# CONGESTION MITIGATION AND AIR QUALITY (CMAQ) IMPROVEMENT PROGRAM

## Cost-Effectiveness Tables Development and Methodology

Prepared for:

**Office of Natural Environment**
**Office of Planning, Environment, and Realty**
**Federal Highway Administration**
**U.S. Department of Transportation**

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# FOREWORD

The SAFETEA-LU directed states and Metropolitan Planning Organizations (MPOs) to give priority to Cost-effective transportation projects, including diesel retrofits and congestion mitigation efforts that also produced an air quality benefit. The MAP-21 continues and expands the project selection focus on efficiency and cost-effectiveness. The MAP-21 also calls for the development of cost-effectiveness tables (Tables) for a range of CMAQ eligible project types. These Tables are intended to assist States, MPOs and other project sponsors as they make the most efficient use of their CMAQ dollars in reducing on road vehicle emissions and traffic congestion.

These online materials provide information regarding the development of estimates of cost-effectiveness for a range of representative project types previously funded under the CMAQ Program. Topics addressed in the development of these Tables include: key limitations of the cost –effectiveness analysis process; utilization of MOVES in determining emissions rates by criteria pollutant; and the selection of specific project types for analysis. The results of the relative cost analysis of CMAQ projects is displayed in bar charts by pollutant type in increasing order of project median cost. An aggregate table of summary finding displays a color coded display for all pollutants and all project types.

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16. Abstract

This document presents summary and detailed findings from a research effort to develop estimates of the cost-effectiveness of a range of project types funded under the Congestion Mitigation and Air Quality (CMAQ) Improvement Program. In this study, cost-effectiveness was measured in terms of dollars per short ton of pollutant reduced. The estimates were generated to satisfy Title 23, Chapter 1, Section 149 of the United States Code, which mandates illustrative estimates of the cost-effectiveness of projects eligible for CMAQ funding.

This research offers separate cost-effectiveness estimates by each criteria pollutant and applicable precursor under the CMAQ program, including: carbon monoxide (CO) monoxide, nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter ($PM_{10}$ and $PM_{2.5}$).

This research utilized EPA's MOVES2010b (Motor Vehicle Emission Simulator 2010, Version B) model to identify emission impacts by criteria pollutant and applicable precursors. In this research, estimates of project-level impacts (e.g., VMT impacts, travel speeds) were combined with unit (e.g., per-mile, per-hour) emission rates from MOVES2010b to yield estimated emission impacts in lieu of using either direct estimates from projects or relatively outdated tools (e.g., MOBILE6.2, (Mobile Source Emission Factor Model)).

The analysis confirmed the presence of distinct levels of cost-effectiveness across types of projects and pollutants. Project types with estimated high cost-effectiveness include:

- Heavy-duty vehicle idle reduction strategies (with high cost-effectiveness for all pollutants in the study);
- heavy vehicle engine replacements (with high cost-effectiveness for all pollutants except for carbon monoxide);
- diesel retrofit technologies (with high cost-effectiveness for $PM_{2.5}$, $PM_{10}$ and CO);
- transit service expansion (with high cost-effectiveness for NOx, VOCs and CO);
- park and ride projects (with high cost-effectiveness for NOx, VOCs and CO);
- extreme-temperature cold start technologies (with high cost-effectiveness for VOCs and CO);
- intermodal freight projects (with high cost-effectiveness for NOx); and
- dust mitigation (with high cost-effectiveness for $PM_{10}$).

17. Key Words
**CMAQ, COST-EFFECTIVENESS TABLES, MOBILE SOURCE EMISSIONS, PM2.5, NOx, VOCs, CO, PM10**

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

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

## APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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# CHAPTER ONE: BACKGROUND AND SUMMARY FINDINGS

## RESEARCH OBJECTIVE

The research detailed in this document centers on the development of estimates of the cost-effectiveness of a range of representative project types funded under the Congestion Mitigation and Air Quality (CMAQ) Improvement Program. The estimates were generated to satisfy Title 23, Chapter 1, Section 149 of the United States Code, which mandates illustrative estimates of the cost-effectiveness of projects receiving CMAQ funding. The estimates were also generated for consistency with the Moving Ahead for Progress in the 21st Century Act (MAP-21, Public Law 112-141), which included changes in both project priorities and project eligibility under the CMAQ Program. Complete details on project eligibility within the CMAQ Program are described in CMAQ Guidance: *November 2013 CMAQ Interim Program Guidance.*

## MAP-21

The central language of relevance to this study of MAP-21, 23 U.S.C. Sec. 149, (i), follows:

> (2) COST EFFECTIVENESS.—
>
> (A) IN GENERAL.—The Secretary, in consultation with the Administrator of the Environmental Protection Agency, shall evaluate projects on a periodic basis and develop a table or other similar medium that illustrates the cost effectiveness of a range of project types eligible for funding under this section as to how the projects mitigate congestion and improve air quality.
>
> (B) CONTENTS.—The table described in subparagraph (A) shall show measures of cost-effectiveness, such as dollars per ton of emissions reduced, and assess those measures over a variety of timeframes to capture impacts on the planning timeframes outlined in section 134.
>
> (C) USE OF TABLE.—States and metropolitan planning organizations shall consider the information in the table when selecting projects or developing performance plans under subsection (l).

The legislative language is somewhat vague in terms of specific requirements, but it is reasonable to expect that the cost-effectiveness tables should achieve the following objectives:

- Cover a range of project types that reflects current practice and potential changes in practice;
- Include analysis based on representative examples within the range of selected project types;

- Present results in an intuitive and useful form (e.g., dollars per ton of pollutant reduced); and

- Cover examples that span a range of relevant timeframes (e.g., short-term operating assistance and long-term infrastructure investment).

Key limitations of the analysis are listed below:

- The range of analytical scenarios is intended to cover neither the full range of potential outcomes within a project type, nor the full range of potential projects.

- The analysis centers on a snapshot of data from the CMAQ database, which limits the scope of inference that can be drawn. In many cases, project details are not reported in the CMAQ database. In cases where project details are available, the details contain their own uncertainties that carry forward into analysis of projects identified within the database. Furthermore, the range of projects available in the CMAQ database may span a varying range of projects by type over different time horizons.

- Some elements in the analysis incorporates estimates of technological effectiveness (i.e., per-unit emission impacts) and usage (e.g., hours of idling, vehicle miles of travel) from EPA's Diesel Emissions Quantifier (DEQ). Hence, analysis calibrated with respect to values from the DEQ is a direct function of the values seeded in the DEQ. At the time of writing, the DEQ was being updated with an expected release in 2016. It is important to note that the DEQ calculates PM2.5 impacts, but not PM10 impacts.

- Difficulties in identifying representative project examples for some project types limited the range of potential projects included in the analysis. It can be difficult to identify key data for some candidate projects (e.g., project costs, associated travel demand). Ultimately, the range of project types included in the analysis is targeted at representing an informative view of the relative performance of predominant (and potentially predominant) project types across the range of pollutants in the study, rather than serving as a census of all projects eligible for CMAQ funding.

- The CMAQ Program's primary objective is to reduce emissions and congestion for the purpose of improving air quality. However, cost-effectiveness with respect to reducing pollutant emissions and congestion is not necessarily the only reason to choose a project for implementation. Rather, a wide range of additional impacts may also be considered when evaluating projects for CMAQ funding. In this analysis, we are focusing on the two central issues relevant to the CMAQ program, emission reductions and reductions in traffic congestion.

## Development and Presentation of Cost-Effectiveness Estimates

### *Disaggregation by Criteria Pollutant*

The most significant information developed within this research is the specification of separate cost-effectiveness estimates for each criteria pollutant and applicable precursor under the CMAQ program, including (listed in order of appearance in the summary tables at the end of this chapter):

- Fine particulate matter ($PM_{2.5}$),
- Nitrogen oxides (NOx),
- Volatile organic compounds (VOCs),
- Carbon monoxide (CO), and
- Particulate matter ($PM_{10}$).

Previous research focused on a smaller subset of pollutants (chiefly VOCs and NOx), and also tended to combine estimated emission impacts of projects into a composite measure (e.g., tons of VOC equivalents). This research focuses on individual estimates of cost-effectiveness by pollutant to avoid combining impacts on multiple pollutants. For example, a composite measure of cost-effectiveness for a project that has strong impacts on VOCs but minimal impacts on $PM_{2.5}$ may indicate high cost-effectiveness in reducing pollutants overall, despite being weakly cost-effective in reducing $PM_{2.5}$.

### *Use of MOVES2010b*

This research utilizes EPA's MOVES2010b (Motor Vehicle Emission Simulator 2010, Version B) model to identify emission impacts by criteria pollutant. In this research, estimates of project-level impacts (e.g., VMT impacts, travel speeds) were combined with unit (e.g., per-mile, per-hour) emission rates from MOVES2010b to yield estimated emission impacts in lieu of using either direct estimates from projects or older emission models like MOBILE6.2.

The analytical work in this study was substantially complete when a new version of MOVES (MOVES2014) was released. Related research was conducted to verify the empirical impacts of the use of MOVES2014 relative to MOVES2010b (e.g., changes in emission rates for a given type of analytical run), after which it was decided to continue with the use of MOVES2010b for this study, rather than replicate the range of completed analytical runs in MOVES2014. It would be appropriate to apply the most recent version of MOVES in any updates to this research, rather than continuing to use estimates from MOVES2010b.

The version of MOVES used in this report does not include the effects of the latest emissions standards for motor vehicles. In particular, MOVES2010b does not include Tier 3 standards that impact model year 2017 and later heavy-duty vehicles, heavy-duty greenhouse gas rules for model year 2014-2018 vehicles, and light-duty greenhouse gas rules for model year 2017-2025 vehicles. As a result, some emissions from the vehicle fleet and the cost-effectiveness of reducing those emissions, especially for projects that have long lifetimes, may be biased upwards.

The Use of MOVES2010b section in Chapter Two outlines the approach taken to incorporate emission data from MOVES2010b within the development of the pollutant-specific cost-effectiveness impacts presented in this document.

### *Assumptions and Limitations*

The analytical process in this research is based on a range of assumptions that were adopted either out of necessity or for consistency with transportation and environmental policy. Central assumptions for the analysis are listed below:

- Emission impacts are not discounted across project lifetimes. The analysis assumes constant annual impacts across project lifetimes, unless variable information across years was available (e.g., changes in expected emission rates calculated within MOVES2010b);
- The cost-effectiveness of a project with respect to one pollutant is independent of the project's impacts on other pollutants;
- The information on projects collected through a review of CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study) and non-FHWA documents is representative of the range of projects seeking CMAQ funding;
- The full project cost is included in calculations of cost-effectiveness measures, rather than the share of project costs receiving CMAQ funding;
- The full project cost is assigned to the first year of the project , rather than discounting across years that projects would be active (or across years that project funds would be applied). This represents the timing of the obligation of funds from the CMAQ Program toward projects (i.e.,as lump sums). ;
- The project cost does not differentiate between shares of funds applied across funding needs for a given project (e.g., capital costs versus operation costs and maintenance costs);
- For project types involving vehicle- or user-specific tools (e.g., diesel retrofits, transit benefits), project costs reflect unit costs only;
- Specifications of vehicle fleet characteristics and travel activity within MOVES are representative of the vehicle fleet and travel activity affected by CMAQ projects for all years represented in the analysis; and

- Median cost-effectiveness estimates are the preferred measures to compare cost-effectiveness across project types. The median cost-effectiveness estimate is identified as the 50th-percentile value across the set of cost-effectiveness estimates generated using the process described above.

These assumptions are detailed in the Use of MOVES2010b section in Chapter Two.

The range of analytical scenarios is intended to cover neither the full range of potential outcomes within a project type, nor the full range of potential projects. The analysis centers on a snapshot of data, which limits the scope of inference that can be drawn. Difficulties in identifying representative project examples for some project types limited the range of potential projects included in the analysis, and the range of project types was further constrained through the relative maturity of some project types (i.e., some project types that have been included in previous analyses are no longer funded commonly within CMAQ). Hence, the range of project types included in the analysis is targeted at representing an informative view of the relative performance of predominant (and potentially predominant) project types across the range of pollutants in the study, rather than serving as a census of all projects eligible for CMAQ funding.

## PROJECT TYPES

The November 2013 CMAQ Interim Program Guidance identifies the eligibility of 17 types of projects under Map-21. Following consultation with stakeholders and a review of relevant content in MAP-21, the range of project types represented in the summary of CMAQ funding was supplemented with additional project types in the analysis, including:

- Park and Ride
- Rideshare Programs
- Employee Transit Benefits
- Carsharing
- Bikesharing
- Electric Vehicle Charging Stations
- Idle Reduction Strategies
- Bicycle and Pedestrian Paths
- Intermodal Freight Facilities and Programs
- Transit Service Expansion
- Transit Amenity Improvements
- Intersection Improvements
- Roundabouts
- Incident Management
- Heavy Vehicle Engine Replacements
- Diesel Retrofit Technologies
- Extreme-Temperature Cold-Start Technologies
- Dust Mitigation
- Natural Gas Re-Fueling Infrastructure

### CMAQ Funding by Project Type

The selection of project types in the analysis was conducted following a review of CMAQ funded projects and consultation with USDOT, EPA and state-level stakeholders. A summary of CMAQ funded projects is useful in gaining an understanding of the prevalence of various project types. According to the CMAQ Public Access System, in 2013 (the most recent fiscal year for which data was available at the time of the analysis), 2023 projects received CMAQ funding; additional funding was applied to joint Surface Transportation Program (STP) and CMAQ projects with different eligibility criteria (around 14 percent of the total). Around 40 percent of the CMAQ projects receiving funding involved traffic flow improvements; bicycle and pedestrian projects represented the next largest group, at 19 percent, followed by transit projects, at nine percent.

In terms of shares of overall CMAQ obligations in FY2013, traffic flow improvements and transit projects received the largest, and approximately equal, shares, at 36 percent and 33 percent respectively. The remaining project types received similar shares of total CMAQ funding, including around four percent for traffic control measures and travel demand management projects, around five percent for shared ride projects, and around seven percent for pedestrian and bicycle projects.

This information provides a meaningful background to help gauge the relative prominence of project types within CMAQ. In particular, traffic flow improvements and transit projects are focal project types when comparing CMAQ project approvals and funding shares. While the analysis in this study is not restricted to a distribution of projects consistent with the funding summary above, the information underscores areas of key activity within the CMAQ program. This is valuable in terms of ensuring both meaningful coverage of projects within the analysis, and effective interpretation of analytical results by including a focus on the relative cost-effectiveness of high-profile project types.

## SUMMARY FINDINGS

This section presents a summary of findings from the cost-effectiveness analysis. Cost-effectiveness estimates for individual pollutants are then presented in the following section: SUMMARY COST-EFFECTIVENESS ESTIMATES. Figure 1 below offers a comparison of the median cost-effectiveness estimates for each project type and pollutant in the analysis:

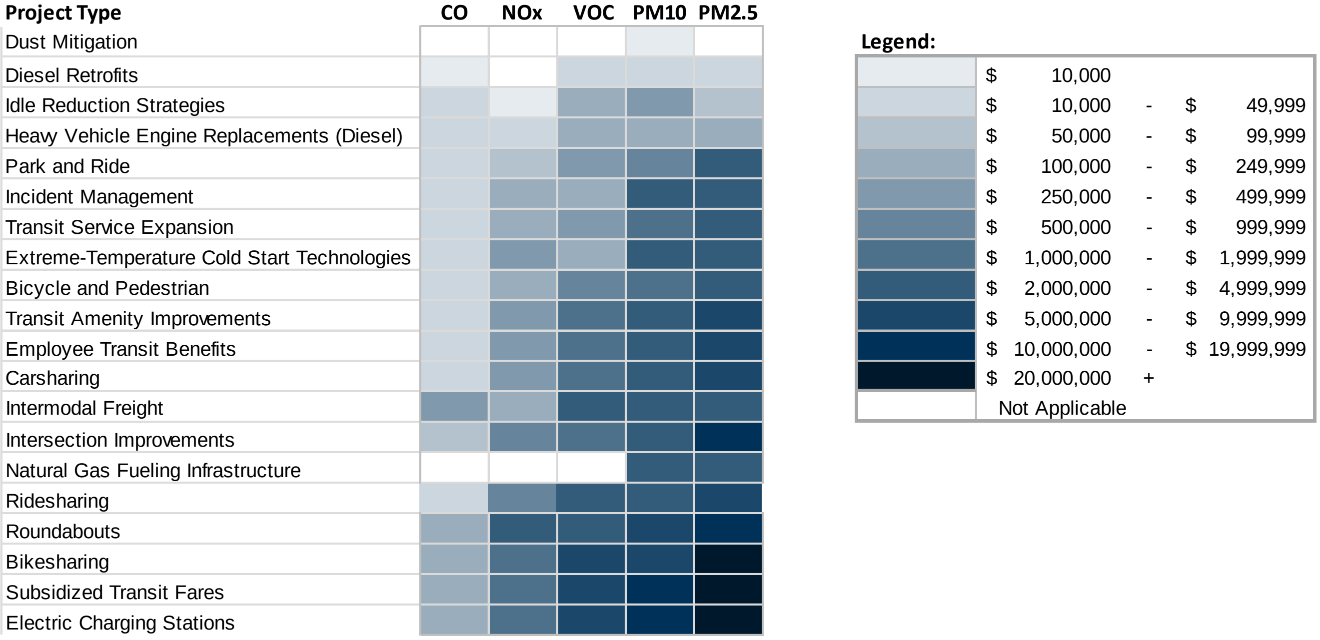

**Figure 1. Median Cost-Effectiveness Estimates (Dollars per Ton of Pollutant Reduced).**

The analysis yielded a broad range of cost-effectiveness estimates, represented in terms of dollars per ton of pollutant reduced. The most critical findings relate to project types that indicate particularly strong or weak cost-effectiveness, for either individual pollutants or across the range of pollutants.

## Project Types with Strong Cost-Effectiveness

Table 1 summarizes the best-performing project types by pollutant, based upon the distributions of cost-effectiveness measures evaluated at the median:

**Table 1. Project Types with Strongest Estimated Cost-Effectiveness.**

| Project Type | Pollutants with Most Cost-Effective Reduction |
|---|---|
| Idle Reduction Strategies | All pollutants |
| Heavy-Duty Vehicle Engine Replacements | NOx, VOCs, $PM_{10}$, $PM_{2.5}$ |
| Diesel Retrofits (DOCs, DPFs) | CO, $PM_{10}$, $PM_{2.5}$ and VOCs |
| Transit Service Expansion | NOx, VOCs, CO |
| Park and Ride | NOx, VOCs, CO |
| Extreme-Temperature Cold Start | CO and VOCs |
| Incident Management | CO and VOCs |
| Intermodal Freight | NOx |
| Dust Mitigation | $PM_{10}$ |

The relative performance of project types can be observed by comparing shading in Figure 1 above (lighter shades indicate stronger cost-effectiveness). The analysis indicated that idle reduction projects can be as cost-effective as diesel retrofits for CO, $PM_{2.5}$ and $PM_{10}$ emission reduction. Idle reduction also demonstrated strong cost-effectiveness for reducing NOx and VOC emissions.

Diesel retrofits demonstrated strong cost-effectiveness for CO, $PM_{2.5}$ and $PM_{10}$. That is, diesel retrofits were estimated to be highly cost-effective at reducing each pollutant that retrofits are capable of affecting, as per EPA's verified technologies list. Heavy-duty vehicle diesel engine replacements demonstrated strong cost-effectiveness for all pollutants in the study with the exception of CO, which indicated moderate cost-effectiveness.

Transit service expansion and park and ride projects appeared to provide strong cost-effectiveness in reducing CO, NOx and VOC emissions. In addition, transit service expansion demonstrated moderate cost-effectiveness with respect to $PM_{2.5}$ and $PM_{10}$, while park and ride projects demonstrated moderate cost-effectiveness with respect to $PM_{10}$.

Extreme-temperature cold start technologies are limited in applicability (i.e., to areas with unusually cold winter weather), but revealed strong cost-effectiveness with respect to CO and VOCs. Furthermore, these projects appeared competitive with respect to cost-effective mitigation of NOx, $PM_{2.5}$ and $PM_{10}$.

Similarly, incident management projects demonstrated strong cost-effectiveness for VOCs and CO. Incident management projects were near the middle of the range of project types for other pollutants.

Intermodal freight projects revealed strong cost-effectiveness with respect to NOx. Dust mitigation projects were clearly the most cost-effective alternative for reducing $PM_{10}$, which is the only pollutant that these projects are expected to affect. This relationship held for both street sweeping and dirt road paving projects, the two types of dust mitigation projects evaluated in the analysis. Similar to extreme-temperature cold start technologies, there may be limitations in the circumstances toward which dust mitigation projects apply.

### Project Types with Poor Cost-Effectiveness

Conversely, several project types demonstrated overall weak cost-effectiveness across the pollutants in the study. These project types include:

- Roundabouts,
- Bikesharing,
- Electric vehicle charging infrastructure, and
- Subsidized transit fares.

These project types are note presented in table format as in Table 1, because these project types were estimated to have the weakest cost-effectiveness for all project types. Roundabouts did not demonstrate strong cost-effectiveness for any of the pollutants in the study. Consequently, roundabouts generally performed less effectively than other intersection improvements.

Bikesharing did not demonstrate strong cost-effectiveness for any pollutant in the study. This was driven chiefly by a relatively small impact on VMT compared to the costs of implementing bikesharing projects. That is, while bikesharing projects are capable of leading to mode shift from light-duty vehicle to bicycle, the types of trips likely to be influenced involve relatively short distances or low frequencies of use.

