Schneider IV, Ph.D., P.E. (University of Akron), J.S. Lee (TTI), P. Bubbosh (U.S. EPA)	April 2009		√						High
17	Diesel Retrofit Technology and Program Experience	Emissions Advantage, LLC (for U.S. EPA, OTAQ)	July 2005	√							Medium
18	Diesel Retrofit Technology Verification	U.S. EPA	November 2007	√							High
19	Heavy-Duty diesel Emission Reduction Project Retrofit/Rebuild Component	U.S. EPA	June 1999	√							Low
20	Volume II Retrofit Technologies, Application and Experience, Section VIII	Emissions Advantage, LLC (for WRAP)	November 2005	√							Medium
21	Closed Crankcase Ventilation Filtration Systems Technical Information	Racor, manufacturer of CCV Filtration Systems	2006	√							High
22	Volume 2 – Section IV WRAP OFFROAD Diesel Retrofit Guidance Document	Emissions Advantage, LLC (for WRAP)	November 2005	√							Medium
23	Cleaning Up Today's Dirty Diesels Retrofitting and Replacing Heavy-Duty Vehicles in the Coming Decade	Kassel, Richard and Diane Bailey, Natural Resources Defense Council	November 2004	√		√					Medium

	Title	Author	Date	Diesel Engine/ Vehicle Retrofits	Idle Reduction	Accelerated Retirement/ Replacement	Alternative Fuels	Inspection/ Maintenance	Hybrid Technology	Fuel Economy Standards	Confidence Ranking
24	Report to Congress Transportation's Impact on Climate Change and Solutions	U.S. DOT	July 2005				√				Medium
25	Santa Barbara County Air Pollution Control District 2006 Old Car Buyback Program	SBCAPCD	2006			√					Medium
26	Fighting Air Pollution in Southern California by Scrapping Old Vehicles	RAND Corp, for the Public Policy Institute of California	2001			√					High
27	Abating Greenhouse Gas Emissions through Cash-for-Clunker Programs	UC-Davis	2009			√					Medium
28	The Enhanced I/M Program in Arizona: Costs, Effectiveness, and a Comparison with Pre-Regulatory Estimates	Harringon, McConnell, and Ando	June 1999					√			Medium
29	Municipality of Anchorage I/M Program Evaluation Study	Sierra Research	January 2007					√			Medium
30	Vehicle Inspection/Maintenance Programs and Other Alternatives to Decrease Greenhouse Gas Emissions from Road Transportation in Alberta	Climate Change Central	2002					√			Low
31	Evaluating Vehicle Emissions Inspection and Maintenance Programs	NRC	2001					√			High
32	Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet	Kromer and Heywood	May 2007						√		High

	Title	Author	Date	Diesel Engine/ Vehicle Retrofits	Idle Reduction	Accelerated Retirement/ Replacement	Alternative Fuels	Inspection/ Maintenance	Hybrid Technology	Fuel Economy Standards	Confidence Ranking
33	Cost-Effectiveness of Greenhouse Gas Emissions Reductions from Plug-in Hybrid Electric Vehicles	Kammen, Arons, Lemoine, Hummel	November 2008						√		Medium
34	Alternative Fuels and Advanced Vehicles Data Center: Natural Gas Emissions	U.S. Department of Energy – Energy Efficiency and Renewable Energy Alternative Fuels and Advanced Vehicles Data Center	Last Accessed 11-24-09				√				High
35	Alternative Fuels and Advanced Vehicles Data Center: E85 Emissions	U.S. Department of Energy	Last Accessed 11-24-09				√				High
36	Alternative Fuels and Advanced Vehicles Data Center: Propane Emissions	U.S. Department of Energy	Last Accessed 11-24-09				√				High
37	A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas	Argonne National Laboratory, Transportation Technology R&D Center, United States DOE	December 1999				√				High
38	Volume 2 – Section II WRAP OFFROAD Diesel Retrofit Guidance Document	Emissions Advantage, LLC (for WRAP)	November 2005	√							Medium
44	Average Fuel Economy Standards, Passenger Cars and Light Trucks Model Year 2011 – Federal Register	U.S. EPA	March 2009							√	High

	Title	Author	Date	Diesel Engine/ Vehicle Retrofits	Idle Reduction	Accelerated Retirement/ Replacement	Alternative Fuels	Inspection/ Maintenance	Hybrid Technology	Fuel Economy Standards	Confidence Ranking
45	Draft Environmental Assessment: NHTSA Proposed Corporate Average Fuel Economy (CAFÉ) Standards	U.S. DOT	August 2005							√	High
46	Corporate Average Fuel Economy Compliance and Effects Modeling System Documentation	NHTSA	April 2009							√	High
47	Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions	ANL/GM	May 2005							√	High
48	Technical Note: Emission Control Strategy Evaluation in the Austin/ San Marcos MSA	ERG for Capital Area Planning Council	2003				√	√			Medium
49	Effects of Biodiesel Blends on Vehicle Emissions; NREL Milestone Report 540-40554	RL McCormick, A. Williams, J. Ireland, M. Brimhall, R.R. Haynes, NREL	October 2006				√				High
50	A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions: EPA420-P-001	U.S. EPA OTAQ/ASD	October 2002				√				High
51	Biodiesel Performance, Costs, and Use, DOE EIA	Anthony Radich, EIA	Last Accessed 12-10-09				√				Medium
52	Quality, Performance, and Emissions Impacts of Biodiesel Blends, NREL	R. McCormick, et al.	05-19-09				√				High

	Title	Author	Date	Diesel Engine/ Vehicle Retrofits	Idle Reduction	Accelerated Retirement/ Replacement	Alternative Fuels	Inspection/ Maintenance	Hybrid Technology	Fuel Economy Standards	Confidence Ranking
53	Impact of Biodiesel Emissions Products from a Multicylinder Direct Injection Diesel Engine on Particulate Filter Performance; SAE 2009-01-1184	A Peterson, et al.	2009				√				High
54	Biodiesel and Renewable Diesel Research Study, ARB PPT	Tom Durbin	03-12-09				√				Medium
55	Heavy-Duty Truck Retrofit Technology: Assessment and Regulatory Approach, TIAX LLC	R. Schubert, M. Kromer	09-12-08	√							Medium
56	Report to Congress: Highlights of the Diesel Emissions Reduction Program	U.S. EPA	August 2009	√	√	√					High
57	Renewable Fuel Standard Program (RFS2): Regulatory Impact Analysis. EPA-420-R-10-006	U.S. EPA	February 2010				√				High
58	Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards: Regulatory Impact Analysis. EPA-420-R-10-009	U.S. EPA	April 2010							√	High

Table A.3 Vehicle and Fuel Technology Strategies – Pollutants and Methodology

	Title	Author	Date	VOC	CO	NO_x	PM	CO_2	Toxics	Other	Methodology
1	Multipollutant Emissions Benefits of Transportation Strategies	FHWA, ICF	2006	√	√	√	PM_{10}, $PM_{2.5}$			NH_3	Modeled
6	TRB Special Report 264. The CMAQ Program. Assessing 10 years of experience.	Transportation Research Board	2002	√	√	√	PM_{10}				Modeled
7	SAFETEA-LU 1808: CMAQ Evaluation and Assessment	FHWA	2008	√	√	√	PM_{10}, $PM_{2.5}$				Modeled
9	The Cost-Effectiveness of Heavy-Duty Diesel Retrofits and Other Mobile Source Emission Reduction Projects and Programs	U.S. EPA	May 2007	√			$PM_{2.5}$				Modeled
10	An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits	U.S. EPA	March 2006				√				Modeled
11	Cleaning the Air: Comparing the Cost-Effectiveness of Diesel Retrofits versus Current CMAQ Projects	R.F. Wescott, for the Emission Control Technology Association	May 2005	√		√	$PM_{2.5}$				Modeled
12	Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks	Gaines, L., C.B. Hartman, M. Solomon, Argonne National Laboratories	January 2009			√	PM_{10}	√			Modeled
13	Which Idling Reduction Technologies Are the Best?	L. Gaines, Argonne National Laboratories	August 2008			√	PM_{10}	√			Modeled
14	Economic Analysis of Commercial Idling Reduction Technologies	L. Gaines and D. Santini, Argonne National Laboratories	2006	√[a]	√[a]	√[a]	√[a]	√[a]	√[a]	√[a]	Modeled
15	Which Idling Reduction System Is Most Economical for Truck Owners?	L. Gaines, Argonne National Laboratories	October 2008	√[a]	√[a]	√[a]	√[a]	√[a]	√[a]	√[a]	Modeled