Electric vehicle charging infrastructure tended to be one of the least cost-effective project types in the study for all pollutants in the study. It is worth noting that this could change if electric vehicle use increases in future years.

Subsidized transit fares are also among the least cost-effective projects. This result is limited by the available estimates of marginal operating costs per passenger mile to assign to these projects; transit services with the capability of assigning low marginal costs to passengers receiving subsidized fares (e.g., services with high demand) may be able to achieve stronger cost-effectiveness in emission reduction associated with light-duty vehicle travel.

### Project Types with Variable Cost-Effectiveness Estimates

The remaining project types demonstrated competitive cost-effectiveness (i.e., near or above the middle of the pack) for at least some pollutants in the study. Carsharing demonstrated competitive (i.e., relative to the entire range of project types) cost-effectiveness with respect to NOx mitigation. Carsharing was less cost-effective in reducing CO and VOC emissions, and weakly cost-effective with respect to $PM_{2.5}$ and $PM_{10}$.

Transit amenity improvements demonstrated competitive cost-effectiveness with respect to NOx and VOC mitigation. These projects appeared to be less cost-effective in reducing CO and $PM_{10}$ emissions, and were weakly cost-effective with respect to $PM_{2.5}$.

Intersection improvements demonstrated competitive cost-effectiveness with respect to CO and VOC mitigation. These projects appeared to be less cost-effective in reducing NOx, $PM_{2.5}$ and $PM_{10}$ emissions.

Bicycle and pedestrian facilities demonstrated cost-effectiveness at or above the middle of the range of project types for all pollutants. Employee transit benefits demonstrated cost-effectiveness near the middle of the range of project types for all pollutants, but below bicycle and pedestrian facilities for all pollutants.

Ridesharing projects generally demonstrated cost-effectiveness at or below the middle of the range of project types for all pollutants. The strongest cost-effectiveness demonstrated by ridesharing projects relative to other project types was for PM2.5.

Lastly, natural gas fueling infrastructure demonstrated moderate cost-effectiveness with respect to $PM_{2.5}$ and $PM_{10}$ mitigation. These projects did not reveal measurable mitigation of CO or NOx. The estimated CO emission rates for natural gas vehicles are uniformly higher than corresponding CO emission rates for corresponding diesel vehicles, resulting in no beneficial CO impacts for projects involving the use of natural gas vehicles.

Similarly, the estimated NOx emission rates for new and late-model (i.e., model year 2010 or more recent) natural gas vehicles are higher than the corresponding emission rates for new and late-model diesel vehicles. Hence, the only natural gas fueling infrastructure projects that would result in reduced NOx emissions would be projects that specifically encouraged the switch from pre-2010 diesel vehicles to pre-2010 natural gas vehicles, which is not likely to be a representative project structure. Projects encouraging the switch from used diesel vehicles to new vehicles (diesel or natural gas) are likely to be more representative; in such cases, the switch to new diesel vehicles would reduce NOx emissions, but the switch to natural gas vehicles would increase NOx emissions either outright or relative to an available diesel alternative.

Data limitations did not allow for an analysis of the cost-effectiveness of natural gas fueling infrastructure projects with respect to VOCs. Specifically, MOVES2010b does not include calculations of VOC emission rates for natural gas vehicles, making it infeasible to identify the impacts of natural gas fueling infrastructure projects on VOC emissions.

## SUMMARY COST-EFFECTIVENESS ESTIMATES

The cost-effectiveness estimates in this section are presented in separate tables for each pollutant or the applicable precursors. Cost-effectiveness is defined in this study as the cost per short ton of pollutant reduced. This specification enables a simple scaled value that can be compared both within project type (and across project size), and across pollutants (and either within or across project types).

Full project costs are specified within the calculation of cost-effectiveness, rather than the subset of project costs covered by CMAQ funds within the projects analyzed. This approach was selected to generate a meaningful comparison of cost-effectiveness across project types, independent of the particular funding opportunities and constraints present in any given setting. It is important to note that some project costs may not include full lifetime project costs, if ongoing maintenance or operating costs are not included in the reported or estimated project cost. The results are presented in descending order of cost-effectiveness (i.e., in increasing order of dollars per ton of pollutant reduced).

The values in the tables center on the median estimates for each project type within the analysis. The primary advantages of using the median rather than the mean or best-case scenarios are that: (1) the median is not distorted by poorly-performing outliers; (2) the median offers an intuitive marker of a cost with equally as many high-cost effective as low-cost effective values for the same project type; (3) the median (among reasonable project proposals) is likely to be more representative within project types than an absolute best-case scenario; and (4) the median (among reasonable project proposals) is likely to be more comparable across project types than an absolute best-case scenario.

For comparison purposes, best-case (i.e., lowest cost per ton reduced) estimates are also presented for each project type. These estimates present insight into the range of outcomes that could be achieved for each project type, but are not likely to be representative of general cost-effectiveness.

This section is intended to serve as a quick reference within and across pollutants. Chapter Two offers detailed information about all project type analyses in the study, along with supplementary analytical results.

### $PM_{2.5}$

Emission control practices most cost-effective at controlling $PM_{2.5}$ are diesel engine technology related projects. Diesel engine replacements and retrofits both address the inefficiencies of highly polluting older diesel vehicles while idle reduction curtails “hoteling”, in which heavy-duty diesel engines idle for extended periods. Median costs of these practices are all under $125,000 per ton of $PM_{2.5}$ reduced.

The rest of the project types examined for this pollutant exhibited variable cost effectiveness efficiencies, ranging in cost from $2.1M to $33M for each ton of $PM_{2.5}$ reduced. Park and ride facilities, transit service expansions, cold start technologies, incident management and bicycle-pedestrian projects all provided the next most cost effective performance in reducing $PM_{2.5}$ emissions with median costs ranging from $2.1M to $3.0M per ton reduced. Other than the cold start technologies, the rest of the project types in this group address transportation mode selection and reduced VMT in order to achieve emission reductions.

Other project types exhibiting relatively high cost efficiencies in reducing fine particulate emissions were intermodal freight, natural gas refueling, improved transit amenities and employee transit benefits. These project types were split in their means to reduce $PM_{2.5}$ emissions with intermodal and transit related projects altering vehicle selection, traveler behavior and modal choice, thus reducing VMT and resulting $PM_{2.5}$ emissions. Natural gas refueling projects encourage the use of alternative fuel vehicles and thereby minimize particulate vehicle emissions. These projects achieved a median cost effectiveness of between $4.5M and $6.1M per ton of emissions reduced.

Additional project types performed less efficiently in their ability to reduce fine particulate emissions either due to their high cost of implementation, such as roadway construction type projects, or their relatively low impact on VMT reduction. Electric charging stations were the least cost effective at reducing $PM_{2.5}$ emissions, but this is likely due to the relatively small number of electric vehicles currently operating in the fleet and the vehicles they replace are mostly gasoline vehicles with low PM2.5 emissions. We assume that as the number of electric vehicles increases that this type of project will become more cost effective in its ability to reduce $PM_{2.5}$ emissions in the future.

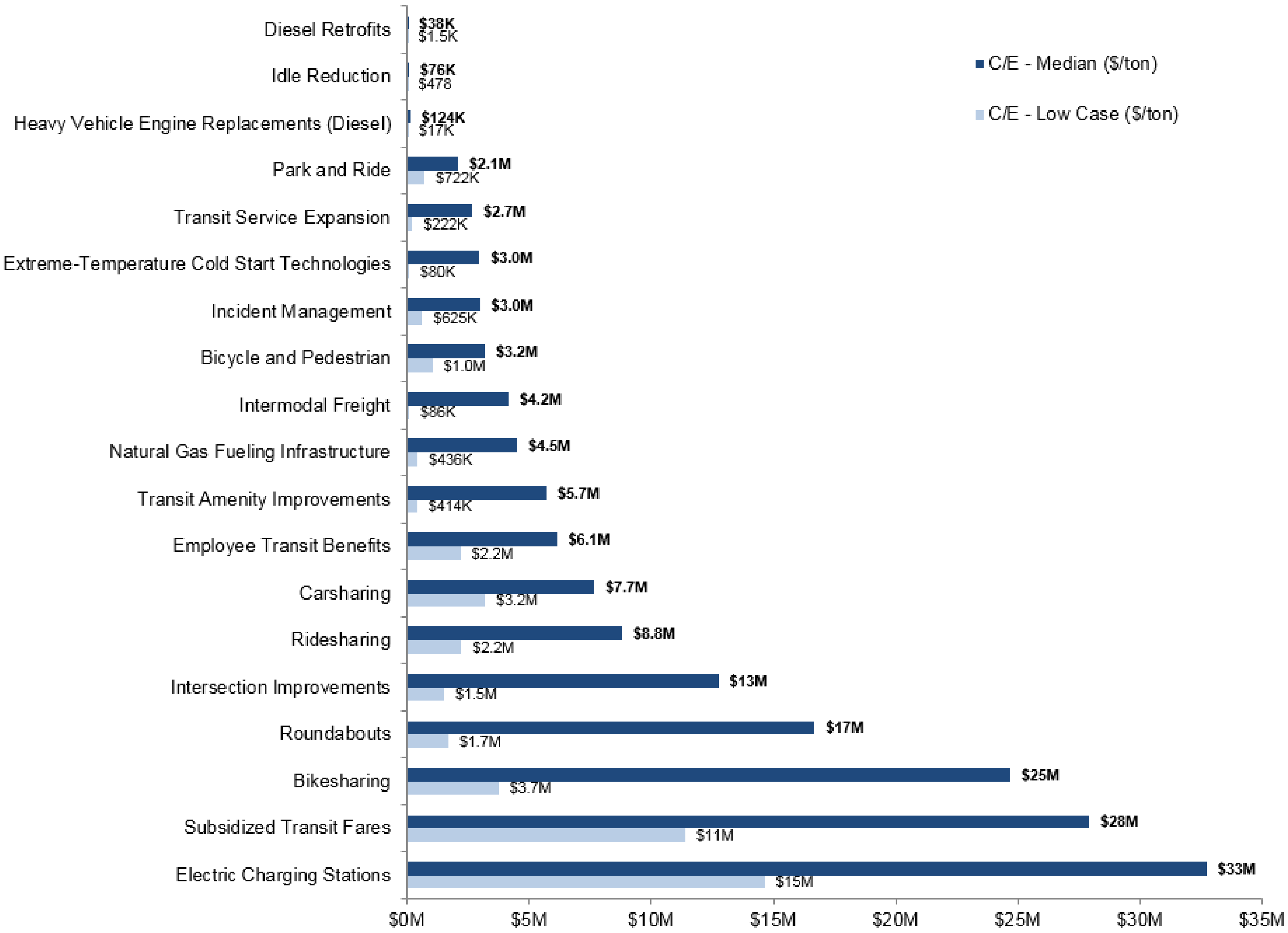

**Figure 2. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of $PM_{2.5}$ Emission Reductions.**

**NOx**

Emission control practices most cost-effective at controlling NOx are diesel engine technology related projects. Idle reduction strategies curtail hoteling, while heavy-duty vehicle diesel engine replacements address the inefficiencies of highly polluting older diesel vehicles. Median costs of these practices are all under $20,000 per ton of $NO_x$ reduced.

Park and ride, transit service expansion, bicycle-pedestrian and incident management projects also exhibited high cost-effectiveness in reducing $NO_x$ emissions. With the exception of incident management, these projects reduce $NO_x$ emissions by encouraging modal shift, thus reducing VMT in order to achieve emission reductions. Incident management projects reduce $NO_x$ emissions by reducing vehicle delay during periods of high congestion, in turn reducing per-mile $NO_x$ emissions. These projects achieved a median cost effectiveness of between $91,000 and $168,000 per ton of emissions reduced.

Intermodal freight, employee transit benefits, transit amenity improvements, carsharing, extreme-temperature cold start technologies and ridesharing all provided the next most cost effective performance in reducing $NO_x$ emissions, with median costs ranging from $249,000 to $367,000 per ton reduced. Other than the cold start technologies, the rest of the project types in this group address transportation mode selection and reduced VMT in order to achieve emission reductions.

Project types exhibiting relatively low cost efficiencies in reducing $NO_x$ emissions were intersection improvements, subsidized transit fares, bikesharing, electric vehicle charging stations and roundabouts. Intersection improvements and roundabouts reduce $NO_x$ emissions by reducing vehicle delay and associated per-mile emission rates. Subsidized transit fares, bikesharing and electric vehicle charging encourage shifts either between modes or types of private vehicle, reducing VMT in the case of modal shift and reducing per-mile emission rates in the case of electric vehicles. These projects achieved a median cost effectiveness of between $744,000 and $3M per ton of emissions reduced.

Diesel retrofits are not included in the analysis of NOx, because the diesel retrofit technologies analyzed in this report (diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs)) do not impact NOx emissions. Natural gas fueling infrastructure projects are also not included in the analysis of NOx, because these projects would be expected to stimulate increases in NOx emissions. This relationship arises because new and late-model natural gas vehicles have higher NOx emission rates than corresponding new and late-model diesel vehicles.

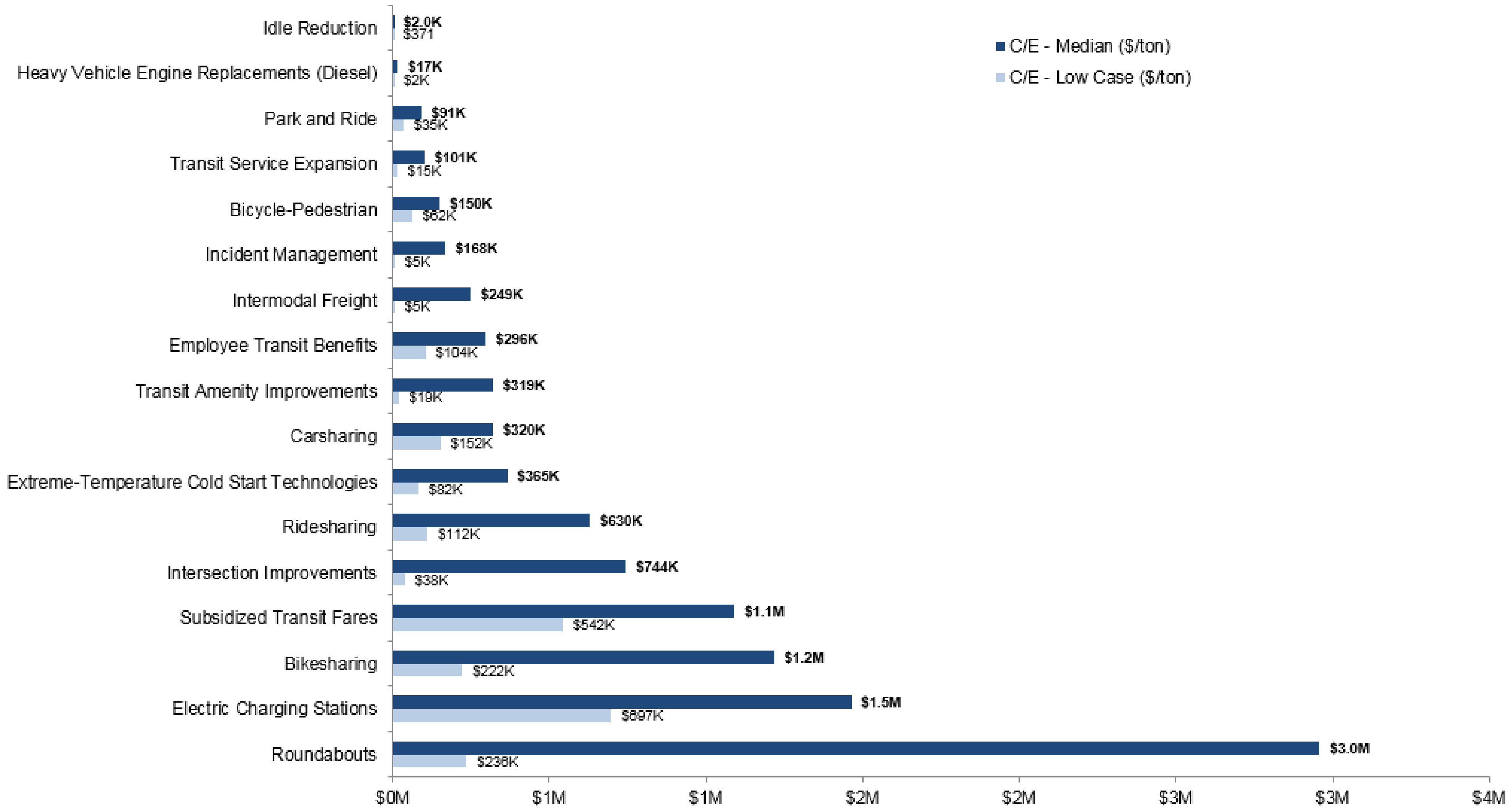

**Figure 3**. **Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of NOx Emission Reductions.**

## VOCs

Emission control practices most cost-effective at controlling VOC are diesel engine technology related projects, extreme-temperature cold start technologies and incident management projects. Diesel retrofits and heavy-duty vehicle diesel engine replacements address the inefficiencies of highly polluting older diesel vehicles. Idle reduction strategies curtail hoteling. Extreme-temperature cold start technologies address the inefficiencies of starting vehicles under unusually low levels of ambient temperature. Incident management projects reduce VOC emissions by reducing vehicle delay during periods of high congestion, in turn reducing associated per-mile VOC emission rates. Median costs of these practices are all under $175,000 per ton of VOC reduced.

Park and ride, transit service expansion, and bicycle-pedestrian projects also exhibited high cost-effectiveness in reducing VOC emissions. These projects reduce VOC emissions by encouraging modal shift, thus reducing VMT in order to achieve emission reductions. These projects achieved a median cost effectiveness of between $464,000 and $685,000 per ton of emissions reduced.

Intersection improvements, transit amenity improvements, employee transit benefits and carsharing all provided the next most cost effective performance in reducing VOC emissions, with median costs ranging from $1.1M to $1.7M per ton reduced. Intersection improvements reduce VOC emissions by reducing vehicle delay and associated per-mile VOC emission rates. The rest of the project types in this group address transportation mode selection and reduce VMT in order to achieve emission reductions.

Project types exhibiting relatively low cost efficiencies in reducing VOC emissions were ridesharing, intermodal freight, roundabouts, bikesharing, subsidized transit fares and electric vehicle charging stations. Ridesharing, intermodal freight, bikesharing, subsidized transit fares and electric vehicle charging stations encourage shifts either between modes or types of private vehicle, reducing VMT in the case of modal shift and reducing per-mile emission rates in the case of electric vehicles. Roundabouts reduce VOC emissions by reducing vehicle delay and associated per-mile emission rates. These projects achieved a median cost effectiveness of between $2.1M and $7.3M per ton of emissions reduced.

The analysis was unable to identify impacts of natural gas fueling infrastructure projects on VOC emissions, because MOVES2010b does not calculate emission rates for natural gas vehicles.

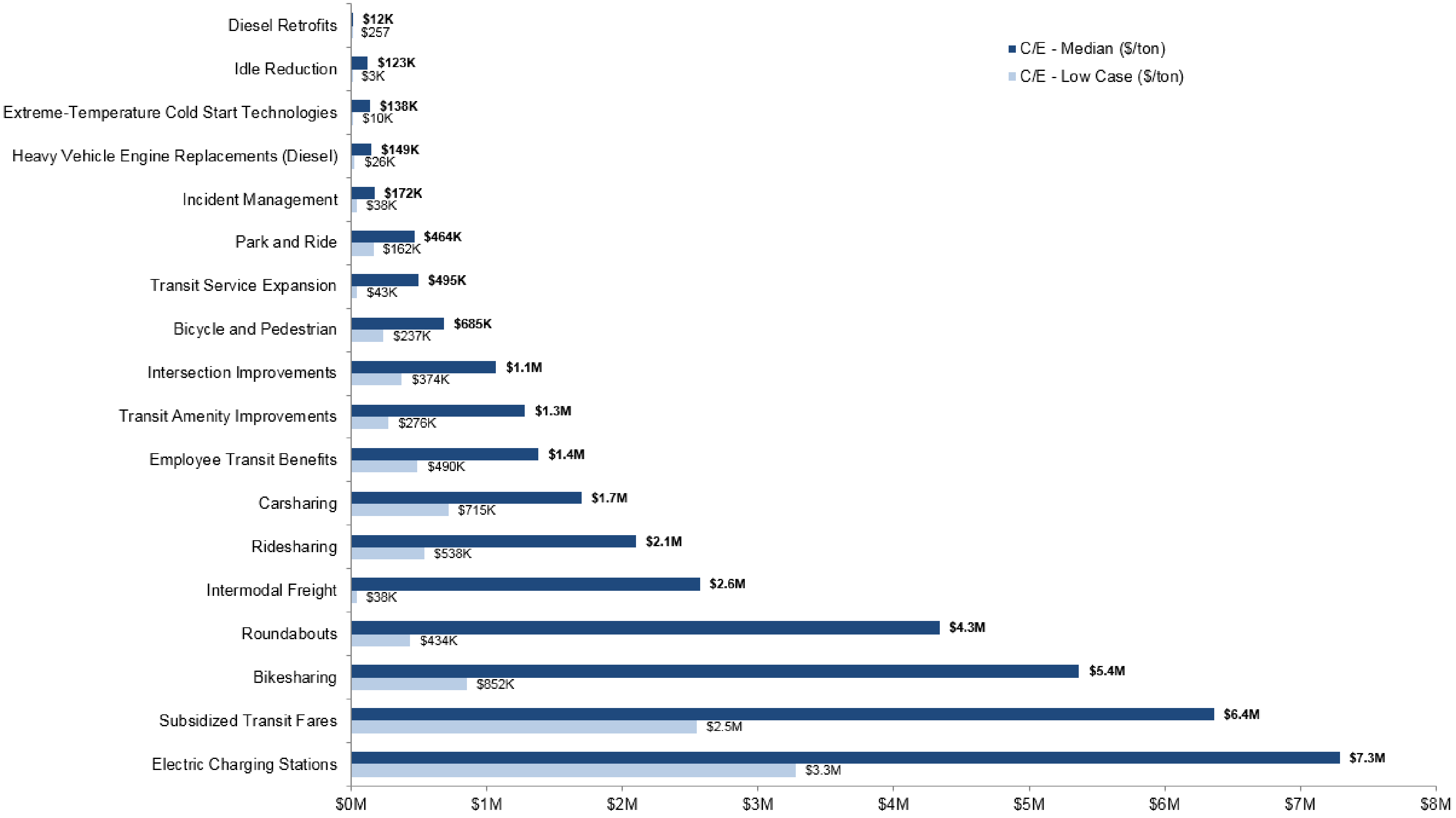

**Figure 4. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of VOC Emission Reductions.**

## CO

Emission control practices most cost-effective at controlling CO are diesel retrofits. Diesel retrofits address highly-polluting older diesel vehicles. Median costs of these practices are around $5,400 per ton of CO reduced. This result was identified based upon EPA estimates of the effectiveness of diesel retrofit technologies in reducing CO emissions, including EPA's Verified Technology List and Diesel Emissions Quantifier.