	Title	Author	Date	VOC	CO	NO_x	PM	CO_2	Toxics	Other	Methodology
16	Truck Stop Electrification as a Strategy to Reduce Greenhouse Gases, Fuel Consumption and Pollutant Emissions	Zietsman, J., M. Farzaneh, W.H. Schneider IV, J.S. Lee, P. Bubbosh	April 2009	√	√	√	√	√	√[a]	√[a]	Observed/Modeled
17	Diesel Retrofit Technology and Program Experience	Emissions Advantage, LLC (for U.S. EPA, OTAQ)	July2005	√	√	√	√		√		Observed/Modeled
18	Diesel Retrofit Technology Verification	U.S. EPA	November 2007	√	√	√	√				Observed
19	Heavy-Duty diesel Emission Reduction Project Retrofit/Rebuild Component	U.S. EPA	June 1999	√	√	√	√				Observed/Modeled
20	Volume II Retrofit Technologies, Application and Experience, Section VIII	Emissions Advantage, LLC (for WRAP)	November 2005		√		√		√		Observed/Modeled
21	Closed Crankcase Ventilation Filtration Systems Technical Information	Racor, manufacturer of CCV Filtration Systems	2006	√	√	√	$PM_{2.5}$	√	√		Observed
22	Volume 2 – Section IV WRAP OFFROAD Diesel Retrofit Guidance Document	Emissions Advantage, LLC (for WRAP)	November 2005	√[b]	√[b]	√	√[b]				Modeled
23	Cleaning Up Today's Dirty Diesels Retrofitting and Replacing Heavy-Duty Vehicles in the Coming Decade	Kassel, R. and D. Bailey, Natural Resources Defense Council	November 2004	√	√	√	√				Observed/Modeled
24	Report to Congress Transportation's Impact on Climate Change and Solutions	U.S. DOT	2010 (Pending)	√	√	√	PM_{10}, $PM_{2.5}$	√	√	SO_x	Modeled
25	Santa Barbara County Air Pollution Control District 2006 Old Car Buyback Program	SBCAPCD	2006	√		√					Measured
26	Fighting Air Pollution in Southern California by Scrapping Old Vehicles	RAND Corp, for the Public Policy Institute of California	2001	√		√					
27	Abating Greenhouse Gas Emissions through Cash-for-Clunker Programs	UC-Davis	2009	√	√	√		√			

	Title	Author	Date	VOC	CO	NO_x	PM	CO_2	Toxics	Other	Methodology
28	The Enhanced I/M Program in Arizona: Costs, Effectiveness, and a Comparison with Pre-Regulatory Estimates	Harringon, McConnell, and Ando	June 1999	√	√	√		√			Measured
29	Municipality of Anchorage I/M Program Evaluation Study	Sierra Research	January 2007	√	√	√					Measured
30	Vehicle Inspection/Maintenance Programs and Other Alternatives to Decrease Greenhouse Gas Emissions from Road Transportation in Alberta	Climate Change Central	2002					√			Measured
31	Evaluating Vehicle Emissions Inspection and Maintenance Programs	National Research Council	2001	√		√					Measured/Modeled
32	Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet	Kromer and Heywood	May 2007					√			Modeled
33	Cost-Effectiveness of Greenhouse Gas Emissions Reductions from Plug-in Hybrid Electric Vehicles	Kammen, Arons, Lemoine, Hummel	November 2008					√			Modeled
34	Alternative Fuels and Advanced Vehicles Data Center: Natural Gas Emissions	U.S. DOE – Alternative Fuels and Advanced Vehicles Data Center	Last Accessed 11-24-09	√	√	√	√	√	√		Observed
35	Alternative Fuels and Advanced Vehicles Data Center: E85 Emissions	U.S. DOE – Alternative Fuels and Advanced Vehicles Data Center	Last Accessed 11-24-09	√	√	√	√		√		Observed
36	Alternative Fuels and Advanced Vehicles Data Center: Propane Emissions	U.S. DOE – Alternative Fuels and Advanced Vehicles Data Center	Last Accessed 11-24-09	√	√	√	√			√	Observed
37	A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas	Argonne National Laboratory, Transportation Technology R&D Center, United States DOE	December 1999	√	√	√	√	√		√	Observed/Modeled

	Title	**Author**	**Date**	**VOC**	**CO**	**NO_x**	**PM**	**CO_2**	**Toxics**	**Other**	**Methodology**
38	Volume 2 – Section II WRAP OFFROAD Diesel Retrofit Guidance Document	Emissions Advantage, LLC (for WRAP)	November 2005	√	√	√	√				Literature Review
44	Average Fuel Economy Standards, Passenger Cars and Light Trucks Model Year 2011 – Federal Register	U.S. EPA	March 2009					√	√		Modeled
45	Draft Environmental Assessment: NHTSA Proposed Corporate Average Fuel Economy (CAFÉ) Standards	U.S. DOT	August 2005	√	√	√	√	√		SO_2	Modeled
46	Corporate Average Fuel Economy Compliance and Effects Modeling System Documentation	NHTSA	April 2009	√	√	√		√			Modeled
47	Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions	Argonne National Laboratory and General Motors	May 2005	√	√	√	√	√		SO_x	Modeled
48	Technical Note: Emission Control Strategy Evaluation in the Austin/ San Marcos MSA	ERG for Capital Area Planning Council	2003	√		√					Modeled
49	Effects of Biodiesel Blends on Vehicle Emissions; NREL Milestone Report 540-40554	RL McCormick, A Williams, J. Ireland, M. Brimhall, R.R. Haynes, NREL	2006	X	X	X	X				Meta study of several measurement studies (using both engine dynamometers and on-road measurements) covering 15 vehicles.
50	A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions: EPA420-P-001	U.S. EPA OTAQ/ASD	2002	X	X	X	X	?	X		Meta analysis of HDDV measurement data, almost all prior to 1998 models. 39 studies reviewed; regression analysis of data employed to develop predictive emission functions for each pollutant.

	Title	Author	Date	VOC	CO	NO_x	PM	CO_2	Toxics	Other	Methodology
51	Biodiesel Performance, Costs, and Use, DOE EIA	A. Radich, EIA	Last Accessed 12-10-09	X	X	X	X	X			Literature review.
52	Quality, Performance, and Emissions Impacts of Biodiesel Blends, NREL	R. McCormick, et al.	2009	X		X	X		X (NPAH)		Engine dyne measurements.
53	Impact of Biodiesel Emissions Products from a Multicylinder Direct Injection Diesel Engine on Particulate Filter Performance; SAE 2009-01-1184	A. Peterson, et al.	2009	X		X	X		X (NO2)		Engine dyne measurements.
54	Biodiesel and Renewable Diesel Research Study, ARB PPT	T. Durbin	03-12-09	X		X	X				Chassis dyne measurements; 2006 turbo with EGR engine; CARB diesel baseline; soy and yellow grease; UDDS, FTP and two cruise cycles.
55	Heavy-Duty Truck Retrofit Technology: Assessment and Regulatory Approach, TIAX LLC	R. Schubert, M. Kromer	09-12-08			X		X			Simulation modeling of aerodynamic retrofits, weight reduction, rolling resistance.
56	Report to Congress: Highlights of the Diesel Emissions Reduction Program	U.S. EPA	August 2009			X	X				
57	Renewable Fuel Standard Program (RFS2): Regulatory Impact Analysis. EPA-420-R-10-006	U.S. EPA	February 2010	X	X	X	X	X	X		
58	Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards: Regulatory Impact Analysis. EPA-420-R-10-009	U.S. EPA	April 2010	X	X	X	X	X	X		

[a] Though not explicitly stated in the document, this impact is expected.

[b] When used with a diesel particulate filter.