A broad group of projects also exhibited strong cost-effectiveness in reducing CO emissions. Incident management, park and ride, extreme-temperature cold start technologies, transit service expansion, heavy-duty vehicle diesel engine replacements, bicycle and pedestrian and idle reduction projects all had median costs between $11,000 and $21,000 per ton of CO reduced. These projects entail distinct mechanisms for reducing CO emissions. Incident management projects reduce vehicle delay during periods of high congestion, in turn reducing per-mile CO emission rates. Park and ride, transit service expansion and bicycle and pedestrian projects reduce CO emissions by encouraging modal shift, thus reducing VMT in order to achieve emission reductions. Extreme-temperature cold start technologies reduce CO emission rates during vehicle starts in cases of unusually low ambient heat. Heavy-duty vehicle diesel engine replacements address the inefficiencies of highly polluting older diesel vehicles, while idle reduction curtails heavy-duty diesel engine idling, one of the most polluting phases of diesel engine operation.

The next most cost-effective projects in reducing CO emissions include employee transit benefits, transit amenity improvements, carsharing, ridesharing and intersection improvements. With the exception of roundabouts, these projects center on modal shift and associated reductions in VMT. Intersection improvements reduce CO emissions by reducing vehicle delay and associated per-mile emission rates. The projects all exhibited median cost-effectiveness of between $36,000 and $66,000 per ton of CO reduced.

Project types exhibiting low cost efficiencies in reducing CO emissions were roundabouts, subsidized transit fares, bikesharing, electric vehicle charging stations and intermodal freight. Roundabouts reduce CO emissions by reducing vehicle delay and associated per-mile emission rates. Subsidized transit fares, bikesharing, electric vehicle charging and intermodal freight encourage shifts either between modes or types of vehicle (i.e., from gasoline- or diesel-powered vehicle to electric vehicle, or from truck to barge or rail), reducing VMT in the case of modal shift and reducing per-mile emission rates in the case of electric vehicles. These projects achieved a median cost effectiveness of between $114,000 and $315,000 per ton of CO emissions reduced.

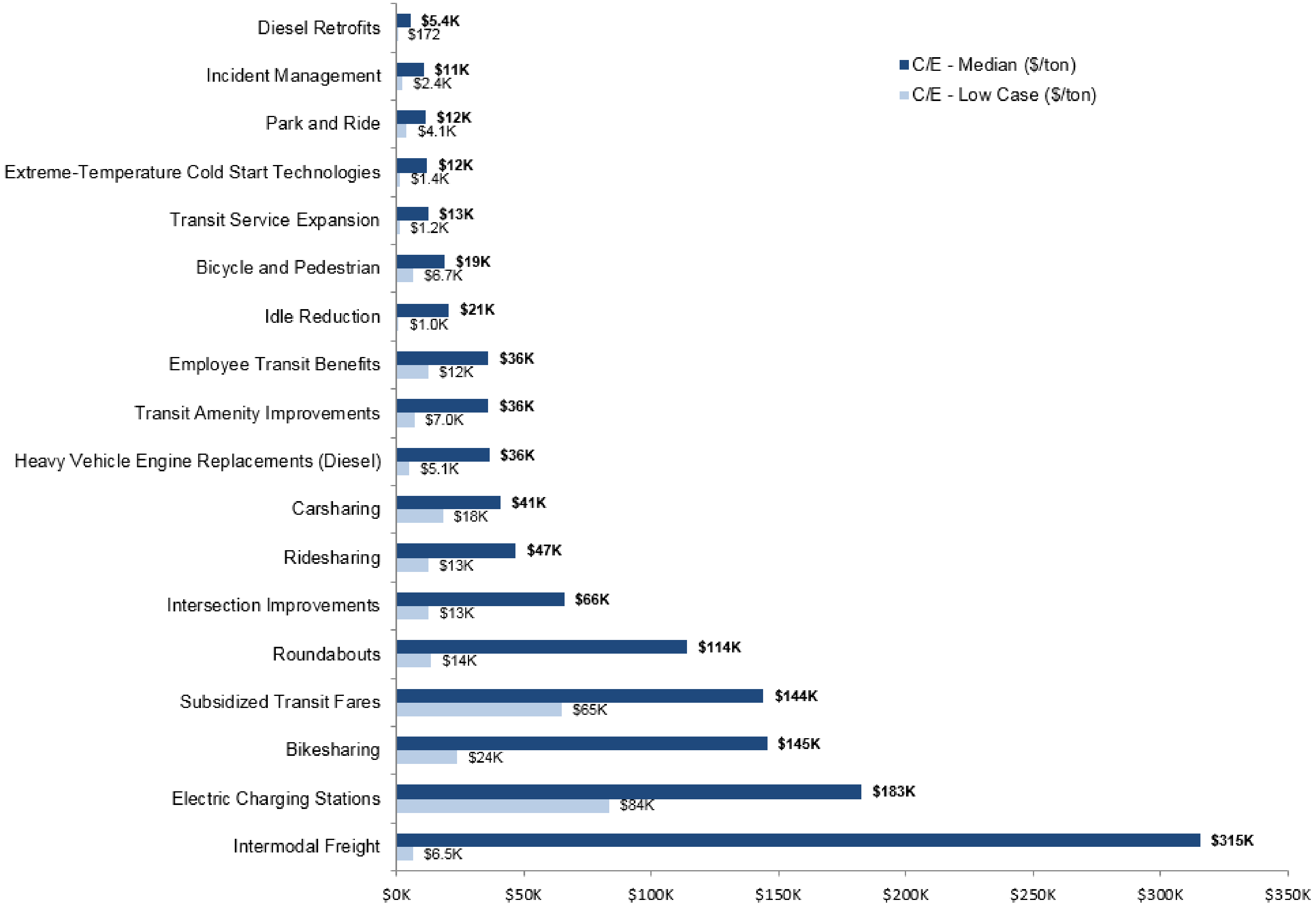

**Figure 5. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of CO Emission Reductions.**

### $PM_{10}$

Emission control practices most cost-effective at controlling $PM_{10}$ are dust mitigation projects, with an estimated median cost-effectiveness of under $300 per ton for $PM_{10}$ emission reduction. Within the range of dust mitigation projects, street sweeping projects were the most cost-effective, followed by paving projects.

Diesel engine technology related projects are also very effective at reducing $PM_{10}$. Diesel engine replacements and retrofits both address the inefficiencies of highly polluting older diesel vehicles. Median costs of these practices are under $125,000 per ton of $PM_{10}$ reduced.

The rest of the project types examined for this pollutant exhibited variable cost effectiveness efficiencies, ranging in cost from $448,000 to $14M for each ton of $PM_{10}$ reduced. Idle reduction strategies curtail heavy-duty diesel engine idling, one of the most polluting phases of diesel engine operation. Park and ride facilities, transit service expansions, and bicycle-pedestrian projects all provided the next most cost effective performance in reducing $PM_{10}$ emissions with median costs ranging from $448,000 to $1.3M per ton of $PM_{10}$ reduced. Each of these projects addresses transportation mode selection and reduces VMT in order to achieve emission reductions.

Other project types exhibiting relatively high cost efficiencies in reducing particulate emissions were: transit amenity improvements, extreme-temperature cold-start technologies, incident management, employee transit benefits, and intermodal freight, ranging in cost from $2.2M to $2.9M per ton of $PM_{10}$ reduced. These project types were split in their means to reduce $PM_{10}$ emissions with intermodal and transit related projects altering vehicle selection and traveler behavior modal choice, thus reducing VMT or emissions intensity and resulting $PM_{10}$ emissions.

The next-most-effective group of projects in reducing $PM_{10}$ emissions includes carsharing, ridesharing, natural gas fueling infrastructure and intersection improvements, ranging in cost from $3.5M to $4.8M per ton of $PM_{10}$ reduced. Carsharing and ridesharing projects reduce VMT in order to achieve emission reductions. Natural gas refueling projects encourage the use of alternative fuel vehicles and thereby minimize particulate vehicle emissions.

Additional project types performed less efficiently in their ability to reduce particulate emissions either due to their high cost of implementation, such as roadway construction type projects, or their relatively low impact on VMT reduction. The median cost-effectiveness for intersection improvements, roundabouts, bikesharing, subsidized transit fares and electric vehicle charging stations was between $4.8M and $15M. Electric charging stations were the least cost effective at reducing $PM_{10}$ emissions, but this is likely due to the relatively small number of electric vehicles currently operating in the fleet. We assume that as the number of electric vehicles increases that this type of project will become more cost effective in its ability to reduce $PM_{10}$ emissions in the future.

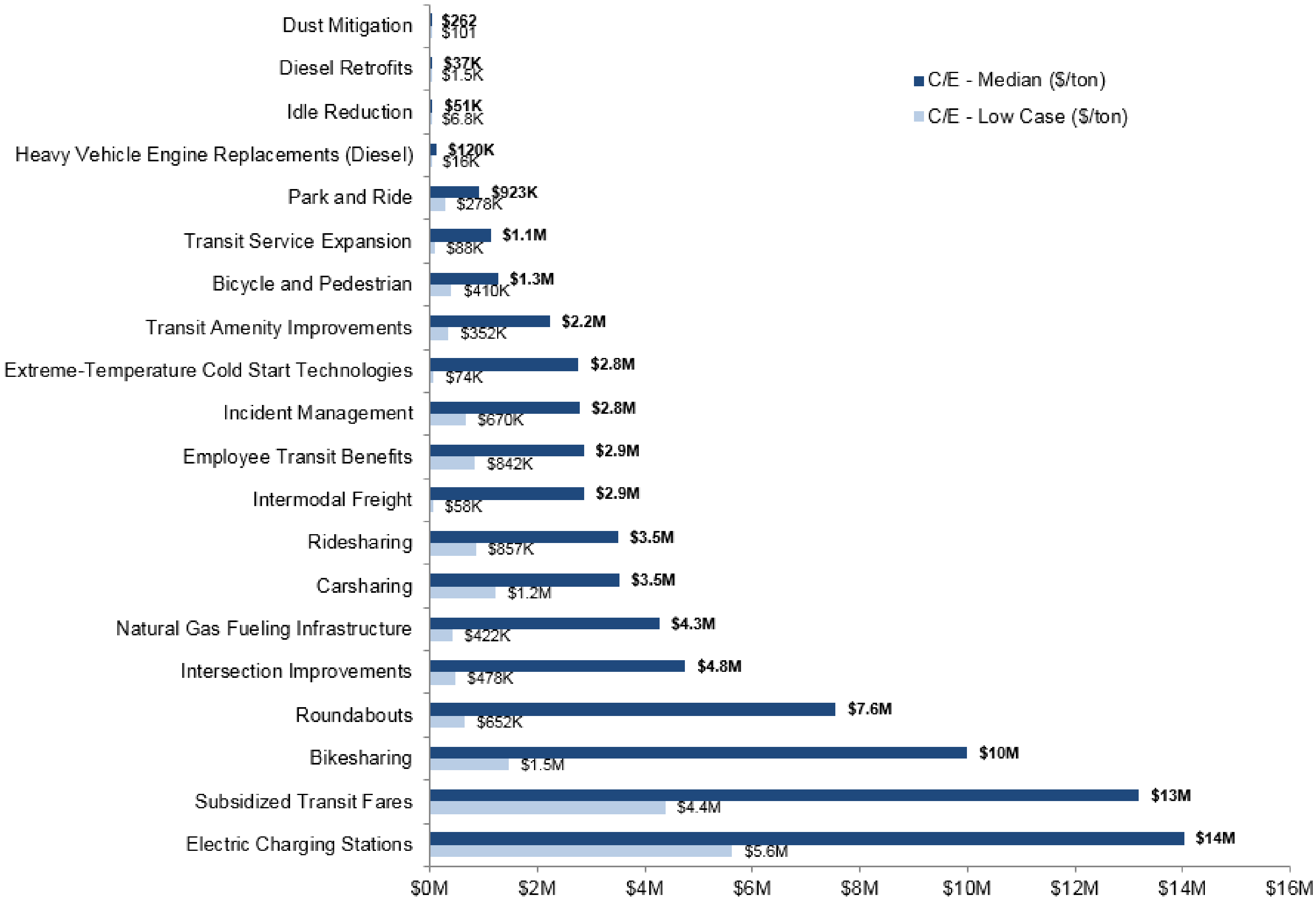

Figure 6. Chart. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of $PM_{10}$ Emission Reductions.

## Congestion Impacts

Along with the analysis of emission impacts, this research also included an analysis of congestion impacts associated with the range of project types. Most project types had measurable impacts limited to emission reductions, and hence had no estimated congestion impacts. Three project types had measurable impacts on congestion: intersection improvements (e.g., left turn lanes, signalization improvements), roundabouts and incident management. The common factor across these project types is a focus on reducing delay.

Other project types – most notably intermodal freight projects and large-scale transit projects – may have significant congestion impacts in addition to emission reductions. However, the available project data did not specify congestion impacts. Hence, no congestion impact was estimated for these projects in the analysis. Future research could be designed to generate estimates of congestion impacts, through means such as travel demand models incorporating freight flows and broad modal shift from light-duty vehicle to transit.

Congestion impacts were estimated as reductions in vehicle-hours of delay generated by projects. For projects involving time at idle, congestion impacts were estimated as reductions in vehicle-hours at idle (e.g., time queuing to turn left, time queuing to pass through an intersection). For projects involving general improvements in throughput (e.g., signal coordination), congestion impacts were estimated as reductions in vehicle-hours spent passing through an affected corridor.

Cost-effectiveness in reducing congestion was estimated as project cost divided by project lifetime reductions in vehicle-hours of delay (i.e., dollars per each reduced vehicle-hours of delay). The median and mean congestion impacts for intersection improvements, roundabouts and incident management are presented in Figure 7:

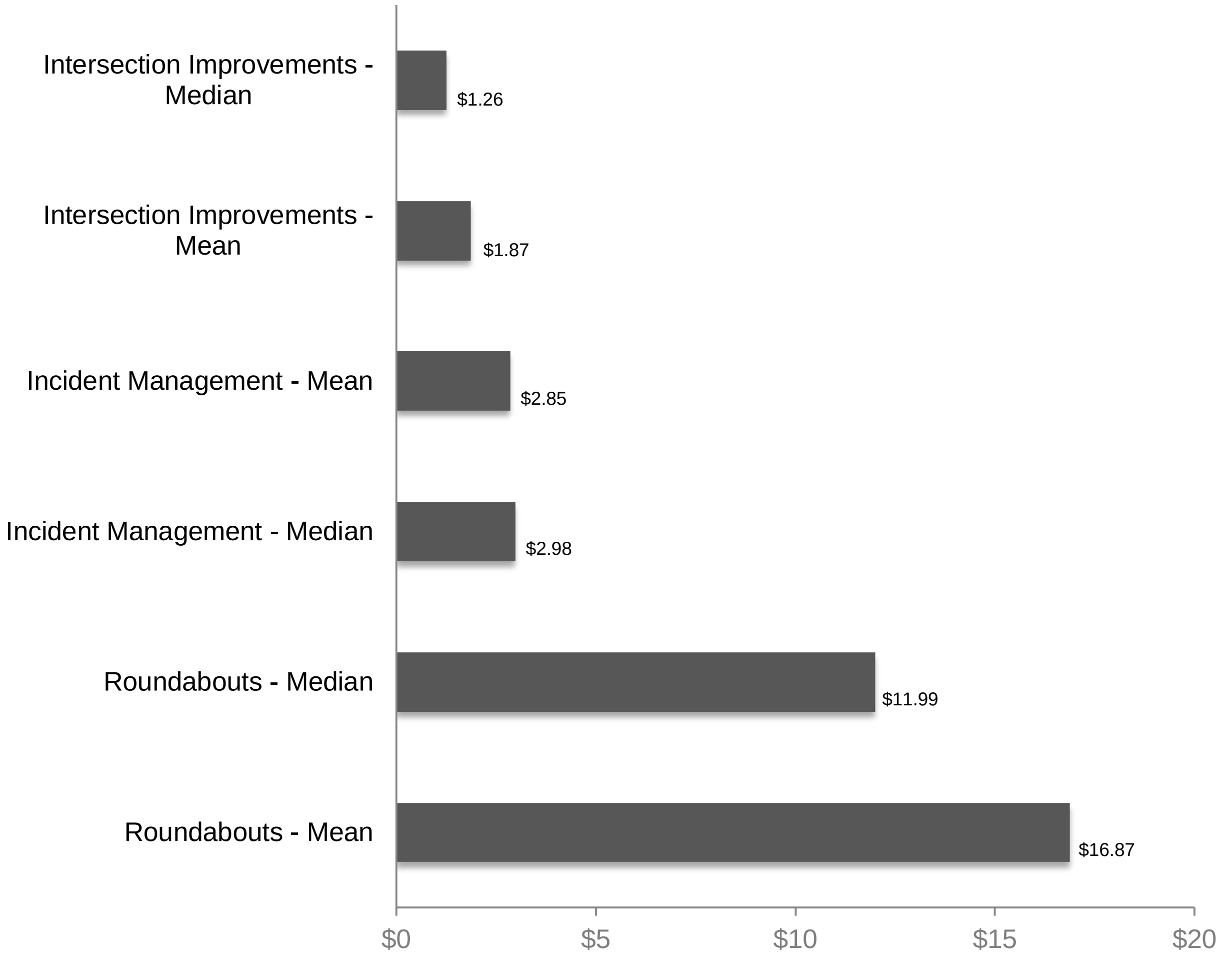

**Figure 7. Median and Mean Cost-Effectiveness Estimates (Cost per Vehicle-Hour of Delay Reduced) of Congestion Reductions.**

The median estimated costs per reduced vehicle-hour of delay for the three project types are all near (depending upon vehicle occupancy) or below the value of travel time savings specified in April 2015 USDOT guidance on the value of time (around $12.50 to $25 per hour, varying by trip purpose). Hence, each project type would be cost-beneficial (i.e., would generate a societal benefit of congestion reduction in excess of project costs) when focusing solely on congestion benefits. This benefit would be independent of benefits associated with emission reductions, and hence may be important to consider when comparing competing project alternatives.

Intersection improvements demonstrated the strongest cost-effectiveness in reducing delay, with median and mean costs below two dollars per reduced vehicle-hour of delay. Incident management projects were also strongly cost-effective in reducing delay, with median and mean costs below three dollars per reduced vehicle-hour of delay; for locations with significant levels of non-recurring congestion (e.g., areas prone to major bottlenecks due to accidents, areas with periodic special events causing major delay), incident management projects may be particularly cost-effective in reducing congestion. Roundabout projects, while yielding costs of reductions in vehicle-hours of delay below the USDOT-specified value of travel time savings, were estimated to be much less cost-effective than other intersection improvements and incident management projects in reducing congestion.

# CHAPTER TWO: ANALYTICAL APPROACH AND DETAILED RESULTS

## INTRODUCTION

The remainder of this document begins with a discussion of components of the general approach used to generate the cost-effectiveness estimates summarized in Chapter One. This discussion includes an outline of data sources used to seed the analysis, and a description of the process used to generate the range of analytical scenarios. The discussion reviews model components, and associated assumptions and limitations. Key components include elements essential to represent impacts on travel demand, emission intensity, project lifetimes, project costs, and associated emission rates represented through the use of MOVES2010b.

Chapter Two of this document concludes with a review of each project type included in the analysis. For each project type, the discussion outlines the inputs and steps required to generate cost-effectiveness estimates. The discussion presents a representative sample calculation of cost-effectiveness estimates for a subset of the relevant pollutants associated with each project type (e.g., cost-effectiveness estimates for NOx and PM2.5), based on the range of inputs identified for use within the analysis. In cases where distinct processes were used to generate cost-effectiveness estimates within a given project type (e.g., distinct types of transit projects, diesel retrofit scenarios involving heavy vehicles and construction equipment), multiple processes and examples are presented. For each project type, the discussion concludes with a summary table of median cost-effectiveness estimates identified in the analysis.