B. Ranges of Cost-Effectiveness by Project Type

Figure B.1 HC Cost-Effectiveness Range and Median by Strategy

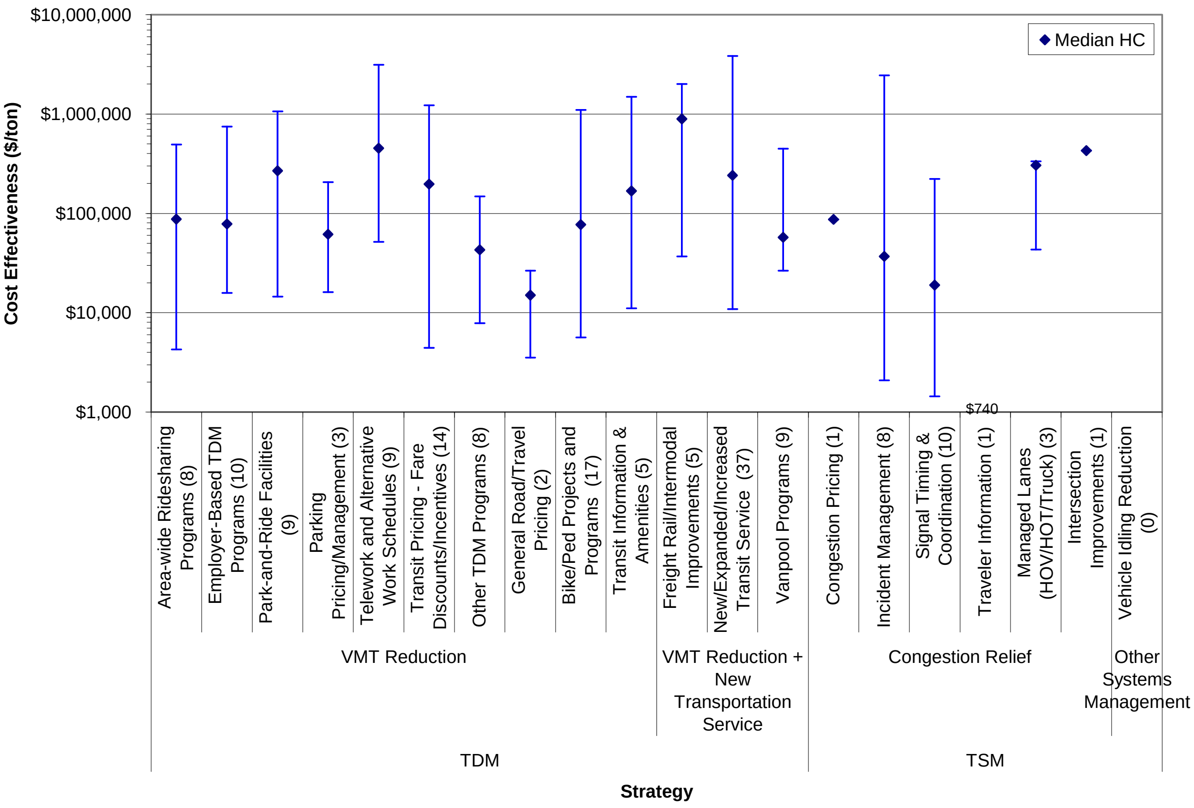


Figure B.2 CO Cost-Effectiveness Range and Median by Strategy

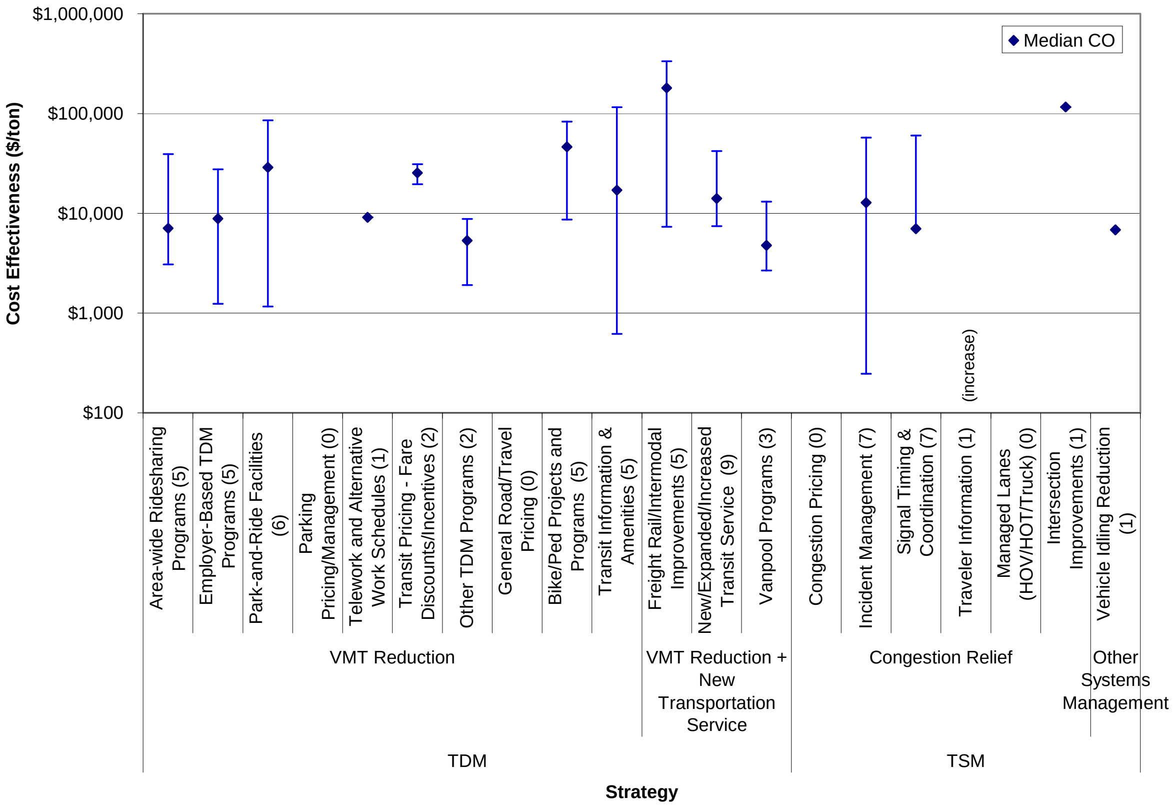


Figure B.3 NO_x Cost-Effectiveness Range and Median by Strategy

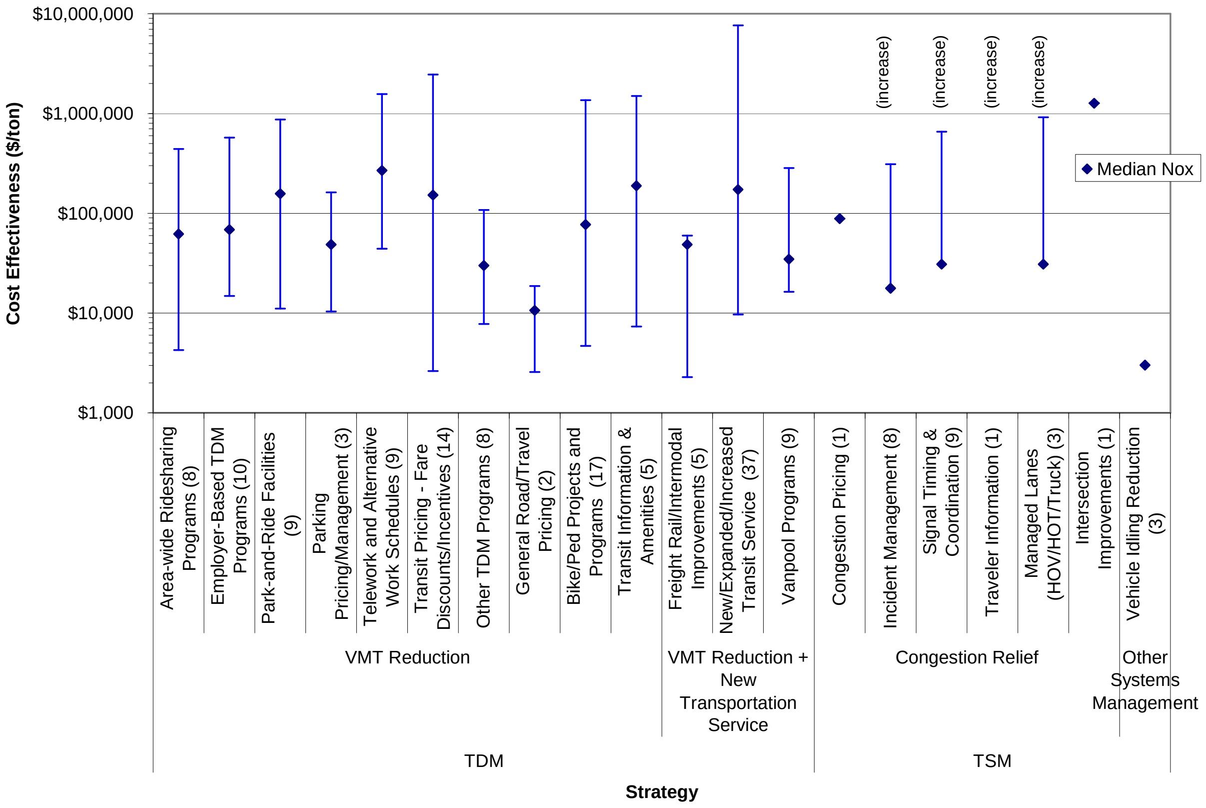


Figure B.4 PM$_{2.5}$ Cost-Effectiveness Range and Median by Strategy

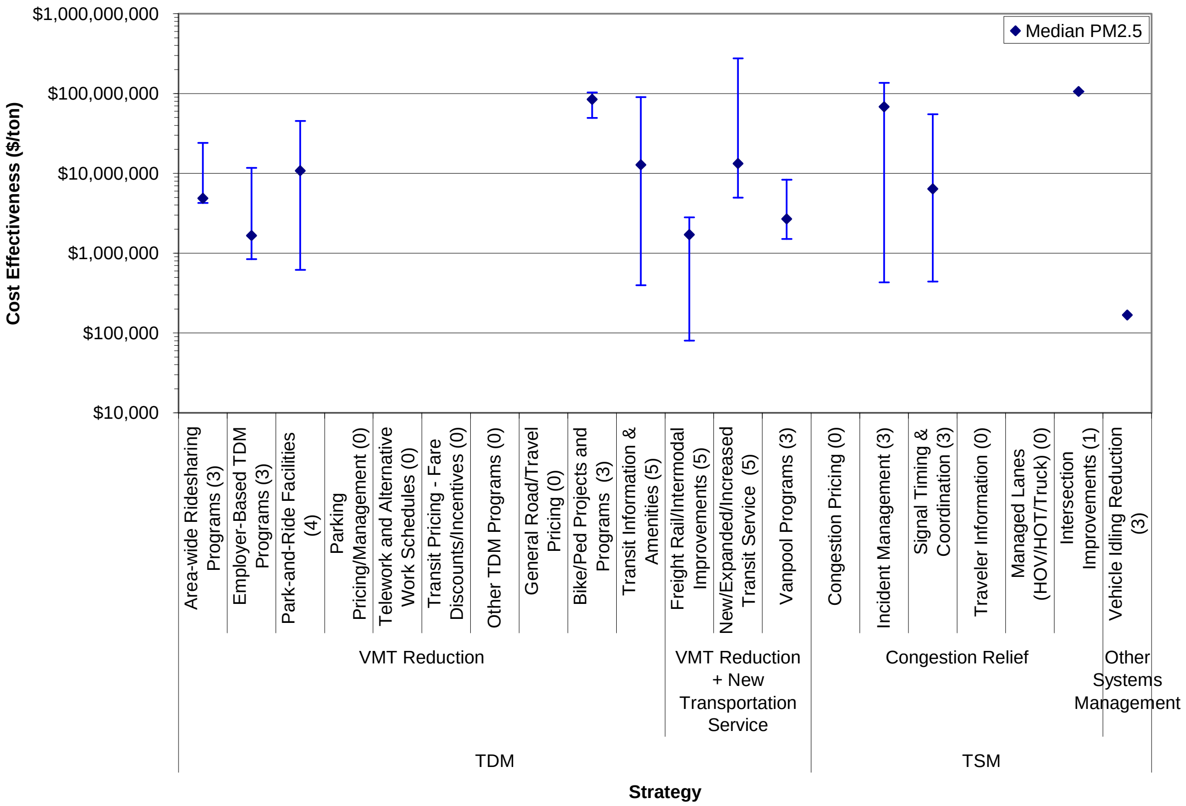
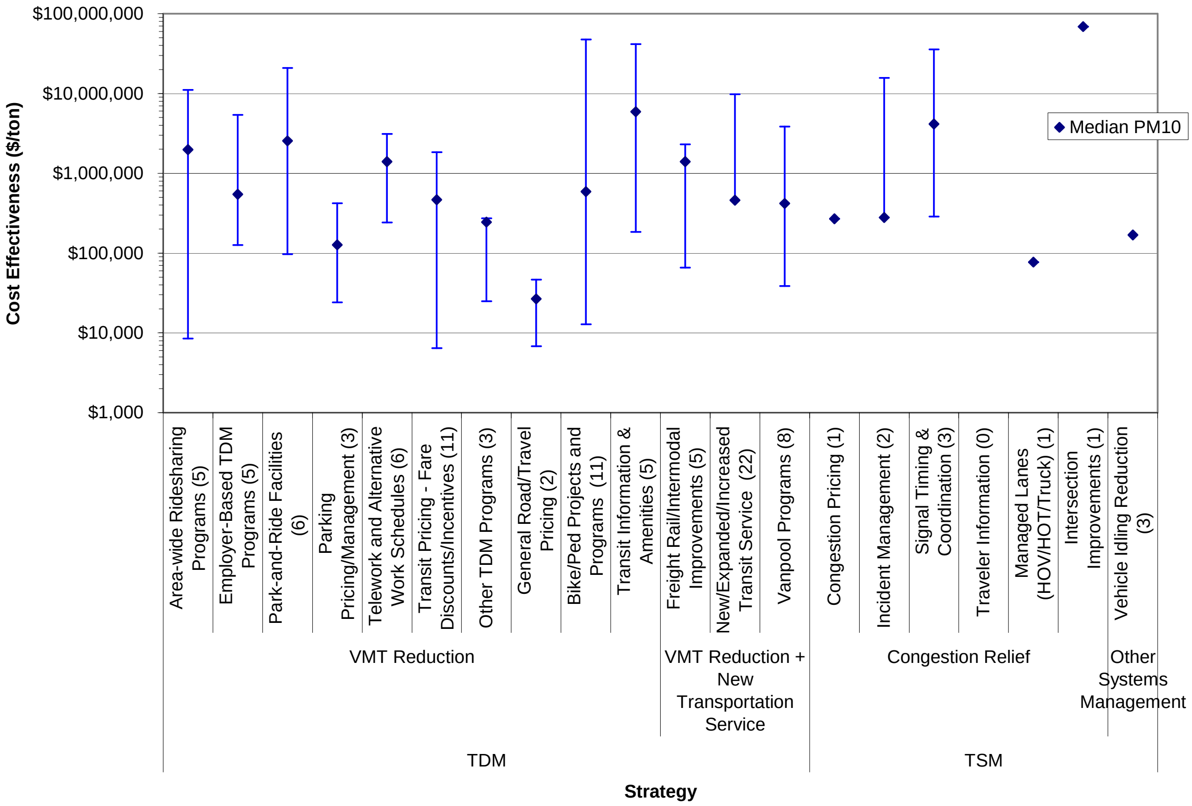


Figure B.5 PM_{10} Cost-Effectiveness Range and Median by Strategy



C. List of Contacts

Table C.1 List of Contacts

State	Area	Agency	8-Hour Ozone (1997)	PM 2.5 (1997)	Other NAAQS	MPO GHG Inventory[a]	State GHG Planning[b]	Contact	E-mail
AZ	Phoenix-Mesa	Maricopa Association of Governments (MAG)	●		PM_{10}			Eric Anderson	eanderson@mag.maricopa.gov
	Yuma	Yuma MPO			PM_{10}			Charlene FitzGerald	cfitzgerald@ympo.org
	Tucson	Pima Association of Governments (PAG)						Cherie Campbell	ccampbell@pagnet.org
	State DOT	Arizona DOT						Beverly Chenausky	bchenausky@azdot.gov
CA	Los Angeles South Coast AQ Basin	Southern California Association of Governments (SCAG)	●	●	PM_{10}, CO/NO_2 maintenance	completed		Jonathan Nadler	nadler@scag.ca.gov
	Sacramento Co	Sacramento Area Council of Governments (SACOG)	●		PM_{10}	completed		Matt Carpenter	mcarpenter@sacog.org
	San Diego	San Diego Association of Governments (SANDAG)	●			completed		Sookyung Kim	ski@sandag.org
	San Joaquin Valley	San Joaquin COG	●	●	PM_{10}, CO maintenance			Tanisha Taylor	taylor@sjcog.org
	State DOT	CalTrans						Jody Tian	Jody.Tian@dot.ca.gov
DC/MD/VA	Washington, D.C.	Metropolitan Washington Council of Governments (MWCOG)	●	●		?	MD/VA – Climate Action Plan complete	Daivamani Sivasailam	siva@mwcog.org
	State DOT	Maryland DOT						Howard Simons	hsimons@mdot.state.md.us
	State DOT	Virginia DOT						Joanne Sorenson	j.sorenson@vdot.virginia.gov
	DOT	DC DOT						Maurice Keys	Maurice.Keys@dc.gov
DE	Philadelphia	Delaware Valley Regional Planning Commission (DVRPC)	●	●		underway		Sean Greene	sgreene@dvrpc.org
GA	Atlanta	Atlanta Regional Commission (ARC)	●	●				Elaine Olivares	EOlivares@atlantaregional.com
	Atlanta	Atlanta Regional Commission (ARC)						Kyung-Hwa Kim	kkim@atlantaregional.com
	State DOT	Georgia DOT						Phillip M. Peevy	phillip.peevy@dot.state.ga.us