## GENERATION OF ANALYTICAL SCENARIOS

### Data Sources

This section outlines the process used to generate the analytical scenarios used in the estimation of cost-effectiveness by project type. Each analytical scenario involves a specific representation of a project, defined primarily in terms of costs, travel demand, travel demand impacts and emission rates. The specification of scenarios was based upon multiple data sources. The fullest representations of project-level data were found in data from the CMAQ project database, including the two most recent CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study), and in additional project summaries from States and localities containing data consistent with CMAQ project summaries. Additional key information was found in existing reviews of mobile emission mitigation projects, in particular *Multi-Pollutant Emissions Benefits of Transportation Strategies* (FHWA, 2006).

A literature review and series of internet searches identified additional information used to populate scenarios in the analysis, including studies of specific policies (e.g., carsharing in San Francisco, bikesharing in Washington, DC, electric vehicle charging stations in Minnesota) and reviews of technological effectiveness (e.g., effects of idle-reduction technologies). Industry documentation offered additional insight into project costs (e.g., school bus replacement costs, vanpool costs) and demand impacts.

Lastly, information from government sources offered integral components of analytical scenarios. Key examples include annual VMT and idling estimates from EPA's Diesel Emissions Quantifier (DEQ). In addition, for scenarios involving off-road activity that cannot be represented in MOVES (chiefly scenarios involving construction equipment), the DEQ was applied independently to yield cost-effectiveness estimates within the analysis. Other critical information was identified via models operated by MPOs (e.g., assumptions regarding project-level factors and impacts for infrastructure projects).

### Scenario Generation

To generate individual scenarios in the analysis, the required model inputs (e.g., project costs, travel demand, travel demand impacts, emission rates) were specified from available sources (e.g., CMAQ assessment studies). In cases where the full set of required information was available for a given case, cost-effectiveness estimates were generated by dividing the project cost by the scenario-specific estimates of emission impacts. The emission impacts were identified as the difference in the products of travel volumes and unit emission rates under the project relative to the status quo across the project lifetime.

For example, consider a simple case of a one-year, $10,000 project that reduces annual passenger vehicle VMT by 50,000, at a prevailing average travel speed of 35 miles per hour, at an estimated CO emission rate of three grams per mile. To estimate the cost-effectiveness of the project with respect to carbon monoxide, one would divide the project cost by the estimated reduction in CO. The reduction in CO is estimated as:

*(Change in VMT) x (CO Emissions per Mile)*

**Figure 7. Equation. Estimation for CO Reduction.**

With a 50,000-mile annual reduction in vehicle travel and an estimated CO emission rate of three grams per mile, the project would yield a reduction of 150 kilograms of CO, or approximately one-sixth of a ton of CO (0.16535 ton). At a cost of $10,000, the cost-effectiveness of the project would be estimated as $10,000 divided by 0.16535 ton, or $60,479 per ton ($0.07 per gram).

When full information is not available for a given case, representative values from related cases or the literature were included to fill in missing details. For example, if a project lifetime was not specified for a given infrastructure project, and if a common project lifetime was observed for related projects, the common value would be substituted into the analysis for the infrastructure project.

Additional scenarios were generated by substituting inputs from one documented project in place of values for other documented projects. For example, if a range of (scaled) project costs are observed across otherwise comparable projects, it would be reasonable to allow for an analysis of hypothetical cases in which alternative, feasible project costs apply to a given emission impact from a project. Such substitution was applied for multiple model inputs (e.g., demand impacts, vehicle mixes affected) to expand the range of scenarios.

Where applicable, a given analytical scenario was expanded into a range of scenarios by varying one or more inputs to represent plausible alternatives. For example, for a given analytical scenario with a particular project cost, travel demand and associated travel speed, alternative scenarios could be generated by using the same project cost and travel demand, but also varying the associated travel speed (e.g., representing congested arterials, uncongested arterials, and uncongested highways). This process was repeated as appropriate to allow for variations in factors including vehicle age (e.g., for diesel retrofits), impacts vehicle use (e.g., to test a range of plausible demand patterns or sensitivities), and road types (e.g., urban versus rural arterials or highways).

By representing a range of values for key inputs, the analytical process is capable of estimating a range of scenario-specific cost-effectiveness estimates that represent the variability of plausible outcomes across proposed projects within a given project type. Two key factors to consider in this regard were identified during the analytical review process: utilization rates and switching factors. Utilization rates represent the uptake of new or improved services and infrastructure (e.g., new bus routes, improved intersections). For a given level of potential demand (e.g., number of potential transit users, daily private vehicle users), variations in utilization rates will lead to different quantities of demand (e.g., transit trips, vehicle miles of travel). In turn, variations in demand will have proportional impacts on cost-effectiveness.

For example, consider a transit project with 100,000 potential transit riders, in which five percent of potential riders are projected to utilize a new transit service, with an estimated impact of a reduction of one ton of NOx over the lifetime of the project. At a project cost of $100,000, the project would have an estimated cost-effectiveness of $100,000 per ton of NOx reduced. If a project with the same characteristics were implemented in an area with 100,000 potential riders but with ten percent of project riders utilizing the service, the estimated reduction of NOx would be twice as large (two tons) and the estimated cost-effectiveness would be doubled ($50,000 per ton).

Similarly, switching factors represent the share of users by status quo mode (e.g., private vehicle drivers, public transit users). For projects centering on reductions in private vehicle VMT, the share of users switching from private vehicles is of critical importance; users coming from other modes would not result in reductions in private vehicle VMT. Hence, for a given impact of changes in private vehicle VMT on a focal pollutant (e.g., per-mile emission rates for CO for private vehicle use), variations in switching rates will lead to different changes in private vehicle usage. In turn, variations in private vehicle use will have proportional impacts on cost-effectiveness.

For example, consider a ridesharing project with 10,000 potential participants, in which 50 percent of potential participants are projected to switch from the use of private vehicles (with the remainder coming from public transit, for whom there would no estimated emissions reduction), with an estimated impact of a reduction of 100 tons of CO over the lifetime of the project. At a project cost of $500,000, the project would have an estimated cost-effectiveness of $5,000 per ton of CO reduced. If a project with the same characteristics were implemented in an area where 25 percent of potential participants are projected to switch from the use of private vehicles, the estimated reduction in CO would be half as large (50 tons), and the resulting estimated cost-effectiveness would be halved as well ($10,000 per ton).

Median cost-effectiveness measures generated across the range of analytical scenarios for a given project type are presented at the end of each subsection in *Analytical Results*.

## ANALYTICAL PROCESS

### Model Inputs

### *General Structure*

The general structure of the analysis centers on linking key inputs from external sources (e.g., CMAQ project proposals, projects consistent with CMAQ proposals) to emission estimates from analysis in MOVES2010b. Key inputs in the generation of estimates of cost-effectiveness (measured in dollars per ton of pollutant reduced) are shown in Table 2.

**Table 2. Key Inputs to Calculations of Cost-Effectiveness**

| Input | Example | Role in Analysis |
|---|---|---|
| Project costs | Cost of park and ride project | Numerator of cost-effectiveness estimates |
| Travel demand estimates | VMT by vehicle type | Travel volumes affected by the project |
| Technological effectiveness measures | Percentage reduction of $PM_{2.5}$ through diesel retrofits | Emission impacts per unit of activity |
| Price measures and associated price elasticities | Changes in public transit costs and changes in public transit travel demand | Travel volumes affected by the project |
| Travel mode shift sensitivities | Share of light-duty trips shifted to public transit | Travel volumes affected by the project |
| Service measures and associated demand elasticities | Changes in public transit quality and changes in public transit travel demand | Travel volumes affected by the project |
| Project lifetimes | 10-year service life of a signalization project | Time interval to apply to annual impacts |
| Travel speeds | Average speeds along an affected roadway | Application of emission rates |

Baseline travel demand estimates and the range of sensitivity estimates serve to quantify the impact of a given project type on travel demand by vehicle type. Technological effectiveness measures (e.g., percentage of emissions captured by a diesel retrofit) represent the share of pollutant emissions that would be captured over a given volume of travel demand or engine use (e.g., hours of idling). Representative travel speeds and road types are used to link specific emission rate estimates from MOVES2010b to estimated impacts on travel volumes. For example, impacts at a relatively low average speeds, which involve frequent acceleration and deceleration, will result  in different per-mile emission rates compared to the same travel volume at free-flow speeds on the same type of road, due to the impact of those frequent accelerations and decelerations. Lastly, project lifetimes expand annualized estimates of emission impacts across a relevant timeframe.

$$\begin{aligned}&[(Travel\ Volume\ under\ the\ Project) \times (Unit\ Emissions\ Rate\ under\ the\ Project)]\\ &\qquad - [(Travel\ Volume\ under\ the\ Status\ Quo)\\ &\qquad \times (Unit\ Emissions\ under\ the\ Status\ Quo)] \times Project\ Lifetime\end{aligned}$$

**Figure 8. Equation. General Terms to Represent the Estimated Emissions Impacts.**

This was kept simple in the example for CO cost-effectiveness estimation above, but was complex in some scenarios. For example, projects involving different travel speeds on different lanes (e.g., under managed lanes) require calculating impacts for each relevant traffic netwo7rk component (e.g., differences between emissions under the project and the status quo for all types of lanes). Similarly, projects involving impacts on different vehicle types (e.g., under increased transit service) require calculating impacts across all vehicle types (e.g., differences between emissions under the project and the status quo for passenger vehicles and buses).

### *Travel Demand Estimates*

Information on baseline (i.e., status quo) travel demand is required for all projects, including projects that do not affect travel volumes (e.g., baseline VMT estimates are required for analyses of diesel retrofit projects). For most projects, associated travel speeds are required to identify per-mile emission rates to apply to the evaluation of a project. The availability of reliable travel demand information may vary across projects, and may include total trips by network link and vehicle type, total vehicle hours or miles of travel, and patronage for transit services. Furthermore, the most appropriate data may be disaggregated by time of day to enable analyses involving peak versus off-peak travel.

### *Technological Parameters*

For the range of projects that focus on in-vehicle technologies, fuel and maintenance, the analysis requires assumed parameters for the expected technical effectiveness of the focus of the project. As a simple example, consider a scenario in which an idle reduction policy is projected to reduce the volume of a given pollutant in average heavy duty truck trips by ten percent. The analysis would involve estimating total heavy duty diesel truck pollutant emissions within a given scenario using MOVES2010b, and then estimate the reduction in emissions resulting from the policy as equal to ten percent of the baseline heavy duty diesel truck emissions from the MOVES2010b analysis.

### *Mode Shift Elasticity*

For the subset of projects with a focus on encouraging mode shift (i.e., from light-duty vehicle to public transit, carpool, vanpool, rideshare or non-motorized travel), the analysis requires assumed parameters for the sensitivity of demand by mode with respect to the project. The assumed relationship between the effects of the project on demand by mode is used to evaluate the net effects on travel behavior.

For example, a given representative project may involve an assumption that a measure will lead to five percent of daily commute trips moving from light-duty vehicle to express bus. In this case, the share of daily commute trips would be scaled down by five percent, with those trips offset by an appropriate volume of express bus trips (modeled separately).

### *Transit Service Parameters*

For the range of projects involving meaningful changes to transit service, the analysis requires information to represent both changes in demand arising from improved facilities, and tangible changes to the transit fleet. With respect to changes in demand, the analysis requires estimates of mode shift resulting from the availability of improved facilities. With respect to changes in the transit fleet, the analysis requires information on changes to the level of service and corresponding changes in transit demand.

### *Project Costs*

The 2008 CMAQ Phase 1 Final Report notes that some states and MPOs report cost-effectiveness estimates that reflect only the relationship between the amounts of CMAQ funds applied to a project relative to the full emission impacts of a project. That is, such measures attribute all emission reductions for projects to the proportion of total project funding that is comprised of CMAQ funds, essentially designating other funds as having no cost-effectiveness at all. The view taken in this research is that it was important to represent the cost of the entire project, rather than just the associated CMAQ funds. A key objective of this effort is to represent the relative cost-effectiveness of CMAQ-eligible projects, independent of the relative share of CMAQ funds that a given project receives. The approach taken in this research is the same as in FHWA (2008), representing total project costs within cost-effectiveness measures, without differentiating by funding source.

### *Project Lifetimes*

Another time-related factor to control for is the duration of benefits (FHWA, 2008). Different projects have different operational lifetimes (e.g., infrastructure projects are likely to be longer-lived than operational programs). The analysis specifies representative project lifetimes across which benefits are applied, consistent with project lifetimes reported in existing CMAQ projects and the literature. As an example of the range of time frames covered within this approach, consider Table 3 below (FHWA, 2008, p. 55), which offers a summary of project lifetimes specified in a CMAQ evaluation under SAFETEA-LU:

**Table 3. Examples of Project Life Periods for Project Evaluation.**

| **Category** | **Project Life Expectancy (Years)** |
|---|---|
| Traffic Flow Improvements | 10-20 |
| Shared Ride Programs – Operational | 1-2 |
| Shared Ride Programs – Infrastructure | 12 |
| Travel Demand Management | 1-2 |
| Bicycle/Pedestrian Facilities | 15 |
| Transit Improvements – Operational/Amenities | 1-2 |
| Transit Improvements – Infrastructure | 10-30 |
| Technology Improvements (New Transit Vehicles) | 4 |
| Dust Mitigation | 20 |
| Freight/Intermodal | 20 |
| Engine Retrofits | Varies |

### Use of MOVES2010b

EPA’s mobile source emissions model (MOVES2010b) was used in the development of the cost-effectiveness tables to generate estimates of emissions for the range of project types evaluated within the analysis. MOVES2010b was designed by the EPA for the purposes of modeling on-road air pollution emissions from motor vehicle activity. (EPA, 2012) The model analyzes all on-road motor vehicle classes, and allows users to incorporate significant local-level detail. MOVES2010b estimates key criteria pollutants and their precursors, including the pollutants evaluated within this research.

There is a broad range of key data that must be specified within MOVES2010b analysis of emission impacts for the representative projects selected for this research, as summarized in Table 4 below. (EPA, 2012) National-average values for the variables in Table 4 were selected as the default values for the analysis within MOVES2010b for most cases; the primary exception was extreme-temperature cold-start technologies, for which a range of data representative of Fairbanks, Alaska was specified.

**Table 4. Required Data Inputs and their Impacts in MOVES2010b.**

| Category | Input | Impact on |
|---|---|---|
| ***Weather*** | Local temperature | Most pollutants |
| | Relative humidity | NOx |
| ***Vehicle Fleet*** | Population of vehicles for 13 types | All pollutants |
| | Distribution of vehicle ages for 13 types | All pollutants |
| ***Travel Demand*** | Annual VMT by vehicle type | All pollutants |
| | VMT by road type | All pollutants |
| ***Travel Speed*** | Distribution of average speed | All pollutants |
| ***Ramp Fraction*** | Share of VHT on ramps | All pollutants |
| ***Fuel Type and Technology*** | Distribution of energy source across diesel, gasoline, CNG and electricity by vehicle type and model year | All pollutants |
| ***Fuel Formulations*** | Volumes of fuel formulations consumed, defined in terms of: Reid vapor pressure, sulfur level, ethanol volume, additives | All pollutants |
| ***Fuel Market Share*** | Proportions of diesel, gasoline, CNG and electricity consumed by fuel formulation | All pollutants |

The range of vehicle types modeled within MOVES2010b is represented in Table 5:

**Table 5. Vehicle Types in MOVES2010b.**

| Vehicle Type | Vehicle Sub-Type |
|---|---|
| Motorcycles | |
| Light-Duty Vehicles | Passenger Cars |
| | Passenger Trucks |
| | Commercial Trucks |
| Single-Unit Trucks | Refuse Trucks |
| | Short-Haul Trucks |
| | Long-Haul Trucks |
| | Motor Homes |
| Combination Trucks | Short-Haul Trucks |
| | Long-Haul Trucks |
| Buses | School Buses |
| | Transit and Urban Buses |

Within each of the vehicle types listed in Table 5, MOVES is capable of modeling distinct estimates of emission rates by fuel type, including gasoline, diesel and natural gas. Separate emission rates for appropriate subsets of vehicle types were identified in MOVES for relevant analyses (e.g., school bus emission rates for diesel retrofits of school buses, heavy truck emission rates for intermodal projects). Fleet-average emission rates were identified for projects influencing a range of vehicle types (e.g., traffic flow improvements).

The set of required information by vehicle type in MOVES2010b is multi-dimensional, covering the population of vehicles by age and fuel source; and annual VMT by road type. The distribution of vehicles by age was of key relevance for scenarios involving engine replacement, vehicle replacement and vehicle technologies. In cases involving either engine/vehicle replacement or vehicle technologies, the age of the replaced vehicle is a critical factor in the volume of emissions abated via replacement (positively, through higher per-mile emission rates as vehicles age, and negatively, through decreased project lifetimes as vehicles age).

EPA (2012) clarifies that the distribution of travel speeds used within a given analysis should be defensible. In this analysis, the travel speeds linking MOVES model runs and calculations of emission impacts were specified both directly from real-world projects and allowed to vary across meaningful ranges as a means of sensitivity analysis.

For example, a given project type could involve examples with prevailing average travel speeds of 30 and 35 miles per hour. In this analysis, the relevant parameters from project descriptions would not only apply to emission rates from MOVES model runs at 30 and 35 miles per hour, but also to emission rates from MOVES model runs at slower and faster speeds. This enables the analysis of similar projects applied under different conditions.

Importantly, specifications of travel speeds are not required for scenarios that are not linked to specific travel conditions (e.g., diesel retrofits, idle reduction). In such scenarios, the specification of a fleet-average travel profile (in cases that apply to all travel, such as retrofits) or no travel at all (in cases that apply to starting, idling or charging, such as idle reduction), are appropriate.

## Assumptions and Limitations

### *Assumptions*

Central assumptions for the analysis are listed below:

- Emission impacts are not discounted across project lifetimes;
- The cost-effectiveness of a project with respect to one pollutant is independent of the project's impacts on other pollutants;
- The information on projects collected through a review of CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study) and non-FHWA documents is representative of the range of projects seeking CMAQ funding;
- All reported or estimated project costs are included in calculations of cost-effectiveness measures, rather than the share of project costs receiving CMAQ funding;
- The full project cost is assigned to the first year of the project, rather than discounting across years that projects would be active (or across years that project funds would be applied);
- The project cost represents all types of reported or estimated costs to which funds would be applied (e.g., capital costs, operating costs, maintenance costs);

- Specifications of vehicle fleet characteristics and travel activity within MOVES are representative of the vehicle fleet and travel activity affected by CMAQ projects;

- Median cost-effectiveness estimates are the preferred measures to compare cost-effectiveness across project types.

- The base year for all projects in 2015.

A key policy-related assumption is that all emissions are accounted for equally across project lifetimes; that is, a ton of pollutant emissions abated in 2015 is treated in the analysis as equivalent to the same ton of pollutant emissions abated in, say, 2025. The purpose of this assumption is to treat all cohorts experiencing emission impacts the same, rather than favoring groups in particular time periods. The alternative would be to discount emissions to a present value. Such an approach could be appropriate if the marginal social benefit of emission mitigation is expected to change significantly over time; this was not expected to be the case for the project lifetimes governing most, if not all, projects in the analysis.

As mentioned earlier in this section, another key assumption is that the cost-effectiveness of a given project for a given pollutant is independent of the project's impacts on other pollutants. That is, the cost-effectiveness measures do not involve any weighting across pollutants, consistent with FHWA (2008) (i.e., an assumption of zero shared costs across pollutant reductions. Hence, we assigned the total cost of a project to each pollutant category, and then estimated the cost per ton reduction for each pollutant; these measures, in turn, are essentially upper-bound estimates of costs per ton.

For example, consider a project with a cost of $100,000 that leads to a reduction of one ton of VOCs and two tons of NOx. Our approach would result in cost-effectiveness estimate of $100,000 per ton for VOCs and $50,000 per ton for NOx.

FHWA (2008) selected their methodology for two key reasons. Firstly, FHWA believed that it was difficult to select one weighting system that was representative at the national level, due to variations in the relative impacts of pollutants by location. Secondly, because some projects are targeted at reductions in a focal pollutant, FHWA believed that weighting systems could obscure the relative effectiveness of different strategies at reducing different pollutants. We agree with both points, and hence chose to generate separate cost-effectiveness tables for each pollutant.

There are three related assumptions governing the representation of project costs in the analysis. Firstly, the full project cost is assigned to projects, rather than the share of project costs covered by CMAQ funds. This assumption was imposed to preserve comparability across scenarios. Ultimately, cost-effectiveness estimates should reflect how effectively a given project type achieves reductions in pollutant emissions (information of paramount importance to State and local decision-makers). Representing only the share of CMAQ funds associated with individual project examples would result in estimates that attribute all pollutant reductions to CMAQ funds (and attribute no pollutant reductions to alternative sources of funds).

The full project cost is assumed to be incurred in the first year of the project. This represents the timing of the obligation of funds from the CMAQ Program toward projects (i.e.,as lump sums). This assumption reflects cost-effectiveness from the perspective of the social cost of funds, rather than at the local, transactional level.

The full project cost is also assumed to incorporate all relevant costs (i.e., capital, operating and maintenance). The estimates of project costs that were used within the analysis do not generally differentiate between components assigned to capital costs versus operation and maintenance costs; the corresponding assumption of funds being applied to all project costs was selected for consistency with the data.