State	Area	Agency	8-Hour Ozone (1997)	PM 2.5 (1997)	Other NAAQS	MPO GHG Inventory[a]	State GHG Planning[b]	Contact	E-mail
IL/IN	Chicago-Gary-Lake County	Chicago Metropolitan Agency for Planning (CMAP)	●	●		CMAP – completed	IL – Climate Action Plan complete	Holly Ostdick	hostdick@cmap.illinois.gov
	State DOT	Illinois DOT						Elizabeth Tracy	Elizabeth.Tracy@Illinois.gov
	State DOT	Indiana DOT						Jerry Halperin	JHalperin@indot.IN.gov
MD	Baltimore	Baltimore Regional Transportation Board (BRTB)	●	●			Climate Action Plan complete	Sara Tomlinson	stomlinson@baltometro.org
MO/IL	St. Louis	East-West Gateway Coordinating Council	●	●				Michael Coulson	Mike.Coulson@ewgateway.org
	State DOT	Missouri DOT						Michael Henderson	Michael.Henderson@modot.mo.gov
MT	Missoula	Missoula County			PM_{10}	completed		Ann Cundy	acundy@co.missoula.mt.us
NV	Las Vegas	RTC of Southern Nevada	●		CO			Allison Blankenship	blankenshipa@rtcsnv.com
NY	Albany-Schenectady-Troy	Capital District Transportation Committee (CDTC)	●			completed	Climate Action Plan complete	John P. Poorman	jpoorman@cdtcmpo.org
	Buffalo-Niagara Falls	Greater Buffalo-Niagara RTC	●			underway?		Hal Morse	hmorse@gbnrtc.org
	New York Co	New York Metropolitan Transportation Council (NYMTC)			PM_{10}	underway?		Angelina Foster	afoster@dot.state.ny.us
	Poughkeepsie	Poughkeepsie-Dutchess County TC	●			underway?		Eoin Wrafter	ewrafter@@co.dutchess.ny.us
	Rochester	Genesee Transportation Council	●			underway?		Richard Perrin	rperrin@gtcmpo.org
	State DOT	New York DOT						John Zamurs	jzamurs@dot.state.ny.us
	State DOT	New York DOT						Christa Ippoliti	cippoliti@dot.state.ny.us
NY/NJ/CT	NY-NJ-Long Island	New York Metropolitan Transportation Council (NYMTC)	●	●			NY/NJ/CT-Climate Action Plan complete	see NYMTC	
	State DOT	Connecticut DOT						Judy Raymond	Judy.Raymond@po.state.ct.us
	State DOT	New Jersey DOT						Brent Barnes	brent.barnes@dot.state.nj.us

State	Area	Agency	8-Hour Ozone (1997)	PM 2.5 (1997)	Other NAAQS	MPO GHG Inventory[a]	State GHG Planning[b]	Contact	E-mail
OH	Cleveland-Akron-Lorain	Northeast Ohio Areawide Coordinating Agency (NOACA)	●	●				Bill Davis	bdavis@mpo.noaca.org
	Columbus	Mid Ohio Regional Planning Commission (MORPC)	●	●				David Abel	dabel@morpc.org
OH/KY/IN	Cincinnati-Hamilton	Ohio Kentucky Indiana Regional COG	●	●				Andy Reser	areser@oki.org
	State DOT	Ohio DOT						Dave Moore	Dave.Moore1@dot.state.oh.us
	State DOT	Kentucky DOT						Jesse Mayes	jesse.mayes@ky.gov
PA	Pittsburgh-Beaver Valley		●	●				Chuck DiPietro	dipietro@spcregion.org
PA/NJ/MD/DE	Philadelphia-Wilmington-Atlantic City		●			Philadelphia – completed	NJ/MD – Climate Action Plan complete. PA-Climate Action Plan underway	See DVRPC	
	State DOT	Pennsylvania DOT						Michael Baker	michaelba@state.pa.us
TN	Knoxville	Knoxville TPO	●	●				Mike Conger	Mike.Conger@knoxtrans.org
	State DOT	Tennessee DOT						Ed Cole	ed.cole@state.tn.us

[a] Federal Highway Administration, Highways and Climate Change Report. Lists transportation-related GHG inventories either completed or underway. http://www.fhwa.dot.gov/HEP/climatechange/chapter_five.htm. Accessed November 2009.

[b] Center for Climate Strategies listing of state climate action plans that are completed or underway. http://www.climatestrategies.us/. Accessed November 2009.

D. Web-Based Survey Text

The research team is collecting information on how agencies make tradeoffs among different pollutants when evaluating transportation emissions reduction strategies, and how cost-effectiveness is evaluated when multiple pollutants are considered. This survey is part of an effort to document the cost-effectiveness of emissions reduction measures and methods for making tradeoffs among different pollutants. The research is being conducted on behalf of the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on the Environment (SCOE), through National Cooperative Highway Research Program (NCHRP) Project 25-25, Task 59.

---

1. Please check all criteria pollutants, pollutant precursors, or other air emissions (including air toxics and greenhouse gases) that your agency considers as part of transportation plan, program, or project evaluation.

☐ Hydrocarbons (HC, VOC, ROG)
☐ Carbon monoxide (CO)
☐ Oxides of nitrogen (NO_x)
☐ Particulate matter (PM)
☐ Carbon dioxide/greenhouse gases (CO_2/GHG)
☐ Air toxins
☐ Other (please specify)

If you selected other, please specify:

2. Do you consider the tradeoff among various air emissions when evaluating the impact of transportation strategies (qualitatively or quantitatively)?

○ Yes
○ No
○ Not sure

2a. What transportation plan, program, or project development activity does this evaluation support? (check all that apply)

☐ CMAQ project selection
☐ Other TIP project prioritization/selection
☐ Transportation conformity analysis

☐ State Implementation Plan TCM development

☐ GHG inventory development or strategy assessment

☐ Other (please specify)

If you selected other, please specify:

3. Do you consider any of the following as part of the emissions evaluation:

☐ Cost-effectiveness of transportation strategy on individual pollutants (i.e., dollars per ton of pollutant)

☐ Cost-effectiveness for multiple pollutants combined (e.g., \$/ton VOC + NO_x)

☐ Weighting of different air emissions (e.g., total of 100 points includes 10 points for pollutant X, five points for pollutant Y)

☐ Target percent of funding for specific pollutants (e.g., X percent for ozone-reducing versus Y percent for PM-reducing)

Additional comments:

Provide additional details here (optional):

4. Please provide link to on-line information documenting the evaluation process, methods, and/or results if available.

5. Please provide your contact information in case the research team would like to follow up with you:

Name:

Agency:

E-mail:

Phone:

6. Please list any other transportation or air quality/environmental agency in your region that is involved in evaluating the emissions impacts of transportation plans, programs, or individual projects for more than one pollutant. If you can provide specific contact information please do so below.

E. Recruitment E-mail Script

To state and regional transportation/air quality program staff:

National Cooperative Highway Research Program (NCHRP) Project 25-25 Task 59 is collecting information on how agencies make tradeoffs among different pollutants when evaluating transportation emissions reduction strategies, and how cost-effectiveness is evaluated when multiple pollutants are considered. Attached is a link to a brief (six-question) survey that will help us identify areas that have considered these issues. The survey should take about three minutes to complete.

Link to the survey here:

http://survey01.camsys.com/survey/wsb.dll/9/pollutant.htm

This survey is part of an effort to document the cost-effectiveness of emissions reduction measures and methods for making tradeoffs among different pollutants. Pollutants of interest include criteria pollutants and precursors, air toxics, and greenhouse gases. The results of this research will be published in a final report and should be useful for agencies undertaking air quality planning as well as greenhouse gas mitigation efforts.

Please complete the survey no later than Wednesday December 16, 2009, or pass along to an appropriate colleague. If you have any questions about the survey or research effort, please reply to this e-mail or contact the research manager:

Chris Porter
Cambridge Systematics, Inc.
cporter@camsys.com
617-354-0167

Thank you for your assistance!

F. Web-Based Survey Responses

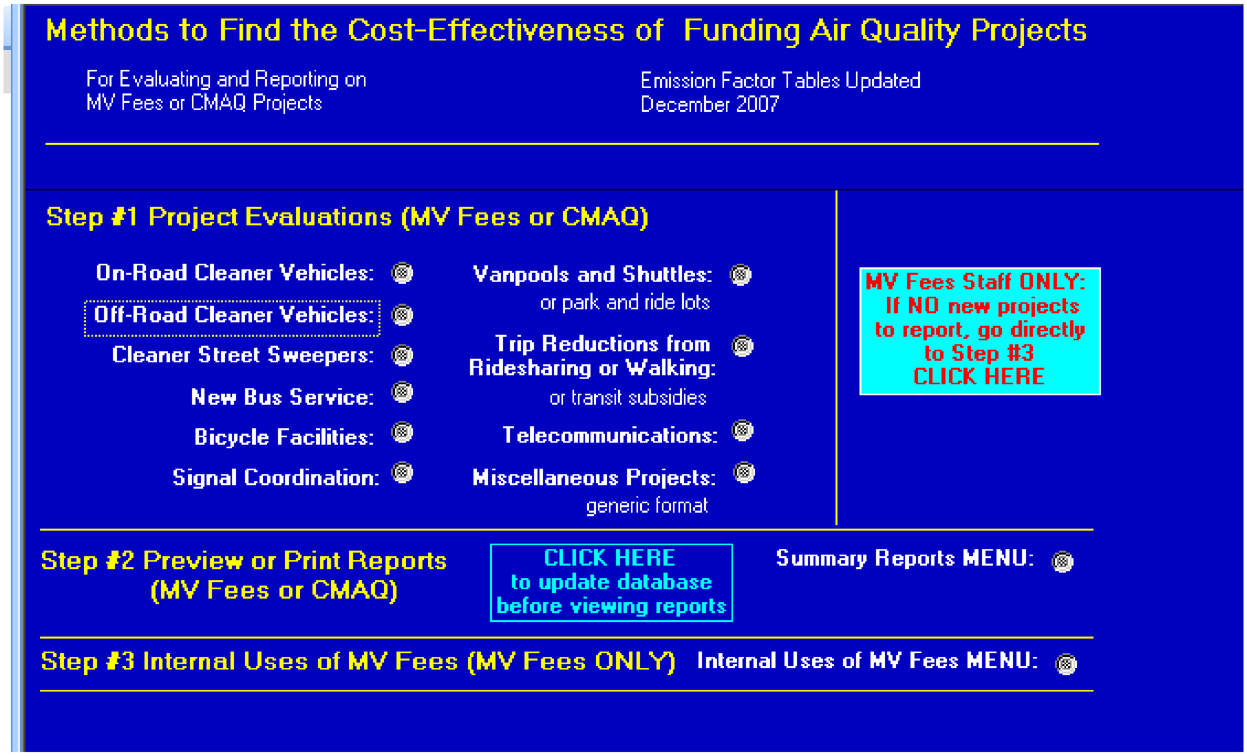
Table F.1 Web-Based Survey Responses

Agency	Q1 HC, VOC	Q1 CO	Q1NOx	Q1 PM	Q1 GHG	Q1 Toxics	Q1 Other	Q2	Q2a CMAQ	Q2a Other TIP	Q2a Conformity	Q2a SIP	Q2a GHG Inventory	Q2a Other	Q3 CE Individual	Q3 CE Multiple	Q3 Weighting
Atlanta Regional Commission	●		●	●			●								●		
Capital District Transportation Committee	●		●		●												
Chicago Metropolitan Agency for Planning (CMAP)	●		●	●	●										●		
Connecticut DOT	●	●	●	●	●				●		●	●	●		●		
Connecticut DOT[a]	●	●	●	●		●											
Delaware Valley Regional Planning Commission (DVRPC)	●	●	●	●													
Georgia DOT			●	●												●	
Kentucky Transportation Cabinet	●	●	●	●													
Maricopa Association of Governments	●	●	●	●				●	●							●	
Metropolitan Washington Council of Governments (MWCOG)	●	●	●	●	●										●		
Mid-Ohio Regional Planning Commission (MORPC)	●		●	●											●		
Missoula Office of Planning and Grants		●		●				●	●	●	●	●					
New York Metropolitan Transportation Council (NYMTC)	●	●	●	●			●	●	●						●		●
North Central Texas Council of Governments	●	●	●	●	●	●		●					●	●	●		
Pima Association of Governments		●															
Poughkeepsie-Dutchess County Transportation Council	●	●	●		●			●	●		●				●		
Sacramento Area Council of Governments	●	●	●	●	●											●	
San Diego Association of Governments (SANDAG)	●	●	●		●											●	
Southern California Association of Governments	●	●	●	●				●	●	●		●					
Virginia DOT	●	●	●	●		●	●	●	●		●	●		●	●		

[a] Two responses were received from this agency.

G. California Air Resources Board Cost-Effectiveness Analysis Tool

Figure G.1 Screenshot from the Tool



Methods to Find the Cost-Effectiveness of Funding Air Quality Projects

For Evaluating and Reporting on
MV Fees or CMAQ Projects

Emission Factor Tables Updated
December 2007

Step #1 Project Evaluations (MV Fees or CMAQ)

On-Road Cleaner Vehicles: ○
Off-Road Cleaner Vehicles: ○
Cleaner Street Sweepers: ○
New Bus Service: ○
Bicycle Facilities: ○
Signal Coordination: ○

Vanpools and Shuttles: ○
or park and ride lots
Trip Reductions from Ridesharing or Walking: ○
or transit subsidies
Telecommunications: ○
Miscellaneous Projects: ○
generic format

MV Fees Staff ONLY:
If NO new projects to report, go directly to Step #3
CLICK HERE

Step #2 Preview or Print Reports
(MV Fees or CMAQ)

CLICK HERE
to update database
before viewing reports

Summary Reports MENU: ○

Step #3 Internal Uses of MV Fees (MV Fees ONLY)

Internal Uses of MV Fees MENU: ○

Data Requirements by Strategy Needed to Run the California ARB Tool

- **On-Road Cleaner Vehicle Purchases and Repowering**
  - Funding dollars
  - Annual vehicle miles traveled (VMT)
  - Engine certification rates or cleaner vehicle classification
- **Off-Road Cleaner Vehicle Purchases and Repowering**
  - Funding dollars
  - Annual vehicle operating hours
  - Horsepower
  - Engine load factor
- **Cleaner Street Sweeper Purchases**
  - Funding dollars
  - Annual fuel usage
  - Engine certification rates
  - Annual miles swept
- **Operation of New Bus Service**
  - Funding dollars
  - Number of operating days per year
  - Average daily ridership of new service (usually less than 100 percent occupancy)
  - Average length of auto trips replaced
  - Percent of riders who drive to the bus service
  - Annual VMT for the new bus service
- **Vanpools and Shuttles**
  - Funding dollars
  - Number of operating days per year
  - Average daily ridership of new service (usually less than 100 percent occupancy)
  - Average length of auto trips replaced
  - Percent of riders who drive to the vanpool or shuttle service
  - Daily VMT for the new shuttle service