Other central assumptions relate to the representativeness of individual analytical scenarios, the range of analytical scenarios, and the estimates yielded within MOVES2010b. Each analytical scenario included in the analysis was identified within documentation on CMAQ projects, other related projects, a literature review and information provided by industry and related groups. The range of scenarios included in the analysis does not include all identified candidate cases, however. Rather, the analysis does not include information from cases that were either considerable outliers (e.g., infrastructure-intensive projects with limited impacts compared to less-intensive projects) or described in vague terms. As a result, the analysis assumes that the range of analytical scenarios to evaluate includes not only best-case scenarios, but also scenarios that are relatively effective for a given project type. Relatively weakly-performing scenarios can feasibly be found for any project type, and do not add much to the information gained within the analysis, at the cost of adding noise to the results.

The range of analyses in MOVES2010b yielding emission rate estimates are also based on a set of assumptions which, in turn, conditions the range of cost-effectiveness estimates. The most critical assumptions within the MOVES analysis include: the composition of relevant components of the vehicle fleet (e.g., shares of passenger cars and trucks on highways, proportions of heavy trucks by age, annual VMT by vehicle type and age across road types), the appropriate drive schedule for a given scenario (i.e., changes in vehicle speed across modeled trips), and the spatial coverage for a given scenario (e.g., project-level, national-average).

Lastly, the analysis generates unique cost-effectiveness estimates for each analytical scenario. This raises an important question of how best to characterize cost-effectiveness for each project type, based upon a given range of scenario-specific estimates. After comparing alternative approaches to representing the cost-effectiveness estimates, the preferred approach was to represent cost-effectiveness in terms of median cost-effectiveness estimates by project type (and, in the case of the detailed results presented in Chapter Two, by project sub-type when applicable). Median estimates, while commonly similar to mean estimates, are not influenced by the magnitude of outliers (i.e., scenarios with unusually high or low estimated costs per ton of pollutant reduced). Rather, in this analysis the median is the closest available measure of a representative (i.e., middle-of-the-pack) project. Best-case estimates were also considered; however, just as mean estimates are prone to being distorted by unusually poorly-performing projects, best-case estimates may overstate the effectiveness of a given project type. For example, diesel retrofits of relatively old long-haul trucks may perform much better than diesel retrofits on average, but old long-haul trucks may represent a very small share of vehicles eligible for retrofits under a given project.

### ***Limitations***

The range of analytical scenarios is intended to cover neither the full range of potential outcomes within a project type, nor the full range of potential projects. The analysis centers on a snapshot of data, which limits the scope of inference that can be drawn. Difficulties in identifying representative project examples for some project types limited the range of potential projects included in the analysis. Hence, the range of project types included in the analysis is targeted at representing an informative view of the relative performance of predominant (and potentially predominant) project types across the range of pollutants in the study, rather than serving as a census of all projects eligible for CMAQ funding.

The analysis is also limited by the scope of factors represented within the analytical scenarios. That is, the results are strictly limited to being representative of projects with prevailing factors consistent with the examples evaluated in the analysis. Hence, States and MPOs considering projects that include features outside the boundaries of the scenarios analyzed in this research should consider external information to confirm the implications of this analysis. This is consistent with a broader limitation: States and MPOs may have access to a range of information and operate under distinct sets of constraints or objectives. Critically, this analysis is targeted at representing a meaningful comparison of the general cost-effectiveness of competing project types, but is not targeted at serving as a single, definitive source in this area. It is expected that States' and MPOs' project- and agency-specific knowledge will serve a critical role in concert with the information presented in this document.

As discussed in the review of assumptions above, a maintained assumption in the analysis is that the estimated project costs cover the full extent of capital, operating and maintenance costs. If projects include operating costs that are not represented within the estimated total project cost (e.g., in cases where only capital costs are evaluated within the application process), estimates of cost-effectiveness would be biased upwards (i.e., a given reduction in pollutant emissions would be associated with a larger total cost than the capital cost associated with the estimate).

The costs for project types centering on user-specific technologies or policies (e.g., diesel retrofits, employee transit passes) are represented as the per-unit costs, rather than expected total costs for a bundle of units including administration and installation fees. Hence, the estimated cost-effectiveness for such project types is essentially a lower bound value; administration and installation costs would raise the effective cost per ton reduction of a given pollutant.

The analysis assumes constant annual impacts across project lifetimes, unless variable information across years was available (e.g., changes in expected emission rates calculated within MOVES2010b). This assumption would bias cost-effectiveness estimates downwards (i.e., lower cost per ton) if impacts would be expected to decrease over time. However, the strongest performing project types in the analysis tend to be shorter-lived, and hence the tendency of any bias would be toward decreasing the relative differences in cost-effectiveness across project types.

It is also important to acknowledge that cost-effectiveness with respect to reducing pollutant emissions and congestion is not necessarily the primary reason to implement a given project. Rather, there can be a wide range of benefits provided by projects (e.g., greenhouse gas mitigation, reductions in fuel consumption, safety improvements). In this analysis, we are focusing on the two central issues relevant to the CMAQ program, air quality improvement and reductions in traffic congestion. While other benefits may be of critical importance to State and local organizations, benefits other than reductions in traffic congestion and pollutants associated with CMAQ Program objectives are outside the scope of this analysis.

## ANALYTICAL RESULTS

This section covers the process used to identify cost-effectiveness estimates for each project type in the analysis, along with a summary of the range of cost-effectiveness estimates (i.e., estimates of cost-effectiveness for $PM_{2.5}$, NOx, VOCs, CO and $PM_{10}$) for each project type. Within the discussion for each project type, this section reviews:

- How each project type affects emissions;
- What range of strategies or technologies were included in the analysis for the project type (e.g., the set of diesel retrofit technologies, the types of vehicles toward which a project type is applied);
- The range of specifications (e.g., model years, number of vehicles affected, number of transit riders, project costs) within the analytical scenarios the analytical steps required to estimate cost-effectiveness for a given project type; and
- The model inputs required to estimate cost-effectiveness for a given project type.

The discussion for each project type also includes one or more representative sample analytical scenarios, presented in terms of:

- A description of the sample scenario(s);

- The model inputs for the sample scenario(s) the steps required to identify cost-effectiveness estimates for the sample scenario(s); and

- The cost-effectiveness estimates identified within the sample scenario(s).

For each sample analytical scenario, examples demonstrate how a subset of cost-effectiveness measures (generally represented in terms of PM2.5 and NOx) are calculated. The use of a subset of calculations was selected for brevity; the same process was used to calculate cost-effectiveness measures for all pollutants in the analysis for a given project type.

The examples presented in the remainder of this document are simplified examples targeted at demonstrating the processes used to generate cost-effectiveness estimates. The examples do not present individual scenarios from the analyses, although some inputs are in common with those used in the analysis. The discussion for each project type concludes with a summary table of the full range of median cost-effectiveness estimates identified in the analysis.

The summary tables present median cost-effectiveness estimates for $PM_{2.5}$, NOx, VOCs, CO and $PM_{10}$; in cases where a given project type does not affect all five pollutants in the analysis, results are presented for the subset of pollutants affected by the project type. The estimates are also split by distinct project sub-types (e.g., splitting dust mitigation into street sweeping and road paving) where applicable.

## Diesel Retrofits

Diesel retrofits involve technologies applied to vehicles and equipment operating on diesel fuel, to reduce the volume of target pollutants emitted while in operation. The two primary types of diesel retrofits evaluated in this analysis are diesel particulate filters (DPFs) and diesel oxidation catalysts (DOCs). DPFs and DOCs reduce some (but not all) $PM_{2.5}$ and CO emissions by capturing these pollutants before they exit the exhaust system of the vehicle or equipment.

In addition, diesel retrofits can reduce the volume of $PM_{10}$ emissions, although specific emission impacts for $PM_{10}$ versus $PM_{2.5}$ were not available. In cases where general impacts of particulate matter were available, the same impact was assumed for $PM_{10}$ as for $PM_{2.5}$ (reflecting the ability to capture fine particulate emissions at least as large as $PM_{2.5}$). In cases where only $PM_{2.5}$ impact estimates were available (i.e., for analyses of diesel retrofits of construction equipment), no impacts on $PM_{10}$ were estimated.

The range of expected performance for DPFs specified within the list of EPA verified technologies includes reductions of: 85%-90% of PM and 75%-90% of carbon monoxide (CO). The range of expected performance for DOCs specified within the list of EPA verified technologies includes reductions of: 20%-26% for PM and 28%-50% for CO. Additional documentation on DPFs and DOCs indicated similar ranges, confirming the validity of the EPA summary data as inputs to the analysis. The lower and upper values within the ranges of technological effectiveness were used to help establish a meaningful range of cost-effectiveness estimates.

No direct estimates of reductions in VOCs were published by EPA. However, DPFs and DOCs reduce hydrocarbon emissions, which are the predominant component of VOC emissions by diesel engines. In this analysis, diesel retrofit reductions in VOCs were assumed to be equal to hydrocarbon reductions. The expected performance of VOC reductions identified by EPA for heavy vehicles is 90% for DPFs and 50% for DOCs. For all scenarios of DPFs and DOCs applied to construction equipment, the estimated emission reductions from the DEQ were applied directly.

In the analysis, the effects of DPFs and DOCs were investigated for:

- Heavy-duty trucks, including engine model years 1999-2006 (1,336 total scenarios by truck type, truck age and road type);
- Transit buses, including engine model years 1999-2006 (128 scenarios by bus type, bus age and road type);
- School buses, including engine model years 1999-2006 (128 scenarios by bus type, bus age and road type); and
- Construction equipment, including pavers, cranes and pavement rollers (104 scenarios by equipment type and age).

Steps required to conduct the analysis of diesel retrofits of heavy-duty trucks and buses include:

- Generate per-mile emission rates for $PM_{2.5}$, $PM_{10}$ and CO in MOVES2010b for each vehicle type, vehicle age and road type;
- Identify estimates of annual vehicle use for each vehicle type;
- Identify estimates of project lifetimes (i.e., representative service lives for DPFs and DOCs);
- Identify estimates of technological effectiveness for DPFs and DOCs; and
- Identify estimates of unit costs for DPFs and unit costs for DOCs.

The MOVES runs yielded estimates of emission rates (in grams per mile) for CO, $PM_{2.5}$ and $PM_{10}$, by vehicle type and model year. That is, a given retrofit technology (e.g., one specific DPF), was estimated by MOVES to have distinct impacts on emission rates depending upon the type and age of the vehicle receiving the retrofit.

Lower- and upper-bound project lifetimes and retrofit technology costs (from $1,000 to $2,000 for DOCs and from $10,000 to $20,000 for DPFs) were selected to generate lower- and upper-bound cost-effectiveness estimates in conjunction with the lower- and upper-bound values of technological effectiveness. The lower bound for project lifetime was specified as five years (i.e., an assumption that the vehicle that was retrofit would last from 2015 through 2019 if it were not replaced), and the upper bound was specified as 11 years (i.e., the vehicle that was retrofit would last from 2015 through 2025), following from the range of project lifetimes identified in the literature review.

To estimate individual cost-effectiveness for each vehicle type/model year/road type combination in the analysis, the estimated cost for a given technology was divided by the product of the estimated change in a given emission rate (i.e., with retrofit versus without), the assumed annual volume of VMT for the vehicle, and project lifetime. This yields a value of dollars per gram of pollutant abated over the project lifetime, which can then be converted to dollars per ton abated. The median cost-effectiveness estimate is then identified as the 50th-percentile value across the set of cost-effectiveness estimates generated using the process described above.

The steps required to conduct the analysis of diesel retrofits of construction equipment, are distinct, due to a lack of construction equipment within MOVES. Instead of applying (unavailable) emission rate estimates for construction equipment from MOVES, EPA's Diesel Emissions Quantifier (DEQ) was used within the analysis of construction equipment. The required analytical steps for analysis using the DEQ include:

- Identify estimates of annual usage for each construction equipment type and age (default values are available in the DEQ);

- Generate per-mile emission rates for $PM_{2.5}$, $PM_{10}$ and CO in the DEQ each construction equipment type and age;

- Identify estimates of project lifetimes (i.e., representative service lives for vehicles using DPFs and DOCs, generated by the DEQ);

- Identify estimates of technological effectiveness for DPFs and DOCs;

- Designate a state in which the retrofit takes place; and

- Identify estimates of costs for DPFs and DOCs.

The specification of annual usage is distinct for construction equipment compared to heavy vehicles; construction equipment activity is specified more appropriately in terms of hours of usage than in VMT. The retrofits were assumed to take place in the base analysis year (2015).

Cost estimates for the specific technologies selected for the DEQ were collected from suppliers, where available, and compared to broader estimates from the literature to confirm representativeness. All equipment was assumed to be used at levels equivalent to default values in the DEQ. Lastly, the DEQ requires the specification of one state for the location of the project. Multiple model runs were conducted across states with climate attributes (i.e., average temperature, heating degree days, cooling degree days, morning and evening relative humidity) at or near the national average. The emission impact estimates calculated using the DEQ were insensitive to the selection of states.

***Sample Analytical Scenario: Diesel Retrofit of a Heavy-Duty Truck***

As an illustrative example, consider a model year 1999 single-unit short-haul truck with a diesel engine traveling on urban arterials, undergoing a retrofit with a DPF.

In this scenario we assume the following details:

- The DPF has effective reductions of 90%, 80%, and 50% for PM, CO and VOCs, respectively;

- The effective fleet-average emission rates for the vehicle (from MOVES2010b) are (in grams per mile): 0.5, 1.02 and 5.56 for $PM_{2.5}$, $PM_{10}$ and CO, respectively;

- The average annual travel volume for the vehicle type is 27,500 miles;

- The DPF is assumed to be effective for ten years; and

- The cost of the DPF is $10,000..

**Step One:** The reduction in exhaust emissions is calculated by multiplying baseline exhaust emissions by the estimated effectiveness of the DPF in reducing emissions, as summarized in Table 6:

**Table 6. Sample Calculation of Emission Impacts of DPF Technology (Model Year 1999 Single-Unit Short-Haul Truck, Urban Arterials).**

| **Pollutant** | **Baseline Exhaust Emissions (grams/mile)** | **DPF Effectiveness** | **Exhaust Emissions under Retrofit (grams/mile)** | ***Difference in Exhaust Emissions (grams/mile)*** |
|---|---|---|---|---|
| $PM_{2.5}$ | 0.48 | 90% | 0.04 | *0.44* |
| $PM_{10}$ | 0.50 | 90% | 0.050 | *0.45* |
| CO | 5.56 | 80% | 1.11 | *4.45* |

**Step Two:** The total estimated annual impact on each pollutant is then identified by multiplying the difference between the baseline and retrofit emission rates for the pollutant (i.e., the per-mile emission reduction) in the table above by the average annual travel volume for the vehicle type (27,500 miles):

**Table 7. Sample Calculation of Total Annual Emission Impacts of DPF Technology (Model Year 1999 Single-Unit Short-Haul Truck, Urban Arterials).**

| **Pollutant** | **Difference in Exhaust Emissions (grams/mile)** | **Average VMT** | ***DPF Emission Reduction (grams/year)*** |
|---|---|---|---|
| $PM_{2.5}$ | 0.44 | 27,500 | *11,979* |
| $PM_{10}$ | 0.45 | | *12,375* |
| CO | 4.45 | | *122,375* |

**Step Three:** Project lifetime emission impacts are identified by multiplying the annual emission reduction by the project lifetime (in years). All conversions of emissions impacts to (short) tons use the conversion factor of 907,185 grams per ton. For simplicity, assume a constant effect for each year and project lifetime of ten years, yielding:

**Table 8. Sample Calculation of Total Emission Impacts of DPF Technology (Model Year 1999 Single-Unit Short-Haul Truck, Urban Arterials).**

| **Pollutant** | **DPF Emission Reduction (grams per year)** | **Project Lifetime (years)** | **DPF Emission Reduction (grams)** | ***Total Reduction in Exhaust Emissions (tons)*** |
|---|---|---|---|---|
| $PM_{2.5}$ | 11,979 | 10 | 123,750 | *0.132* |
| $PM_{10}$ | 12,375 | | 123,750 | *0.136* |
| CO | 122,375 | | 1,223,750 | *1.349* |

**Step Four:** The values in Table 8 above represent the denominator of the cost-effectiveness measures in the example. To identify the cost-effectiveness measures (in dollars per ton), it is necessary to divide the cost of the DPF by the estimates of total ton reductions:

**Table 9. Sample Calculation of Cost-Effectiveness Estimates for DPF Technology (Model Year 1999 Single-Unit Short-Haul Truck, Urban Arterials).**

| Pollutant | DPF Cost | Total Reduction in Exhaust Emissions (tons) | *Cost-Effectiveness (dollars per ton)* |
|---|---|---|---|
| $PM_{2.5}$ | $10,000 | 0.132 | *$75,758* |
| $PM_{10}$ |  | 0.136 | *$7,353* |
| CO |  | 1.349 | *$7,413* |

*Sample Analytical Scenario: Diesel Retrofit of a Construction Crane*

As an illustrative example, consider a case of a model year 1999 construction crane, retrofitted with a DPF in 2012 (the latest retrofit year available in the DEQ).

In this scenario we assume the following details:

- The crane operates in Massachusetts;
- The crane runs on ultra-low-sulfur diesel fuel;
- The crane operates at the DEQ default intensities of 990 hours per year at 175 horsepower; and
- The DPF operates at the DEQ default efficiency of 85% and 90% reductions of $PM_{2.5}$ and CO, respectively.

**Step One:** The DEQ reports annual emission totals based on annual hours of operation and emission rates represented in terms of grams per hour. Rather than calculating emission impacts manually based on emission rates and estimated usage, the analysis incorporates the estimates of baseline emissions and emission reductions directly from the DEQ. Applying the selected retrofit technology would reduce the crane emission rates to: 0.0.194 and 0.0587 tons per year of $PM_{2.5}$ and CO, respectively, as estimated by the DEQ and summarized in Table 10 below:

**Table 10. Sample Calculation of Annual Emission Impacts of DPF Technology (Model Year 1999 Crane, from DEQ).**

| Pollutant | Baseline Exhaust Emissions (tons/year) | DPF Effectiveness | Exhaust Emissions under Retrofit (tons/year) | *Difference in Exhaust Emissions (tons/year)* |
|---|---|---|---|---|
| $PM_{2.5}$ | 0.1293 | 85% | 0.0194 | *0.1099* |
| CO | 0.5870 | 90% | 0.0587 | *0.5283* |

**Step Two:** Project lifetime emission impacts are identified by multiplying the annual emission reduction by the project lifetime (7.9 years, as reported by the DEQ in this example). The project lifetime represents the interval over which the project would have an impact, which in this case is the expected remaining years of service for the vehicle:

**Table 11. Sample Calculation of Total Emission Impacts of DPF Technology (Model Year 1999 Crane, from DEQ).**

| **Pollutant** | **Difference in Exhaust Emissions** | **Project Lifetime (years)** | ***Total Reduction in Exhaust Emissions (tons)*** |
|---|---|---|---|
| $PM_{2.5}$ | 0.1099 | 7.9 | *0.8682* |
| CO | 0.5283 | | *4.1736* |

**Step Three:** The values in Table 11 above represent the denominator of the cost-effectiveness measures in the example. To identify the cost-effectiveness measures (in dollars per ton), it is necessary to divide the cost of the DPF by the estimates of total ton reductions in Table 11 above:

**Table 12. Sample Calculation of Cost-Effectiveness Estimates for DPF Technology (Model Year 1999 Crane).**

| **Pollutant** | **DPF Cost** | **Total Reduction in Exhaust Emissions (tons)** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| $PM_{2.5}$ | $20,000 | 0.8682 | *$23,040* |
| CO | | 4.1736 | *$4,800* |

### *Summary Cost-Effectiveness Estimates: Diesel Retrofits*

The median cost-effectiveness estimates for the range of project scenarios for heavy-duty trucks, transit buses, school buses and construction equipment are presented in Table 13 below. The median estimates were identified as the 50th-percentile value for each subset of individual cost-effectiveness estimates reported below:

**Table 13. Median Cost-Effectiveness Estimates (Dollars per Ton) – Diesel Retrofits.**

| **Project Type** | **$PM_{2.5}$** | **$PM_{10}$** | **CO** | **VOCs** |
|---|---|---|---|---|
| Heavy-Duty Truck DPFs | $61,140 | $59,307 | $7,703 | $30,123 |
| Heavy-Duty Truck DOCs | $24,096 | $23,373 | $1,711 | $2,341 |
| Transit Bus DPFs | $69,582 | $63,717 | $11,608 | $38,345 |
| Transit Bus DOCs | $19,160 | $16,147 | $1,147 | $4,261 |
| School Bus DPFs | $372,070 | $311,366 | $54,855 | $167,383 |
| School Bus DOCs | $94,364 | $69,979 | $7,417 | $17,440 |
| Construction Equipment DPFs | $20,881 | $20,881 | $2,462 | $2,601 |
| Construction Equipment DOCs | $8,874 | $8,874 | $738 | $3,029 |

In all cases except for one (school bus DPF retrofits measured at the mean), retrofit technologies are highly cost-effective relative to other alternatives in mitigating $PM_{2.5}$, CO and, where estimated, $PM_{10}$ emissions. Overall, DOCs were estimated to be more cost-effective than DPFs, due to favorable trade-offs between technology cost (DOCs generally cost less than DPFs, as low as one-tenth the cost of DPFs) and technological effectiveness (DPFs are more effective at mitigating emissions, but not sufficiently to overcome differences in cost).

Retrofits of heavy-duty trucks (including both short-haul and long-haul trucks) and transit vehicles were estimated to be reasonably competitive with one another in terms of cost-effectiveness; retrofits of trucks were estimated to be more cost-effective in mitigating CO and $PM_{2.5}$ emissions, but retrofits of heavy-duty trucks and transit buses were estimated to be roughly equivalent in mitigating $PM_{10}$ emissions. Retrofits of school buses were estimated to be less cost-effective than retrofits of heavy-duty trucks and transit buses; this appears to be primarily a factor of vehicle usage (estimated annual VMT for school buses of around 15,000, compared to around 50,000 for transit buses and up to 100,000 for heavy-duty trucks).

## Heavy-Duty Vehicle Engine Replacements

This section reviews the analysis of replacements of heavy duty vehicle engines. These projects center on substituting new, low-emission engines in place of relatively older, high-emission engines. A basic example of a relevant engine replacement would be substituting a new (model year 2015) engine for a long-haul combination truck in place of a model year 2000 engine. Not only would the MY2015 engine operate free of the effects of long-term wear and tear (unlike the MY2000 engine), but the MY2015 engine would also be designed under more rigorous emission standards for key pollutants such as PM and NOx.

In the analysis, the effects of heavy duty vehicle engine replacements were investigated for:

- Short-haul single-unit trucks;
- Short-haul combination trucks;
- Long-haul single-unit trucks;
- Long-haul combination trucks;
- School buses; and
- Transit buses.

In all, 512 scenarios were analyzed for heavy-duty trucks, 64 scenarios were analyzed for school buses and 64 scenarios were analyzed for transit buses. The scenarios covered variations by engine age, vehicle size and road type.

The steps required to conduct the analysis of heavy duty vehicle engine replacements include:

- Generate per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for each vehicle type, engine age and road type;
- Identify estimates of annual vehicle use for each vehicle type;
- Identify estimates of project lifetimes (i.e., representative remaining service lives for the status quo engine); and
- Identify estimates of costs for replacement engines.

The MOVES runs yielded estimates of emission rates (in grams per mile) for each of the pollutants in the study, by vehicle type and engine model year, using national-average travel speed profiles. The estimated annual impacts on pollutants were identified by taking the difference between emission rates for a base-model-year (2015) and focal-model-year vehicle (i.e., a single model year between 1991 and 2006), and multiplying the rates by estimated annual travel volumes from the DEQ.

Lower- and upper-bound project lifetimes and engine replacement costs were selected to generate lower- and upper-bound cost-effectiveness estimates. Consistent with the analysis of diesel retrofits, the lower bound for project lifetime was specified as five years (i.e., an assumption that the original engine would have lasted from 2015 through 2019 had it not been replaced), and the upper bound was specified as 11 years (i.e., the original engine would have lasted from 2015 through 2025 had it not been replaced), following from estimates of heavy-duty truck engine lifetime VMT relative to annual usage estimates.

To estimate individual cost-effectiveness for each vehicle type/model year/road type combination in the analysis, the estimated cost for a given engine replacement was divided by the sum of estimated annual emission impacts across project lifetimes. Each estimated annual emission impact was identified as the product of the estimated change in a given emission rate (i.e., with replacement versus without) and the assumed annual volume of VMT for the vehicle. This yields a value of dollars per gram of pollutant abated over the project lifetime, which can then be converted to dollars per ton abated.

### *Sample Analytical Scenario: Replacement of a School Bus Diesel Engine*

As an illustrative example, consider the replacement of a model year 1999 diesel school bus engine with a model year 2015 engine, for a bus traveling on rural roads.

In this scenario, we assume the following details:

- The effective fleet-average emission rates for MY1999 school bus engines for travel on rural roads are (from MOVES2010b):
    - 3.142 grams per mile for CO from 2015-2019, and 3.43 grams per mile for CO from 2020-2024; and
    - 0.446 grams per mile for $PM_{2.5}$ from 2015-2024;
- The effective fleet-average emission rates for MY2015 school bus engines for travel on rural roads are (from MOVES2010b):
    - 0.22 grams per mile for CO from 2015-2018, 0.249 for CO from 2019-2020, and 0.253 for CO from 2021-2024; and
    - 0.028 grams per mile for $PM_{2.5}$ from 2015-2018, and 0.032 for $PM_{2.5}$ from 219-2024;
- The average annual travel volume for school buses traveling on rural roads is 15,000 miles;
- The MY1999 engine would have stayed in service for ten more years if it were not replaced; and
- The cost of the engine replacement is $50,000.

**Step One:** Replacing the MY1999 engine with a MY2015 engine would lead to the following reductions in per-mile emissions of CO and $PM_{2.5}$:

### Table 14. Sample Calculation of Annual CO and $PM_{2.5}$ Emission Rate Impacts of a School Bus Engine Replacement (Model Year 1999 Engine, Replaced with Model Year 2015 Engine, Traveling on Rural Roads).

| Year | Baseline CO Emission Rate (grams/mile) | CO Emission Rate after Replacement (grams/mile) | *Reduction in CO Emission Rate (grams/mile)* | Baseline $PM_{2.5}$ Emission Rate (grams/mile) | $PM_{2.5}$ Emission Rate after Replacement (grams/mile) | *Reduction in $PM_{2.5}$ Emission Rate (grams/mile)* |
|---|---|---|---|---|---|---|
| 2015 | 3.142 | 0.220 | *2.922* | 0.446 | 0.028 | *0.418* |
| 2016 | 3.142 | 0.220 | *2.922* | 0.446 | 0.028 | *0.418* |
| 2017 | 3.142 | 0.220 | *2.922* | 0.446 | 0.028 | *0.418* |
| 2018 | 3.142 | 0.220 | *2.922* | 0.446 | 0.028 | *0.418* |
| 2019 | 3.142 | 0.249 | *2.893* | 0.446 | 0.032 | *0.414* |
| 2020 | 3.430 | 0.249 | *3.181* | 0.446 | 0.032 | *0.414* |
| 2021 | 3.430 | 0.253 | *3.177* | 0.446 | 0.032 | *0.414* |
| 2022 | 3.430 | 0.253 | *3.177* | 0.446 | 0.032 | *0.414* |
| 2023 | 3.430 | 0.253 | *3.177* | 0.446 | 0.032 | *0.414* |
| 2024 | 3.430 | 0.253 | *3.177* | 0.446 | 0.032 | *0.414* |

**Step Two:** Each of the estimated per-mile emission impacts is multiplied by the assumed annual travel volumes for the vehicle to identify annual emission impacts:

### Table 15. Sample Calculation of Annual CO and $PM_{2.5}$ Emission Impacts of a School Bus Engine Replacement (Model Year 1999 Engine, Replaced with Model Year 2015 Engine, Traveling on Rural Roads).

| Year | VMT | Difference in CO Emission Rate after Replacement (grams/mile) | Annual CO Reduction after Replacement (grams) | Difference in $PM_{2.5}$ Emission Rate after Replacement (grams/mile) | Annual $PM_{2.5}$ Reduction after Replacement (grams) |
|---|---|---|---|---|---|
| 2015 | 15,000 | 2.922 | 43,830 | 0.418 | 6,270 |
| 2016 | | 2.922 | 43,830 | 0.418 | 6,270 |
| 2017 | | 2.922 | 43,830 | 0.418 | 6,270 |
| 2018 | | 2.922 | 43,830 | 0.418 | 6,210 |
| 2019 | | 2.893 | 43,395 | 0.414 | 6,210 |
| 2020 | | 3.181 | 47,715 | 0.414 | 6,210 |
| 2021 | | 3.177 | 47,655 | 0.414 | 6,210 |
| 2022 | | 3.177 | 47,655 | 0.414 | 6,210 |
| 2023 | | 3.177 | 47,655 | 0.414 | 6,210 |
| 2024 | | 3.177 | 47,655 | 0.414 | 6,210 |
| **TOTAL** | **--** | **--** | **457,050** | **--** | **62,340** |

**Step Three:** The estimated annual impacts are then summed across the project lifetime to identify the total emission impacts of the engine replacement (457,050 grams, or 0.504 tons of CO, and 62,340 grams, or 0.069 tons of $PM_{2.5}$), as shown in the bottom row of Table 15 above.

**Step Four:** The values identified in Step Three represent the denominator of the cost-effectiveness measures in the example. To identify the cost-effectiveness measures (in dollars per ton), it is necessary to divide the cost of the engine replacement by the estimates of total emission impacts:

**Table 16. Sample Calculation of Cost-Effectiveness Estimates for a School Bus Engine Replacement (Model Year 1999 Engine, Replaced with Model Year 2015 Engine, Traveling on Rural Roads).**

| Pollutant | Project Cost | Total Reduction in Exhaust Emissions (tons) | *Cost-Effectiveness (dollars per ton)* |
|---|---|---|---|
| CO | $50,000 | 0.504 | *$99,206* |
| $PM_{2.5}$ | | 0.069 | *$724,638* |

*Summary Cost-Effectiveness Estimates: Heavy-Duty Vehicle Diesel Engine Replacements*

The median cost-effectiveness estimates for the range of scenarios for replacements of heavy-duty vehicle diesel engines are presented in Table 17 below:

**Table 17. Median Cost-Effectiveness Estimates (Dollars per Ton) – Heavy-Duty Vehicle Diesel Engine Replacements.**

| Project Type | PM2.5 | PM10 | CO | NOx | VOCs |
|---|---|---|---|---|---|
| Heavy-Duty Truck Engines | $103,866 | $100,917 | $32,099 | $13,748 | $133,047 |
| Transit Bus Engines | $954,397 | $925,795 | $90,035 | $51,131 | $576,035 |
| School Bus Engines | $1,317,410 | $1,277,930 | $169,825 | $77,315 | $677,599 |

## Idle Reduction Strategies

This section reviews the analysis of idle reduction strategies (IR), including truck stop electrification projects. These projects center on the use of technologies to provide power to heavy-duty trucks when the vehicles are not in motion. By providing means to power heavy-duty trucks that do not rely on idling, IR can support shifts to lower-emission energy consumption by heavy-duty trucks. Additionally, IR reduces localized community and driver exposure to diesel engine emissions. Also, plug-in truck stop electrification may enable refrigerated trailers to plug in rather than operating a small non-road engine.

Key IR technologies include auxiliary power units (APUs), overhead ducting systems (chiefly, IdleAire) and plug-in electric power and heating and cooling systems (e.g., Shorepower). The set of available project information centered on plug-in systems and IdleAire projects; each of these project sub-types were included in the analysis.

In the analysis, the effects of IR projects were investigated at the heavy-vehicle-fleet-average level for combinations of heavy vehicle model years and road types. The central emission information for the analysis came from MOVES model runs, which reported emission rates for vehicles at idle (in grams per hour), by model year (weighted by the share of vehicles in operation within each model year) and road type. In all, 101 IR scenarios were analyzed.

The steps required to conduct the analysis of IR projects involving plug-in systems include:

- Generate per-hour emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for each model year and road type in the analysis;
- Identify estimates of annual vehicle use (idling hours) for vehicles;
- Identify estimates of the technological effectiveness of IR technologies;
- Identify estimates of IR use (percentage of time facilities are used, or hours of idling reduced per day per unit);
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

The MOVES runs yielded estimates of emission rates (in grams per hour) for each of the pollutants in the study, by model year and road type, using national-average travel profiles. The estimated annual impacts on pollutants were identified by multiplying the estimated effectiveness of IR technology (e.g., a 60-percent reduction in NOx emissions at idle per device per hour) by the number of idling hours reduced per year and the per-hour emission rates for vehicles at idle.

Lower- and upper-bound values for device utilization rates (15 percent and 60 percent per hour), impact of idling activity (reduction of 25 percent of hoteling and reduction of 100 percent of hoteling) and project costs ($4,500 and $11,500 per space) were used to identify lower- and upper-bound cost-effectiveness estimates. A constant, 15-year project lifetime was assumed.

To estimate individual cost-effectiveness for each model year/road type combination in the analysis, the estimated cost for a given project was divided by the sum of estimated annual emission impacts across project lifetimes. Each estimated annual emission impact was identified as the product of the estimated change in a given emission rate (i.e., with the use of idle reduction versus without) and the assumed annual volume of idling activities for vehicles. This yields a value of dollars per gram of pollutant abated over the project lifetime, which can then be converted to dollars per ton abated.

The analysis of IR projects involving IdleAire was conducted primarily using outputs from the DEQ, and included the following steps:

- Identify the vehicle type toward which the IR strategy would be applied (e.g., Class 8 long-haul truck);
- Identify the model year for the vehicle (endpoints of 1995 and 2010 were selected for the analysis);
- Identify estimates of annual vehicle use (hoteling hours) for vehicles, with the DEQ default values applied;
- Identify estimates of the technological effectiveness of IR technologies, with the DEQ default values applied;
- Identify estimates of IR use (percentage of time facilities are used, or hours of idling reduced per day per unit), with the DEQ default values applied;
- Identify estimates of project lifetimes, with the DEQ default values applied; and
- Identify estimates of project costs.

***Sample Analytical Scenario: Idle Reduction Strategy (IdleAire)***

As an illustrative example, consider the use of an IdleAire device by model year 2000 heavy-duty trucks traveling on urban unrestricted (i.e., highway) roads.

In this scenario, we assume the following details:

- The effective fleet-average emission rates for MY2000 heavy-duty trucks for travel on urban unrestricted roads are 109.7 grams per hour for NOx, and 6.096 grams per hour for $PM_{2.5}$;
- the IdleAire device is utilized 60 percent of the time (i.e., 60 percent occupancy rate);
- the IdleAire device reduces 100 percent of idling activity, with no offsetting emissions;
- the facility is used 365 days per year;
- the service life of the technology is 15 years; and
- the cost of the project is $11,500 per electrified space.

**Step One:** Shifting MY2000 heavy-duty trucks using the facility from 100 percent idling to 40 percent idling (i.e., using the facility 60 percent of the time) would lead to the following annual reductions in emissions of NOx and $PM_{2.5}$:

**Table 18. Sample Calculation of Annual Emission Impacts of an Idle Reduction Project (Model Year 2000 Fleet-Average Heavy-Duty Vehicle with IdleAire Technology, Urban Unrestricted Roads).**

| **Pollutant** | **Emission Reduction from Idle Reduction Strategy (IR)** | **Baseline Idle Emission Rate (grams/hour)** | **Daily Idling Activity Affected (hours)** | **Daily Reduction in Emissions from IR (grams)** | ***Annual Reduction in Emissions from IR (grams)*** |
|---|---|---|---|---|---|
| NOx | 100% | 109.7 | 14.4 | 1,580 | *576,583* |
| $PM_{2.5}$ | 100% | 6.096 | | 87.8 | *32,041* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 19. Sample Calculation of Total Emission Impacts of an Idle Reduction Project (Model Year 2000 Fleet-Average Heavy-Duty Vehicle with Plug-In Technology, Urban Unrestricted Roads).**

| **Pollutant** | **Annual Reduction in Emissions from IR (grams)** | **Project Lifetime (years)** | **Total Reduction in Emissions from IR (grams)** | ***Total Reduction in Emissions from IR (tons)*** |
|---|---|---|---|---|
| NOx | 576,583 | 15 | 8,648,748 | *9.534* |
| $PM_{2.5}$ | 32,041 | | 480,609 | *0.530* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 20. Sample Calculation of Cost-Effectiveness Estimates for an Idle ReductionProject (Model Year 2000 Fleet-Average Heavy-Duty Vehicle with Plug-In Technology, Urban Unrestricted Roads).**

| **Pollutant** | **Total Reduction in Emission from IR (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 9.534 | $11,500 | *$1,206* |
| $PM_{2.5}$ | 0.530 | | *$21,707* |

### *Summary Cost-Effectiveness Estimates: Idle Reduction Strategies*

The median cost-effectiveness estimates for the range of scenarios for idle reduction strategies are presented in Table 21 below:

**Table 21. Median Cost-Effectiveness Estimates (Dollars per Ton) – Idle Reduction Projects.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $76,342 |
| $PM_{10}$ | $51,139 |
| CO | $20,724 |
| NOX | $2,040 |
| VOCs | $122,587 |

## Extreme-Temperature Cold-Start Technologies

The analysis of extreme-temperature cold-start (ETCS) technologies projects center on the use of technologies to mitigate the inefficiencies of starting vehicles at low temperatures; for the purposes of this analysis, the relevant temperature range was from -40 degrees to zero degrees Fahrenheit.

The most prevalent technology with supporting information useful for analysis was engine block heaters, which serve as the representative technology in the analysis. Engine block heaters are a plug-in device that warms engines above ambient temperature, resulting in vehicle start emissions comparable to starts under non-extreme conditions.

In the analysis, the effects of ETCS projects were investigated at the fleet-average level for a range of vehicle types, including:

- Single-unit short-haul and long-haul trucks;
- Combination short-haul and long-haul trucks;
- Refuse trucks;
- School, transit and intercity buses; and
- Passenger cars and trucks.

The central emission information for the analysis came from MOVES model runs, which reported emission rates for vehicles at startup (in grams per start), by vehicle type and ambient temperature (-40, -20 and zero degrees Fahrenheit), and estimates of the effectiveness of relevant technologies from Alaskan projects involving block heaters. National average fleet composition estimates by vehicle type were used to seed the analysis, to represent an assumption that users of block heaters would be distributed consistently with the composition of the national vehicle fleet. In all, 132 ETCS scenarios were analyzed.

Key variables to account for within the analysis include ambient (extreme cold) temperature and the amount of time vehicles are out of operation before starting (i.e., the soak time). Three alternative ambient temperatures were selected (in degrees Fahrenheit): 0, -20, and -40, the latter of which represents the lower bound of expected cold start conditions within the United States (i.e., winter in Fairbanks, Alaska). The upper bound of soak time (greater than 12 hours) was selected for the analysis, to represent cold starts following overnight parking. Estimates of emission reductions under the use of block heaters were identified by multiplying cold-start emission rates (per start) from MOVES by estimates of the number of cold starts per year and estimates of proportional reductions in emissions from cold-start technologies, as identified in a project involving the Municipality of Anchorage (reductions of up to 60%).

The steps required to conduct the analysis of ETCS projects include:

- Generate per-start emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for each vehicle type in the analysis;
- Identify estimates of annual vehicle use (cold starts) for vehicles;
- Identify estimates of the technological effectiveness of ETCS technologies;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

The MOVES runs yielded estimates of emission rates (in grams per start) for each of the pollutants in the study, by vehicle type and ambient temperature, using national-average travel profiles. The estimated annual impacts on pollutants were identified by multiplying the estimated effectiveness of ETCS technologies (e.g., a 50-percent reduction in $PM_{2.5}$ emissions at startup) by the number of cold starts per year and the per-start emission rates by vehicle type and ambient temperature.

Lower- and upper-bound values for usage rates (60 and 120 annual cold starts), project lifetimes (5 and 10 years), and project costs ($250 and $500 per block heater) were used to identify lower- and upper-bound cost-effectiveness estimates.

To estimate individual cost-effectiveness for each vehicle type/ambient temperature combination in the analysis, the estimated cost for a given project was divided by the sum of estimated annual emission impacts across project lifetimes. Each estimated annual emission impact was identified as the product of the estimated change in a given emission rate (i.e., with the use of ETCS technology versus without) and the assumed annual volume of cold starts for vehicles. This yields a value of dollars per gram of pollutant abated over the project lifetime, which can then be converted to dollars per ton abated.

### *Sample Analytical Scenario: Extreme-Temperature Cold Start Technologies (Block Heater)*

As an illustrative example, consider the use of a block heater for a passenger vehicle, making 120 starts in zero-degree weather.

In this scenario, we assume the following details:

- The effective fleet-average emissions for passenger vehicles during starts in zero-degree weather are: 1.429 grams of NOx and 0.347 grams of $PM_{2.5}$;
- The ETCS technology reduces 60 percent of cold-start emissions;
- The service life of the technology is 10 years; and
- The cost of the project is $500 per unit.

**Step One:** Using a block heater during 120 zero-degree starts would lead to the following annual reductions in emissions of NOx and $PM_{2.5}$:

**Table 22. Sample Calculation of Annual Emission Impacts of Block Heaters (Fleet-Average Passenger Vehicles, Vehicle Starts at an Ambient Temperature of Zero Degrees Fahrenheit).**

| **Pollutant** | **Emission Reduction from Block Heater** | **Baseline Idle Emission Rate (grams/start)** | **Annual Cold Starts** | ***Annual Reduction in Emissions from Block Heater (grams)*** |
|---|---|---|---|---|
| NOx | 60% | 1.429 | 120 | *102.9* |
| $PM_{2.5}$ | 60% | 0.347 | | *24.98* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 23. Sample Calculation of Total Emission Impacts of Block Heaters (Fleet-Average Passenger Vehicles, Vehicle Starts at an Ambient Temperature of Zero Degrees Fahrenheit).**

| **Pollutant** | **Annual Reduction in Emissions from Block Heater (grams)** | **Project Lifetime (years)** | **Lifetime Reduction in Emissions from Block Heater (grams)** | ***Lifetime Reduction in Emissions from Block Heater (tons)*** |
|---|---|---|---|---|
| NOx | 120.9 | 10 | 1209 | *0.00133* |
| $PM_{2.5}$ | 24.98 | | 249.8 | *0.00028* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 24. Sample Calculation of Cost-Effectiveness Estimates for Block Heaters (Fleet-Average Passenger Vehicles, Vehicle Starts at an Ambient Temperature of Zero Degrees Fahrenheit).**

| **Pollutant** | **Block Heater Cost** | **Lifetime Reduction in Emissions from Block Heater (tons)** | ***Cost-Effectiveness of Block Heater (dollars per ton)*** |
|---|---|---|---|
| NOx | $500 | 0.00133 | *$375,180* |
| $PM_{2.5}$ | | 0.00028 | *$1,815,823* |

### *Summary Cost-Effectiveness Estimates: Extreme-Temperature Cold-Start Technologies*

The median cost-effectiveness estimates for the range of scenarios for all vehicle types and ambient temperatures are presented in Table 25 below:

**Table 25. Median Cost-Effectiveness Estimates (Dollars per Ton) – Extreme-Temperature Cold-Start Technologies.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $2,972,599 |
| $PM_{10}$ | $2,773,192 |
| CO | $12,235 |
| NOX | $364,817 |
| VOCs | $137,975 |

## Intelligent Transportation Systems/Intersection Improvements

This section reviews the analysis of projects involving improvements to intersections, including signalization improvements and re-purposed lanes (i.e., left-turn lanes). These projects focus on the use of technological and engineering approaches to improve the flow of traffic through intersections and along corridors. The analyses of intelligent transportation systems scenarios were conducted using outputs from MOVES2010b and project-level inputs from CMAQ projects, *Multi-Pollutant Emissions Benefits of Transportation Strategies (MPEBTS)*, and documentation by Curbed L.A. and San Bernardino Associated Governments. Emission rate data were identified in national-average-fleet-level MOVES runs for passenger vehicles.