- **Signal Coordination**
  - Funding dollars
  - Number of operating days per year
  - Traffic volumes for the congested periods of the day
  - Length of the roadway segment impacted by the project
  - Before and after average traffic speeds
- **Bicycle Facilities**
  - Funding dollars
  - Number of operating days per year
  - Average length of bicycle trips
  - Average daily traffic volume on roadway parallel to bicycle project
  - City population
  - Project class (1 or 2)
  - Types of activity centers in the vicinity of the bicycle project
  - Length of bicycle path or lane
- **Telecommunications**
  - Funding dollars
  - Work weeks per year
  - Weekly one-way auto trips eliminated (i.e., home-work trips or work-meeting trips)
  - Average length of auto trips eliminated
  - (i.e., distance from home to work or from work to meeting)
  - Weekly one-way auto trips to telesite
  - Average length of auto trips to telesite
- **Ridesharing and Pedestrian Facilities**
  - Funding dollars
  - Work weeks or operating weeks per year
  - Weekly one-way auto trips eliminated
  - Average length of auto trips eliminated

H. Multipollutant Effects of Emission Reduction Strategies

Table H.1 Travel Demand Management Strategies

Air Pollutant Control Strategy	Direction/Magnitude of Impact						Level of Confidence in Cost-Effectiveness Estimates	Key Uncertainties			Comments
	VOC	CO	NO_x	PM	Toxics	CO_2/GHG		Technological	Implementation	Time-Dimension Effects	
VMT Reduction											
Employer-Based TDM Programs	↓	↓	↓	↓	↓	↓	Moderate		• Population reached • Response rate (mode-shifting) • Prior mode of travel • Amount/quality of alternative transport modes available	• Most VMT reduction strategies will become relatively less cost-effective over time as technology improves and emission rates decrease • Land use and nonmotorized strategy benefits may take longer to be realized in practice, versus short-term benefits from most strategies	
Other TDM Programs (School, Community/ Residential, etc.)	↓	↓	↓	↓	↓	↓	Low				Little evidence available
Areawide Ridesharing Programs	↓	↓	↓	↓	↓	↓	Moderate				
Telework and Alternative Work Schedules	↓	↓	↓	↓	↓	↓	Low	• Incremental cost of telework equipment and services			High uncertainty over costs
Bicycle/Pedestrian Projects and Programs	↓	↓	↓	↓	↓	↓	Low		• Quality of bicycle/pedestrian facilities • Surrounding land use and trans network		Wide range of reductions for projects implemented
Land Use Strategies	↕	↕	↕	↕	↕	↓	Low (Local) Moderate (Regional)	• Localized emissions changes as a result of changes in local congestion	• Effects of land use policies on development patterns • Effects of development patterns on travel		Should result in regional emission reductions for all pollutants, but may be some localized increases
General Road/Travel Pricing (VMT fee, fuel tax)	↓	↓	↓	↓	↓	↓	Moderate		• Amount of charge (including geographic and temporal extent) • Amount/quality of alternative transportation options or destinations		
Parking Pricing/Management	↓	↓	↓	↓	↓	↓	Moderate				
Transit Pricing – Fare Discounts/Incentives	↓	↓	↓	↓	↓	↓	Moderate				
Park-and-Ride Facilities	↓	↓	↓	↓	↓	↓	Moderate	• Trip lengths and contribution of start emissions	• Demand for facilities		
Transit Marketing, Information, and Amenities	↓	↓	↓	↓	↓	↓	Low		• Population reached • Response rate (mode-shifting) • Prior mode of travel		Little evidence available
VMT Reduction + New Transportation Service											
New/Expanded/Increased Transit Service	↓	↓	↕	↕	↕	↕	Low	• Transit vehicle and fuel technology versus automobile emissions characteristics	• Ridership/load factors • Prior mode of travel of transit riders	Will depend upon relative advancements in vehicle technology over time	Could be net increase in emissions if insufficient ridership
Vanpool Programs	↓	↓	↓	↓	↓	↓	Moderate	• Vanpool vehicle and fuel technology versus automobile emissions characteristics	• Ridership/load factors • Prior mode of travel of transit riders		Could be net increase in emissions if insufficient ridership
Freight Rail/Intermodal Improvements	↓	↓	↕	↕	↕	↓	Low	• Freight rail technology versus truck emissions characteristics	• Freight mode shift potential • Total supply chain emissions		Little evidence available

Table H.2 Transportation System Management Strategies

	Direction/Magnitude of Impact						Level of Confidence in Cost-Effectiveness Estimates	Key Uncertainties			
Air Pollutant Control Strategy	**VOC**	**CO**	**NO_x**	**PM**	**Toxics**	**CO_2/GHG**		**Technological**	**Implementation**	**Time-Dimension Effects**	**Comments**
Congestion Relief											
Managed Lanes (HOV/HOT/Truck-Only)	↓	↕	↕	↓	↓	↓	Low	• Uncertainty over speed-emissions relationships for some pollutants, especially PM and for direction of relationship at higher speeds	• Increase in HOV and transit use • General purpose lane changes in traffic flow	• Most TSM strategies likely to become less cost-effective over time as emission rates decrease • Widespread penetration of hybrid or electric-drive vehicles will further decrease effectiveness	
Congestion Pricing	↓	↕	↕	↓	↓	↓	Low		• Method of administration • Amount and variation of charge • Changes in traffic flow by time of day		
Signal Timing and Coordination	↓	↕	↕	↓	↓	↓	Low		• Induced demand		
Intersection Improvements	↓	↕	↕	↓	↓	↓	Low		• Induced demand		
Incident Management	↓	↕	↕	↓	↓	↓	Low		• Induced demand • Changes in traffic flow		
Ramp Metering	↓	↕	↕	↓	↓	↓	Low		• Metering patterns and effect on mainline flow • Impacts on arterial roadways		
Traveler Information	↓	↕	↕	↓	↓	↓	Low		• Alternatives available and utilized • Effect on travelers' decision-making • Systemwide effects on traffic flow		Little evidence available
Other Systems Management											
Speed Limit Enforcement/Reduction	↓	↓	↓	↓	↓	↓	Low	• Uncertain speed-emissions relationships at highway speeds	• Specific speed limit change • Strictness of enforcement		It is assumed that speed reduction would push emission rates to most efficient part of speed versus emission rate curve
Vehicle Idling Restrictions/Programs	↓	↓	↓	↓	↓	↓	Moderate	• Some offsetting increases from alternative power equipment	• Participation rates		

Table H.3 Vehicle and Fuel Technology Strategies

		Direction/Magnitude of Impact						Level of Confidence in Estimates of:			Key Uncertainties			
Air Pollutant Control Strategy	**Technology**	**VOC**	**CO**	**NO_x**	**PM**	**Toxics**	**CO_2/GHG**	**Effectiveness**	**Costs**	**Cost-Effectiveness**	**Technological**	**Implementation**	**Time-Dimension Effects**	**Comments**
Vehicle Technologies														
Diesel Engine Retrofits (HD)	DPF	↓ 60%-90%	↓ 60%-90%		↓ 90%	↕ Varies by species	↑ 2%-4%	High	High	High	Many PM-related retrofits well-demonstrated through EPA/CARB certification process. Unit-specific uncertainty can be significant due to uncertainty in load/exhaust temperature profiles.	Market penetration facilitated by DERA and related grants. Substantial uncertainties regarding quality and frequency of required maintenance for PM retrofits; and for reductant recharge for SCR/SNCR.	ALL diesel retrofit options become relatively less important with time as 2007-2010 emission standards will require many of these technologies. On the other hand, the need for HDV I/M will likely increase to minimize advanced component degradation.	
	CDPF	↓ 20%-90%	↓ 20%-90%	↓ 0%-5%	↓ 90%		↑ 1%-4%	High	High	High				
	DOC	↓ 20%-90%	↓ 20%-90%		↓ Up to 50%		↑ 2%	High	High	High				
	CCV	↓ 30%-40%	↓ 30%-35%		↓ 10%-25%	▯		High	High	High				
	FBC	↓ Up to 50%	↓ Up to 50%	↓ Up to 10%	↓ Up to 33%	↑ Fine metallic		High	High	High				
	FBC/CDPF	↓ 80%	↓ 80%	↓ < 10%	↓ 85%		↑ Up to 2%	High	High	High				
	FBC/DOC	↓ Up to 50%	↓ Up to 50%	↓ Up to 10%	↓ 30%-60%	↑ Fine metallic	↑ 4%-6%	High	High	High				
	EGR			↓ Up to 40%-50%	↑		↑ Up to 5%	High	Moderate	Moderate	Further demonstration and testing needed for NO_x-related retrofits. Equipment costs uncertain for full production volumes. Substantial uncertainty due to load profile dependence.			
	EGR/DPF	↓ 60%-90%	↓ 60%-90%	↓ Up to 50%	↓ Up to 90%		↑ Up to 5%	High	Moderate	Moderate				
	LNC			↓ 10%-25%			↑ 3%-7%	High	Moderate	Moderate				
	LNC/DPF	↓ 60%-90%	↓ 60%-90%	↓ 20%-25%	↓ Up to 90%		↑ 4%-7%	High	Moderate	Moderate				
	NO_x Adsorber	↓ Up to 90%	↓ Up to 90%	↓ > 90%	↓ 10%-30%			High						
	SCR	↓ 50%-90%	↓ 50%-90%	↓ Up to 90%	↓ Up to 50%		↑ 3%-6%	Moderate	Moderate	Moderate				
	SNCR			↓				Moderate						
	Reflash	↓	↓	↓ Up to 25%	▯		↑ <1%	High	High	High		Participation rates uncertain as fuel economy may suffer as a result.		