Distinct to other project types, each of the intersection improvement scenarios involved a specific improvement in travel speeds (or reduction in delay, in the case of left-turn lanes), generally around five miles per hour (from bases ranging from 15 to 40 miles per hour). In all, 20 scenarios were included in the analysis.

The steps required to conduct the analysis of intersection improvement projects include:

- Generate per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the range of relevant travel speeds, including time at idle;
- Identify estimates of vehicle travel activity;
- Identify estimates of pre- and post-implementation travel speeds;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

In the analysis, the effects of intersection improvement projects were investigated at the fleet-average level for passenger vehicles. Emission impacts (in grams per mile) were identified in MOVES as the difference between emissions under pre- and post-implementation travel speeds, both estimated as the product of per-mile passenger vehicle emission rates and VMT reductions per mitigated trip, and project lifetimes (15 or 20 years, depending upon the specification of the scenario). Most projects did not indicate expectations of increased VMT under higher travel speeds; for these scenarios, no increase in VMT was assumed. Some projects did not specify costs; for the corresponding analysis, per-mile and per-signal costs from other scenarios were applied as appropriate.

To estimate individual cost-effectiveness for each scenario in the analysis, the estimated cost for a given project was divided by the sum of estimated annual emission impacts across project lifetimes. Each estimated annual emission impact was identified as the product of the estimated change in a given emission rate (i.e., the change from pre- to post-implementation) and the assumed annual travel volumes for vehicles. This yields a value of dollars per gram of pollutant abated over the project lifetime, which can then be converted to dollars per ton abated.

### *Sample Analytical Scenario: Signalization Improvement*

As an illustrative example, consider a scenario involving ten new signals added along a three-mile urban corridor.

In this scenario, we assume the following details:

- Average annual traffic volume is 21 million VMT (approximately 30,000 vehicles per day along the corridor);
- The average pre-implementation travel speed is 15 miles per hour;
- The average post-implementation travel speed is 20 miles per hour;
- The average pre-implementation per-mile emission rates are 0.413 grams per mile for NOx, and 0.025 grams per mile for $PM_{2.5}$;
- The project lifetime is 20 years; and
- The project cost is $4 million.

**Step One:** Improving the average travel speed from 15 miles per hour to 20 miles per hour would lead to the following per-mile reductions in emissions of NOx and $PM_{2.5}$:

**Table 26. Sample Calculation of Emission Rate Impacts from a Signalization Improvement (in Grams per Mile, from 15 mph to 20 mph).**

| **Pollutant** | **Before Improvement (grams per mile)** | **After Improvement (grams per mile)** | ***Emission Rate Impact (grams per mile)*** |
|---|---|---|---|
| NOx | 0.413 | 0.394 | *0.019* |
| $PM_{2.5}$ | 0.025 | 0.021 | *0.004* |

**Step Two:** The per-mile emissions rate impact is multiplied by annual VMT along the corridor to identify the annual emission impact:

**Table 27. Sample Calculation of Annual Emission Impacts from a Signalization Improvement (from 15 mph to 20 mph).**

| **Pollutant** | **Emission Rate Impact (grams/mile)** | **Annual VMT** | **Annual Emission Impact (grams)** | ***Annual Emission Impact (tons)*** |
|---|---|---|---|---|
| NOx | 0.434 | 21,000,000 | 9,114,000 | *10.05* |
| $PM_{2.5}$ | 0.019 |  | 399,000 | *0.440* |

**Step Three:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 28. Sample Calculation of Project Total Emission Impacts from a Signalization Improvement (from 15 mph to 20 mph).**

| **Pollutant** | **Annual Emission Impact (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 10.05 | 20 | *200.9* |
| $PM_{2.5}$ | 0.440 | | *8.796* |

**Step Four:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 29. Cost-Effectiveness Estimates, Signalization Improvement (in Dollars per Ton, from 15 mph to 20 mph).**

| **Pollutant** | **Lifetime Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness ($/ton)*** |
|---|---|---|---|
| NOx | 200.9 | $4,000,000 | *$19,908* |
| $PM_{2.5}$ | 8.796 | | *$454,729* |

### *Summary Cost-Effectiveness Estimates: Intelligent Transportation Systems/Intersection Improvements*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 30 below:

**Table 30. Median Cost-Effectiveness Estimates (Dollars per Ton) – Intelligent Transportation Systems/Intersection Improvements.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $12,734,683 |
| $PM_{10}$ | $4,753,463 |
| CO | $65,793 |
| NOx | $744,474 |
| VOCs | $1,069,154 |

## Freight and Intermodal Projects

This section reviews the analysis of projects involving efforts to encourage mode shift for heavy-duty truck freight (e.g., from truck to rail, from truck to barge). Key projects identified include an intermodal freight facility in San Joaquin, California; two maritime scenarios including the Brooklyn Marine Terminal and Red Hook Container Barge, and one case of extending railroad access to a port at the Columbia Slough in Portland, Oregon.

In the analysis, the effects of freight and intermodal projects were investigated at the national-average fleet level for heavy-duty trucks. The central emission information for the analysis came from MOVES model runs, which reported emission rates for heavy-duty trucks (in grams per mile), across a range of average travel speeds representing different travel conditions (ranging from 15 to 30 miles per hour on arterials and at 50 miles per hour on highways). In all, 16 freight and intermodal scenarios were analyzed.

The steps required to conduct the analysis of freight and intermodal projects include:

- Generate per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the range of relevant travel speeds;
- Identify estimates of vehicle travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

To estimate individual cost-effectiveness for each scenario in the analysis, the estimated cost for a given project was divided by the sum of estimated annual emission impacts across project lifetimes. Each estimated annual emission impact was identified as the product of the estimated emission rate (i.e., the change from pre- to post-implementation) and the assumed annual reduction in travel volumes for vehicles. This yields a value of dollars per gram of pollutant abated over the project lifetime, which can then be converted to dollars per ton abated.

***Sample Analytical Scenario: Truck-to-Barge Intermodal Project***

As an illustrative example, consider a scenario involving the use of barges to mitigate heavy-duty truck travel within a metropolitan area.

In this scenario, we assume the following details:

- the national fleet average emission rates are 5.752 grams per mile for NOx and 0.349 for $PM_{2.5}$, representing an assumed average heavy-duty truck travel speed of 25 miles per hour for status quo travel affected by the project;
- the average reduction of heavy-duty truck VMT per affected trip is 25 miles;
- 50,000 heavy-duty truck trips are affected annually by the project;
- the project involves a three-year operating subsidy; and
- the project cost is $15 million.

**Step One:** Annual emission impacts are identified by multiplying per-trip emission rates by the number of affected trips:

**Table 31. Sample Calculation of Annual Emission Impacts from a Barge Project (in Grams per Mile, Offloading Truck Freight to Barges, Average Truck Travel Speed of 25 mph).**

| **Pollutant** | **Truck Emission Mitigation (grams/mile)** | **Annual Truck VMT Reduction** | **Annual Emission Impact (grams)** | ***Annual Emission Impact (tons)*** |
|---|---|---|---|---|
| NOx | 5.752 | 1,250,000 | 7,190,000 | *7.926* |
| $PM_{2.5}$ | 0.349 | | 436,250 | *0.481* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 32. Sample Calculation of Total Emission Impacts from a Barge Project (in Grams per Mile, Offloading Truck Freight to Barges, Average Truck Travel Speed of 25 mph).**

| **Pollutant** | **Annual Emission Impact (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 7.926 | 3 | *23.78* |
| $PM_{2.5}$ | 0.481 | | *1.443* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 33. Cost-Effectiveness Estimates for a Barge Project (in Dollars per Ton, Offloading Truck Freight to Barges, Average Truck Travel Speed of 25 mph).**

| **Pollutant** | **Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 23.78 | $15,000,000 | *$630,867* |
| $PM_{2.5}$ | 1.443 | | *$10,397,536* |

### *Summary Cost-Effectiveness Estimates: Freight and Intermodal Projects*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 34 below:

**Table 34. Median Cost-Effectiveness Estimates (Dollars per Ton) – Freight and Intermodal Projects.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $4,153,174 |
| $PM_{10}$ | $2,864,417 |
| CO | $315,485 |
| NOx | $248,854 |
| VOCs | $2,570,012 |

### Transit Projects

There are four distinct types of transit projects in the analysis:

- Park and ride projects;
- Transit facility and amenity improvements (e.g., passenger information systems, bus shelters);
- Transit service projects (e.g., additional services on existing routes, new routes); and
- Subsidized transit fare programs (e.g., free travel on ozone action days).

Park and ride projects focus on the provision of new park and ride lots to encourage transfers from light-duty vehicle to public transit. Transit facility and amenity improvement projects center on improving the experience of transit users, in turn stimulating demand for travel by public transit.

Transit service projects center on direct support of transit services, supporting demand for travel by public transit. Consistent with the full range of projects in the analysis, the full range of relevant costs were considered when evaluating transit service projects, rather than focusing on the subset representing CMAQ funding. This is of particular relevance with respect to operating assistance; projects involving operating assistance were represented as having equivalent project costs to projects involving greater levels of financial support, to enable like-with-like comparisons of the impacts of transit service on emissions across all transit service projects.

Subsidized transit fare programs are targeted at stimulating shifts to public transit at times of peak environmental need through the use of temporary discounts on fares, such as during periods with high ozone levels.

In the analyses of all transit projects, the key inputs included:

- Estimates of bus and light-duty vehicle emission rates from national-average fleet-level MOVES runs across a range of average travel speeds;
- And estimates of:
  - Project size (e.g., the number of buses involved),
  - Travel demand (light-duty vehicle VMT reduced through travel by transit),
  - Project costs, and
  - Project lifetimes of projects as identified in CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study).

The estimated emission impacts centered on shifts of travel via light-duty vehicle to transit. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated light-duty-vehicle trips (less additional bus emissions), and project lifetimes. In all, 68 transit project scenarios were analyzed, including 20 park and ride projects, 12 transit service amenity improvement projects, 15 transit service expansion projects, and 21 subsidized transit fare projects.

The steps required to conduct the analysis of transit projects include:

- Generate light-duty and bus per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the range of relevant travel speeds;
- Identify estimates of light-duty vehicle travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of new bus travel activity (daily and annual VMT) associated with projects;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

### *Sample Analytical Scenario: Park and Ride Project*

As an illustrative example, consider a scenario involving a new park and ride lot to encourage transfers from light-duty vehicle to public transit.

In this scenario, we assume the following details:

- The average travel speed for public transit trips and light-duty vehicle trips is 35 miles per hour;
- The average light-duty emission rates for travel at 35 miles per hour are 0.338 grams per mile for NOx and 0.011 grams per mile for $PM_{2.5}$;
- There are no increases with corresponding public transit trips (i.e., the trips take place on vehicles already in service);
- The park and ride lot has 500 spaces;
- The spaces are utilized at an average rate of 80 percent, for 250 days per year;
- The average light-duty vehicle round trip replaced by a public transit trip is 30 miles (leading to a daily reduction of 24 miles per space, or 12,000 miles per day in total);

- The project lifetime is 20 years; and
- The project cost is $1,500,000.

**Step One:** Annual emission impacts are identified by multiplying per-trip emissions by the number of affected trips:

### Table 35. Sample Calculation of Annual Emission Impacts from a Park-and-Ride Project (in Grams per Mile, Average Light-Duty-Vehicle Travel Speed of 35 mph).

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Daily VMT Reduction** | **Annual VMT Reduction** | **Annual Emission Impact (grams)** | ***Annual Emission Impact (tons)*** |
|---|---|---|---|---|---|
| NOx | 0.338 | 12,000 | 3,000,000 | 1,014,000 | *1.1177* |
| PM$_{2.5}$ | 0.011 | | | 33,000 | *0.0364* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

### Table 36. Sample Calculation of Total Emission Impacts from a Park-and-Ride Project (in Grams per Mile, Average Light-Duty-Vehicle Travel Speed of 35 mph).

| **Pollutant** | **Annual Emission Impact (tons)** | **Project Lifetime (years)** | ***Total Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 1.1177 | 20 | *22.35* |
| PM$_{2.5}$ | 0.0364 | | *0.728* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

### Table 37. Sample Calculation of Cost-Effectiveness Estimates for a Park-and-Ride Project (in Grams per Mile, Average Light-Duty-Vehicle Travel Speed of 35 mph).

| **Pollutant** | **Total Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 22.35 | $1,500,000 | *$67,099* |
| PM$_{2.5}$ | 0.728 | | *$2,061,784* |

***Sample Analytical Scenario: Transit Amenity Improvement***

As an illustrative example, consider a scenario involving the installation of a new traveler information system.

In this scenario, we assume the following details:

- The average travel speed for public transit trips and light-duty vehicle trips is 25 miles per hour;
- The average light-duty emission rates for travel at 25 miles per hour are 0.376 grams per mile for NOx and 0.018 grams per mile for $PM_{2.5}$;
- The project stimulates the shift of 300 light-duty vehicle trips to public transit trips per day, for 250 days each year;
- There are no increases with corresponding public transit trips (i.e., the trips take place on vehicles already in service);
- The average light-duty vehicle round trip replaced by a public transit trip is 10 miles;
- the project lifetime is 10 years; and
- the project cost is $400,000.

**Step One**: Annual emission impacts are identified by multiplying per-trip emissions by the number of affected trips:

**Table 38. Sample Calculation of Annual Emission Impacts from a Transit Amenity Project (in Grams per Mile, Average Light-Duty-Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Daily VMT Reduction** | **Annual VMT Reduction** | **Annual Emission Impact (grams)** | ***Annual Emission Impact (tons)*** |
|---|---|---|---|---|---|
| NOx | 0.376 | 3,000 | 750,000 | 282,000 | *0.3109* |
| $PM_{2.5}$ | 0.018 | | | 13,500 | *0.0149* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 39. Sample Calculation of Total Emission Impacts from a Transit Amenity Project (in Grams per Mile, Average Light-Duty-Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Annual Emission Impact (tons)** | **Project Lifetime (years)** | ***Total Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 0.3109 | 10 | *3.1085* |
| $PM_{2.5}$ | 0.0149 | | *0.1488* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 40. Sample Calculation of Cost-Effectiveness Estimates for a Transit Amenity Project (in Grams per Mile, Average Light-Duty-Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Total Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 3.1085 | $400,000 | *$128,679* |
| $PM_{2.5}$ | 0.1488 | | *$2,687,956* |

### *Sample Analytical Scenario: Transit Service Expansion*

As an illustrative example, consider a scenario involving the addition of a new transit route.

In this scenario, we assume the following details:

- The new route operates ten times each weekday (2,600 round-trips per year);
- The route covers 20 miles round-trip;
- Average daily ridership on the route is 200 people;
- Each transit trip offsets an average of 10 miles by light-duty vehicle (per transit passenger);

- The bus travels at an average speed of 25 miles per hour;
- The average light-duty emission rates for travel at 25 miles per hour are 0.376 grams per mile for NOx and 0.018 grams per mile for $PM_{2.5}$;
- The average emission rates for the new bus service at 25 miles per hour are 0.862 grams per mile for NOx and 0.037 grams per mile for $PM_{2.5}$;
- The funding for the new route covers a period of three years (after which separate funding not evaluated here could be applied; the annual impacts of the project are assumed to be constant over time, and hence the resulting cost-effectiveness estimates are insensitive to the specification of project lifetime under a corresponding specification of constant cost per year) ; and
- The project cost is $700,000.

**Step One:** Annual emission benefits are identified by multiplying per-trip light-duty vehicle emissions by the number of offset trips:

**Table 41. Sample Calculation of Annual Emission Benefits from a New Bus Route (in Grams per Mile, Average Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Annual Light-Duty-Vehicle VMT Reduction** | ***Annual Emission Benefit (grams)*** |
|---|---|---|---|
| NOx | 0.376 | 520,000 | *195,520* |
| $PM_{2.5}$ | 0.018 | | *9,360* |

**Step Two:** Annual emission impacts are identified by subtracting new annual bus emissions from the annual emission benefit identified in Step One:

**Table 42. Sample Calculation of Annual Emission Impacts from a New Bus Route (Average Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Annual Emission Benefit (grams)** | **New Bus Emissions (grams/mile)** | **Annual New Bus VMT** | **Annual New Bus Emissions (grams)** | **Annual Net Emission Impact (grams)** | ***Annual Net Emission Impact (tons)*** |
|---|---|---|---|---|---|---|
| NOx | 195,520 | 0.862 | 52,000 | 44,824 | 150,696 | *0.1661* |
| $PM_{2.5}$ | 9,360 | 0.037 | | 1,924 | 7,436 | *0.0082* |

**Step Three:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 43. Sample Calculation of Total Emission Impacts for a New Bus Route (Average Travel Speed of 25 mph).**

| **Pollutant** | **Annual Net Emission Impact (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 0.1661 | 3 | *0.4983* |
| $PM_{2.5}$ | 0.0082 | | *0.0246* |

**Step Four:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 44. Cost-Effectiveness Estimates for a New Bus Route (in Dollars per Ton, Average Travel Speed of 25 mph).**

| **Pollutant** | **Lifetime Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness ($/ton)*** |
|---|---|---|---|
| CO | 0.4983 | $700,000 | *$1,404,659* |
| NOx | 0.0246 | | *$28,466,447* |

***Sample Analytical Scenario: Subsidized Transit Fares***

As an illustrative example, consider a scenario involving a fare-free program for ozone action days.

In this scenario, we assume the following details:

- The fare-free program leads to 6,000 trips per day;
- There are an average of five ozone action days per year covered by the project;
- The average distance traveled by new passengers is six miles;
- There are no additional bus emissions associated with the new passengers;
- The average travel speed for offset light-duty vehicle trips is 25 miles per hour;
- The average light-duty emission rates for travel at 25 miles per hour are 0.376 grams per mile for NOx and 0.018 grams per mile for $PM_{2.5}$;
- The project involves three years of funding (additional years could be funded separately; the effects of the project are assumed to be linear over time, so the choice of project lifetime does not affect the cost-effectiveness estimates) to cover the incremental per-passenger-mile operating costs of the buses (75 cents per mile,

consistent with values reported by the Victoria Transport Policy Institute after accounting for fare recovery in normal operations and with values reported by the National Transit Database); and

- The total project cost is $67,500.

**Step One:** Annual emission impacts are identified by multiplying per-trip emissions by the number of affected trips:

**Table 45. Sample Calculation of Annual Emission Benefits from a Subsidized Transit Fare Project (Average Light-Duty-Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Daily VMT Reduction** | **Annual VMT Reduction** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|---|
| NOx | 0.376 | 36,000 | 180,000 | 67,680 | *0.3109* |
| $PM_{2.5}$ | 0.018 | | | 3,240 | *0.0036* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 46. Sample Calculation of Total Emission Benefits from a Subsidized Transit Fare Project (Average Light-Duty-Vehicle Travel Speed of 25 mph).**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Total Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 0.3109 | 3 | *0.2238* |
| $PM_{2.5}$ | 0.0036 | | *0.0107* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 47. Cost-Effectiveness Estimates for a Subsidized Transit Fare Project (in Dollars per Ton, Average Travel Speed of 25 mph).**

| **Pollutant** | **Lifetime Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 0.2238 | $67,500 | *$301,591* |
| $PM_{2.5}$ | 0.0107 | | *$6,299,895* |

### *Summary Cost-Effectiveness Estimates: Transit Projects*

The median cost-effectiveness estimates for the range of transit project scenarios are presented in Table 48 below:

**Table 48. Median Cost-Effectiveness Estimates (Dollars per Ton) – Transit Projects.**

| **Project Type** | **$PM_{2.5}$** | **$PM_{10}$** | **CO** | **NOx** | **VOCs** |
|---|---|---|---|---|---|
| Park and Ride | $2,084,289 | $922,892 | $11,553 | $91,204 | $463,612 |
| Transit Amenity Improvements | $5,702,705 | $2,230,832 | $36,219 | $318,872 | $1,282,620 |
| Transit Service Expansion | $2,674,619 | $1,131,417 | $12,511 | $101,001 | $495,021 |
| Subsidized Transit Fares | $27,915,007 | $13,189,594 | $144,298 | $1,091,004 | $6,361,800 |

## Bicycle and Pedestrian Projects

This section reviews the analysis of bicycle and pedestrian projects. The analysis focused on infrastructure projects supporting walking and bicycling in place of travel by light-duty vehicle. Sample calculations of relevant projects include sidewalks, crosswalks, bicycle lanes on existing roads and bicycle and walking paths separated from existing roads. There were no assumed emission impacts involving public transit; both additional public transit trips chained to new bicycle and walking trips and changes from transit to bicycle or walking trips were assumed to have a negligible effect on transit vehicle emissions. In all, 48 bicycle and pedestrian scenarios were included in the analysis.