		Direction/Magnitude of Impact						Level of Confidence in Estimates of:			Key Uncertainties			
Air Pollutant Control Strategy	**Technology**	**VOC**	**CO**	**NO_x**	**PM**	**Toxics**	**CO_2/GHG**	**Effectiveness**	**Costs**	**Cost-Effectiveness**	**Technological**	**Implementation**	**Time-Dimension Effects**	**Comments**
Vehicle Technologies (continued)														
Diesel Vehicle/ Trailer Retrofits (HD)	Aerodynamics, rolling resistance, weight reduction	↕	↕	↓	↕		↓ (Typically < 5% for individual measures)	High (CO_2); Moderate (NO_x); Low (Others)	Moderate/ High	Moderate/High	Further testing needed to quantify non-CO_2 benefits over different drive cycles and vehicle types. Equipment costs uncertain at full production. Performance varies greatly depending upon speed profile.	Uncertainty in market penetration given moderate up-front capital costs (a few thousand dollars typically); payback period made more uncertain by fuel price volatility. Subsidy/low interest loan programs such as SmartWay help facilitate adoption.	May become less effective if these strategies are adopted by OEMs to meet potential Federal HD fuel economy standards.	Long-haul operation more effective for both CO_2 and NO_x reductions than short-haul.
Accelerated Retirement (LD and HD)		↓	↓	↓	↓		↕	Moderate/High	Moderate	Moderate	Per-mile benefits relatively certain based on difference in vehicle certification standards.	Substantial uncertainty associated with programmatic differences (e.g., which ages qualify, incentive fee), and miles traveled before and after scrappage. If use of new vehicle induces mode shifts and/or net increases in VMT, benefits will be diminished or even negated.	Programs become less effective with time as base fleet becomes cleaner.	LD programs may inflate the local resale market, with disproportionate impacts on low-income drivers.
Hybrid and Electric Vehicles (LD and HD)	Light-Duty – HEV	↕	↕	↕	↕		↓	High (CO_2); Moderate (Others)	High	High	HEVs well-demonstrated at full production volumes, with no criteria pollutant concerns encountered.		HEV, PHEV, and BEV efficiency are projected to improve over time, so the impact of improving fleet average fuel economy will be lessened.	
	Light-Duty – PHEV	↕	↕	↕	↕	↕	↓		Moderate	Moderate	PHEV costs relatively uncertain as battery costs remain at very low production volumes. Impact of EGU emissions relatively unknown, varying with location and over time. Further battery demonstration needed.	Substantial uncertainty associated with charger access and battery charging times, which varies costs and emission benefits.		
	Light-Duty – Full Elec	↕	↕	↕	↕	↕	↓		Low	Low	Highly uncertain costs associated with large scale BEV production. EGU emissions uncertainty. Further battery-range improvements required.			
	Heavy-Duty – HEV	↕	↕	↕	↕		↓		Moderate	Moderate	Hydraulic hybrid (MDV) and HEV (HDV) technologies require further development and demonstration for effectiveness and cost determination.	Hybrid applications restricted by drive-cycle constraints, as well as up-front costs.		

		Direction/Magnitude of Impact						Level of Confidence in Estimates of:			Key Uncertainties			
Air Pollutant Control Strategy	**Technology**	**VOC**	**CO**	**NO_x**	**PM**	**Toxics**	**CO_2/GHG**	**Effectiveness**	**Costs**	**Cost-Effectiveness**	**Technological**	**Implementation**	**Time-Dimension Effects**	**Comments**
Vehicle Technologies (continued)														
Idle Reduction Technologies (HD)	APU	↓	↓	↓ > 90%	↑		↓ ~50-75%	High (NO_x, CO_2)/ Moderate (PM)	High	High (NO_x, CO_2)/ Moderate (PM)		Utilization rates uncertain without mandates – largely dependent on fuel prices, which are volatile.	Unlike many other strategies, idle emissions become relatively more important with time, as many 2007+ OEM technologies have limited impact at idle.	Emissions changes relative to 2007 diesel truck using 15 ppm sulfur fuel.
	APU+DPF	↓	↓	↓ > 90%	↓ ~30-50%		↓ ~50-75%	High (NO_x, CO_2)/ Moderate (PM)	High	High (NO_x, CO_2)/ Moderate (PM)	DPF required for PM reductions, as per CARB requirements.			
	DFH	↓	↓	↓ > 95%	↓ ~55%		↓ ~90%	High (NO_x, CO_2)/ Moderate (PM)	High	High (NO_x, CO_2)/ Moderate (PM)				
	Storage cooling	↓	↓	↓ > 95%	↓ ~65%		↓ ~85%	High (NO_x, CO_2)/ Moderate (PM)	High	High (NO_x, CO_2)/ Moderate (PM)				
	TSE	↓	↓	↓ > 95%	↑		↓ ~80%	High (NO_x, CO_2)/ Moderate (PM)	High	High (NO_x, CO_2)/ Moderate (PM)	Substantial variability by time of day, region of country, especially for PM		Will improve over time as new cleaner EGUs are brought on-line.	
Inspection/Maintenance Programs (LD)	TSI	↓	↓	↕	↕		↕	High	High	High	Well established test procedures, cost, and effectiveness.	Some programmatic variation in fees, model years covered, waiver rates, failure cutpoints.	Becoming less cost-effective as pre-1996 vehicles become a smaller fraction of test fleet, with lower VMT.	
	ASM/IM240	↓ Up to 15%	↓ Up to 15%	↓ Up to 8%	↓		↓ <=1%							
	OBD	↓	↓	↓	↕			Moderate/High		Moderate/High	Well established test procedures and cost, but effectiveness more uncertain as results are not often correlated with emissions tests.	Some programmatic variation in fees, model years covered, exempted codes.	Becoming more cost-effective as OBD-equipped vehicles begin to dominate the fleet, AND begin to develop more component failures with age.	
National Fuel Economy and Emission Standards (LD)	Various CAFE measures	↕	↕	↕	↕		↓	High (CO_2); Low (Others)	High/ Moderate	High (CO_2); Low (Others)	No strong correlation between criteria and GHG emissions observed. Few technical concerns with meeting stringent Tier 2 standards and beyond.		Proposed standards progressive through 2025.	
Low-Carbon Fuels														
Biodiesel (B20) (HD)		↓ ~12%	↓ ~17%	↕ Up to 2% increase	↓ ~16%	↓	↕ Varies by tailpipe/life cycle	High	Moderate	Moderate	Significant emission testing with different blend percentages and engine technologies; uncertainty remains regarding NO_x impacts.	Substantial uncertainty regarding fuel availability and purchase frequency (for bi/dual/flex fuel vehicles); fuel price differentials increase likelihood of choosing conventional fuel.	Uncertain impacts with 2010 technologies (e.g., SCR).	Also uncertain interaction with retrofits.
Compressed/Liquefied Natural Gas, LPG (HD)		↓	↓	↓	↓		↓ Likely CH_4 increase	High	Moderate	Moderate	Uncertain OEM vehicle costs at high volumes.		Incremental benefits will diminish relative to HDDVs as 2007-2010 standards are introduced.	Benefits associated with dedicated vehicles greater than bi/dual/flex fuel models.
Ethanol (E85) (LD)		↑	↓	↓	↓	↕ Varies by species	↕ Varies by tailpipe/life cycle	High	Moderate	Moderate	Fuel costs largest source of uncertainty.			