The key inputs for the analysis of bicycle and pedestrian projects include:

- Emission rates estimates for offset light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds;
- Estimates of the volume of offset light-duty driving from CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study) and the Atlanta Regional Commission;
- Estimates of project lifetimes; and
- Project cost values from CMAQ assessment studies and other project reports.

The steps required to conduct the analysis of bicycle and pedestrian projects include:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the range of relevant travel speeds;
- Identify estimates of light-duty vehicle travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

### *Sample Analytical Scenario: Bicycle and Pedestrian Path*

As an illustrative example, consider a new bicycle path along an existing roadway.

In this scenario, we assume the following details:

- The path is two miles long;
- The existence of the path will shift 300 trips per day from light-duty vehicle to bicycle or walking;
- The path will be used 200 days per year;
- Each offset light-duty vehicle trip will result in a reduction of two miles of vehicle travel at an average travel speed of 35 miles per hour;
- The average light-duty emission rates for travel at 35 miles per hour are 0.338 grams per mile for NOx and 0.011 grams per mile for $PM_{2.5}$;
- The project lifetime is 10 years; and
- The project cost is $250,000.

**Step One:** Annual emission impacts are identified by multiplying per-trip emissions by the number of affected trips:

**Table 49. Sample Calculation of Annual Emission Impacts from a Bicycle-Pedestrian Path Project (Average Light-Duty-Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Annual VMT Reduction** | **Annual Emission Impact (grams)** | ***Annual Emission Impact (tons)*** |
|---|---|---|---|---|
| NOx | 0.338 | 120,000 | 40,560 | *0.0447* |
| $PM_{2.5}$ | 0.011 | | 1320 | *0.0015* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 50. Sample Calculation of Total Emission Impacts from a Bicycle-Pedestrian Path Project (Average Light-Duty-Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Annual Emission Impact (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 0.0447 | 10 | *0.4471* |
| $PM_{2.5}$ | 0.0015 | | *0.0146* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 51. Cost-Effectiveness Estimates for a Bicycle-Pedestrian Path Project (in Dollars per Ton, Average Light-Duty-Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Lifetime Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 0.4471 | $250,000 | *$559,162* |
| $PM_{2.5}$ | 0.0146 | | *$17,181,534* |

### *Summary Cost-Effectiveness Estimates: Bicycle and Pedestrian Projects*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 52 below:

**Table 52. Median Cost-Effectiveness Estimates (Dollars per Ton) – Bicycle and Pedestrian Projects.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $3,179,371 |
| $PM_{10}$ | $1,268,478 |
| CO | $19,060 |
| NOx | $150,235 |
| VOCs | $684,883 |

### Employee Transit Benefits

This section reviews the analysis of employee transit benefit projects. The two types of employee transit benefit projects considered in the analysis were:

- Transit passes, which involve employees receiving (partially or fully) subsidized transit passes as part of their compensation; and
- Parking cash-out programs, which involve employees compensating employees with a monthly stipend to forego the use of an available employer-provided parking space.

In both types of projects, employees receive compensation intended to encourage mode shift from light-duty vehicle to public transit. A notable difference between the two types of projects is that parking cash-out may be associated with more discrete changes in driving activity, in cases where transit pass recipients could feasibly access employer-provided parking intermittently. In all, 36 employee transit benefit project scenarios were analyzed.

Key inputs for the analysis of employee transit benefit projects include:

- Emission rates estimates for offset light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds;
- Estimates of the volume of offset light-duty driving from CMAQ assessment studies, (2008 Assessment Study, 2014 Assessment Study) other project documentation and academic literature (e.g., MPEBTS, Shoup (1997));
- Estimates of project lifetimes; and
- Project cost values from CMAQ assessment studies and other project reports.

The steps required to conduct the analysis of employee transit benefit projects include:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the range of relevant travel speeds;
- Identify estimates of light-duty vehicle travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

### *Sample Analytical Scenario: Employee Transit Passes*

As an illustrative example, consider a project involving subsidized transit passes provided by employers.

In this scenario, we assume the following details:

- One hundred employees participate in the program per year;
- Participating employees reduce their travel by light-duty vehicle by 15 miles per workday (250 workdays per year);
- The average travel speed for offset light-duty vehicle trips is 35 miles per hour;
- the average light-duty emission rates for travel at 35 miles per hour are 0.338 grams per mile for NOx and 0.011 grams per mile for $PM_{2.5}$;
- There are no incremental emission associated with travel by public transit made by participating employees;
- The project lifetime is three years; and
- The project cost is $270,000 ($75 per monthly pass).

**Step One:** Annual emission impacts are identified by multiplying per-trip emissions by the number of affected trips:

**Table 53. Sample Calculation of Annual Emission Impacts from an Employee Transit Pass Project (Average Light-Duty-Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Annual VMT Reduction** | **Annual Emission Impact (grams)** | ***Annual Emission Impact (tons)*** |
|---|---|---|---|---|
| NOx | 0.338 | 375,000 | 126,750 | *0.1397* |
| $PM_{2.5}$ | 0.011 | | 4,125 | *0.0045* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 54. Sample Calculation of Total Emission Impacts from an Employee Transit Pass Project (Average Light-Duty-Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Annual Emission Impact (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 0.1397 | 3 | *0.4192* |
| $PM_{2.5}$ | 0.0045 | | *0.0136* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 55. Sample Calculation of Cost-Effectiveness Estimates for an Employee Transit Pass Project (Dollars per Ton, Average Light-Duty-Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Lifetime Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 0.4192 | $270,000 | *$644,155* |
| $PM_{2.5}$ | 0.0136 | | *$19,793,127* |

### *Summary Cost-Effectiveness Estimates: Employee Transit Benefits*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 56 below:

**Table 56. Median Cost-Effectiveness Estimates (Dollars per Ton) – Employee Transit Benefits.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $6,140,209 |
| $PM_{10}$ | $2,859,391 |
| CO | $36,202 |
| NOx | $296,490 |
| VOCs | $1,382,295 |

### Roundabouts

These projects are distinct to other intersection improvements in the analysis, in that roundabouts involve a clear focus on infrastructure improvements rather than the use of signalization technology in conjunction with physical changes to intersections. In all, 52 roundabout scenarios were included in the analysis.

An additional positive factor supporting the implementation of roundabouts is the potential for significant reductions in crash rates at project sites. For example, the CMF Clearinghouse reveals that roundabouts may be expected to reduce crash rates by between 44 and 87 percent (for all crash types, according to the top-rated study in the CMF Clearinghouse). The crash reductions reported by the CMF Clearinghouse indicate that safety benefits could comprise a large share of total project benefits for roundabout projects at locations with relatively high crash rates.

Key inputs to the analysis of roundabout projects include:

- Emission rates estimates for offset light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds;
- Estimates of vehicle travel activity at project sites (i.e., vehicles per day, hours of idling per day, VMT along adjacent roadways affected by the project) from CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study) and other project reports;
- Estimates of pre- and post-implementation travel speeds from CMAQ assessment studies and other project reports;
- Estimates of project lifetimes from CMAQ assessment studies and other project reports; and
- Estimates of project costs from CMAQ assessment studies and other project reports.

The steps required to conduct the analysis of roundabout projects include:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the relevant travel speeds before and after implementation of the project;
- Identify estimates of travel activity (daily and annual VMT) affected by the project;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

***Sample Analytical Scenario: Roundabout***

As an illustrative example, consider a project involving the construction of a new roundabout.

In this scenario, we assume the following details:

- Travel speeds are affected by the intersection for quarter-mile stretches in all directions of travel running through the intersection;
- Twenty thousand vehicles pass through the intersection each workday (250 days per year);
- The roundabout improves average travel speeds around the intersection from 15 to 30 miles per hour;
- The average fleet-level emission rates for travel at 15 miles per hour are 0.413 grams per mile for NOx and 0.025 grams per mile for $PM_{2.5}$;
- The average fleet-level emission rates for travel at 30 miles per hour are 0.345 grams per mile for NOx and 0.015 grams per mile for $PM_{2.5}$;
- The project lifetime is 20 years; and
- The project cost is $3 million.

**Step One:** Annual pre- and post-implementation emissions are identified by multiplying per-trip emissions by the number of affected trips under the per- and post-implementation travel speeds:

**Table 57. Sample Calculation of Annual Emission Levels with and without a Roundabout Project (Average Travel Speeds of 15 and 30 mph).**

| **Pollutant** | **Emission Rates – No Roundabout (grams/mile)** | **Emission Rates – Roundabout (grams/mile)** | **Annual VMT** | ***Annual Emissions – No Roundabout (grams)*** | ***Annual Emissions - Roundabout (grams)*** |
|---|---|---|---|---|---|
| NOx | 0.413 | 0.345 | 1,250,000 | *516,250* | *431,250* |
| $PM_{2.5}$ | 0.025 | 0.015 | | *31,250* | *18,750* |

**Step Two:** Annual emission impacts are identified by subtracting pre-implementation emissions from post-implementation emissions (a negative difference is shown below as a positive benefit):

### Table 58. Sample Calculation of Annual Emission Benefits of a Roundabout Project (Average Travel Speeds of 15 and 30 mph).

| **Pollutant** | **Annual Emissions – No Roundabout (grams)** | **Annual Emissions - Roundabout (grams)** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|
| NOx | 516,250 | 431,250 | 85,000 | *0.4754* |
| $PM_{2.5}$ | 31,250 | 18,750 | 12,500 | *0.0138* |

**Step Three:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

### Table 59. Sample Calculation of Total Emission Benefits of a Roundabout Project (Average Travel Speeds of 15 and 30 mph).

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| NOx | 0.4754 | 20 | *9.5074* |
| $PM_{2.5}$ | 0.0138 | | *0.2756* |

**Step Four:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

### Table 60. Sample Calculation of Cost-Effectiveness Estimates for a Roundabout Project (Average Travel Speeds of 15 and 30 mph).

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 9.5074 | $3,000,000 | *$315,543* |
| $PM_{2.5}$ | 0.2756 | | *$10,886,220* |

### *Summary Cost-Effectiveness Estimates: Roundabouts*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 61 below:

### Table 61. Median Cost-Effectiveness Estimates (Dollars per Ton) – Roundabouts.

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $16,686,148 |
| $PM_{10}$ | $7,552,437 |
| CO | $114,251 |
| NOx | $2,958,769 |
| VOCs | $4,338,299 |

## Carsharing

Carsharing projects center on offering access to vehicles owned and maintained by third parties (e.g., cities) for intermittent trips best served by light-duty vehicles. Access to shared vehicles provides alternatives to reduce overall usage of a light-duty vehicles by households, and in some cases, enables households to carry out travel activities while reducing the number of cars owned by households, both of which may result in decreases in VMT through eliminating some discretionary trips and mode shift to public transit).

Information on carsharing projects was identified through a review of carsharing project documentation and supporting literature (e.g., Cervero et al., 2006). In all, 48 carsharing scenarios were included in the analysis.

Key inputs for the analysis of carsharing projects include:

- emission rates estimates for offset light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds;
- estimates of reductions in light-duty vehicle usage for each user through the use of carsharing;
- estimates of participation rates in carsharing projects;
- estimates of project lifetimes; and
- estimates of project costs, including adjustment factors accounting for related (but separate) costs that could be bundled within reported costs, and vehicle depreciation (i.e., reasonable re-sale value at the end of the project life).

The steps required to conduct the analysis of carsharing projects include:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for relevant travel speeds for travel affected by the project;
- identify estimates of travel activity (daily and annual VMT) affected by the project;
- identify estimates of project lifetimes; and
- identify estimates of project costs.

***Sample Analytical Scenario: Carsharing***

As an illustrative example, consider a project involving a new carsharing project.

In this scenario, we assume the following details:

- the project includes the purchase and maintenance of 80 light-duty vehicles;
- each shared vehicle is used by 10 owners of light-duty vehicles;
- each participant reduces net annual VMT by 4,000;
- the average travel speed for offset travel is 25 miles per hour;
- the average fleet-level emission rates for travel at 25 miles per hour are 0.376 grams per mile for NOx and 0.018 grams per mile for $PM_{2.5}$;
- the project lifetime is 5 years; and
- the project cost, after accounting for revenue and the sale of used vehicles at the end of the project, is $2 million.

**Step One:** Annual emission impacts are identified by multiplying per-mile emission rates by the number of affected trips under the relevant travel speed:

**Table 62. Sample Calculation of Annual Emission Benefits of a Carsharing Project (Average Travel Speed of 25 mph).**

| **Pollutant** | **Emission Rates (grams/mile)** | **Annual VMT Reduction** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|
| NOx | 0.376 | 3,200,000 | 1,203,200 | *1.3263* |
| $PM_{2.5}$ | 0.018 | | 57,600 | *0.0635* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 63. Sample Calculation of Total Emission Benefits of a Carsharing Project (Average Travel Speed of 25 mph).**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| NOx | 1.3263 | 5 | *6.6315* |
| $PM_{2.5}$ | 0.0635 | | *0.3175* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 64. Sample Calculation of Cost-Effectiveness Estimates for a Carsharing Project (Average Travel Speed of 25 mph).**

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 6.6315 | $2,000,000 | *$301,591* |
| $PM_{2.5}$ | 0.3175 | | *$6,299,896* |

### *Summary Cost-Effectiveness Estimates: Carsharing*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 65 below:

**Table 65. Median Cost-Effectiveness Estimates (Dollars per Ton) – Carsharing.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $7,668,684 |
| $PM_{10}$ | $3,524,324 |
| CO | $40,919 |
| NOx | $319,608 |
| VOCs | $1,698,827 |

## Bikesharing

Similar to carsharing projects, bikesharing projects center on providing incentives to shift travel mode from light-duty vehicle to bicycle for some trips (rather than reducing the number of cars owned by households), by offering access to bicycles owned and maintained by third parties (e.g., cities) for intermittent trips that can be served via bicycle. Information on bikesharing projects was identified through a review of bikesharing project documentation, with a focus on the Washington metropolitan area's Capital Bikeshare. In all, 24 bikesharing scenarios were included in the analysis.

Key inputs for the analysis of bikesharing projects include:

- Emission rates estimates for offset light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds;
- Estimates of travel demand reduced for each user per trip through mode shift to shared bicycle;
- Estimates of participation rates (users and annual trips) in bikesharing projects;
- Estimates of project lifetimes; and
- Estimates of project costs, including adjustment factors accounting for revenue recovery.

The steps required to conduct the analysis of carsharing projects include:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for relevant travel speeds for travel affected by the project;
- Identify estimates of travel activity (daily and annual VMT) affected by the project;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

***Sample Analytical Scenario: Bikesharing***

As an illustrative example, consider a project involving a new bikesharing project.

In this scenario, we assume the following details:

- 50,000 people participate in the bikesharing project each year;
- the average net impact of each trip by shared bicycle is a reduction in travel by light-duty vehicle of 2 miles (the average impact accounts for cases of users switching from transit and pedestrian activity, in which there is no impact on light-duty vehicle use);
- each participant takes 20 trips per year via shared bicycle;
- the average travel speed for offset travel is 35 miles per hour;
- the average fleet-level emission rates for travel at 35 miles per hour are 0.338 grams per mile for NOx and 0.013 grams per mile for $PM_{2.5}$;
- the project lifetime is 5 years; and
- the project cost, after accounting for revenue recovery, is $5 million.

**Step One:** Annual emission impacts are identified by multiplying per-mile emission rates by the number of affected trips under the relevant travel speed:

**Table 66. Sample Calculation of Annual Emission Benefits of a Bikesharing Project (Average Travel Speed of 35 mph).**

| **Pollutant** | **Emission Rates (grams/mile)** | **Annual VMT Reduction** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|
| NOx | 0.338 | 2,000,000 | 676,000 | *0.7452* |
| $PM_{2.5}$ | 0.013 | | 26,000 | *0.0287* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 67. Sample Calculation of Total Emission Benefits of a Bikesharing Project (Average Travel Speed of 35 mph).**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| NOx | 0.7452 | 5 | *3.7258* |
| $PM_{2.5}$ | 0.0287 | | *0.1433* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 68. Sample Calculation of Cost-Effectiveness Estimates for a Bikesharing Project (Average Travel Speed of 35 mph).**

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 3.7258 | $5,000,000 | *$1,341,990* |
| $PM_{2.5}$ | 0.1433 | | *$34,891,730* |

***Summary Cost-Effectiveness Estimates: Bikesharing***

The median cost-effectiveness estimates for the range of scenarios are presented in Table 69 below:

**Table 69. Median Cost-Effectiveness Estimates (Dollars per Ton) – Bikesharing.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $24,686,369 |
| $PM_{10}$ | $9,996,978 |
| CO | $145,393 |
| NOx | $1,217,644 |
| VOCs | $5,369,399 |

## Electric Vehicle Charging Infrastructure

These projects center on the provision of infrastructure to support the use of electric vehicles in place of conventional light-duty vehicles. Information on electric vehicle charging infrastructure (EVCI) projects was difficult to identify; information from a project in Minnesota and supplementary information from Vermont formed the basis of the analysis. In the analysis, it was assumed that there are no emissions associated with the use of electric vehicles. In all, 6 EVCI projects were analyzed.

Key inputs for the analysis of EVCI projects include:

- Emission rates estimates for offset conventional light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds;
- Estimates of offset travel demand via conventional light-duty vehicles;
- Estimates of project lifetimes; and
- Estimates of project costs.

The steps required to conduct the analysis of EVCI projects include:

- Generate conventional light-duty per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for relevant travel speeds for travel affected by the project;
- Identify estimates of travel activity (daily and annual VMT) affected by the project;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

### *Sample Analytical Scenario: Electric Vehicle Charging Infrastructure*

As an illustrative example, consider a project involving a new EVCI project.

In this scenario, we assume the following details:

- The presence of the EVCI project offsets 100 trips per day (260 weekdays per year) by conventional light-duty vehicle;
- Each offset conventional light-duty vehicle trip would have covered 20 miles;
- The average travel speed for offset travel is 35 miles per hour;
- The average fleet-level emission rates for travel at 35 miles per hour are 0.338 grams per mile for NOx and 0.013 grams per mile for $PM_{2.5}$;

- The project lifetime is 5 years; and

- The project cost is $700,000.

**Step One:** Annual emission impacts are identified by multiplying per-mile emission rates by the number of affected trips under the relevant travel speed:

**Table 70. Sample Calculation of Annual Emission Benefits of an Electric Vehicle Charging Infrastructure Project (Average Travel Speed of 35 mph).**

| **Pollutant** | **Emission Rates (grams/mile)** | **Annual VMT Reduction** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|
| NOx | 0.338 | 520 ,000 | 175,760 | *0.1934* |
| $PM_{2.5}$ | 0.013 | | 6,760 | *0.0075* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 71. Sample Calculation of Total Emission Benefits of an Electric Vehicle Charging Infrastructure Project (Average Travel Speed of 35 mph).**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| NOx | 0.1934 | 5 | *0.9687* |
| $PM_{2.5}$ | 0.0075 | | *0.0373* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 72. Sample Calculation of Cost-Effectiveness Estimates for an Electric Vehicle Charging Infrastructure Project (Average Travel Speed of 35 mph).**

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 0.9687 | $700,000 | *$722,610* |
| $PM_{2.5}$ | 0.0373 | | *$18,787,855* |

### *Summary Cost-Effectiveness Estimates: Electric Vehicle Charging Infrastructure*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 73 below:

**Table 73. Median Cost-Effectiveness Estimates (Dollars per Ton) – Electric Vehicle Charging Infrastructure.**

| Pollutant | Cost-Effectiveness |
|---|---|
| $PM_{2.5}$ | $32,712,348 |
| $PM_{10}$ | $14,019,827 |
| CO | $182,646 |
| NOx | $1,462,694 |
| VOCs | $7,288,503 |

## Incident Management

These projects center on the provision of equipment or personnel to advise or re-route drivers during incidents of non-recurring congestion (e.g., accidents, special events). Information on incident management projects was obtained from CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study) and supplementary project information on equipment used within incident management projects (chiefly, variable message signs). In all, 18 incident management projects were included in the analysis.

Key inputs for the analysis of incident management projects include:

- Emission rates estimates for offset conventional light-duty vehicle trips from national-average fleet-level MOVES2010b runs for a range of relevant travel speeds, including time at idle;
- Estimates of delay reductions associated with incident management projects;
- Estimates of project lifetimes; and
- Estimates of project costs.

The steps required to conduct the analysis of incident management projects include:

- Generate light-duty per-mile and per-hour (for time at idle) emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for relevant travel speeds for travel affected by the project;
- Identify estimates of travel activity (daily and annual VMT, hours of delay) affected by the project;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

### *Sample Analytical Scenario: Incident Management*

As an illustrative example, consider a project involving the provision of variable message signs along a corridor subject to non-recurring congestion.

In this scenario, we assume the following details:

- The corridor is subject to 25 incidents that would be mitigated by the project;
- Each incident involves an average of 5,000 hours of vehicle delay;
- Vehicles are at idle during incidents;

- The average fleet-level emission rates at idle are 1.341 grams per hour for NOx and 0.075 grams per hour for $PM_{2.5}$;

- The project lifetime is 10 years; and

- The project cost is $400,000.

**Step One:** Annual emission impacts are identified by multiplying per-hour emission rates by the number of affected trips involving time at idle:

**Table 74. Sample Calculation of Annual Emission Benefits of an Incident Management Project (Driving Time at Idle).**

| **Pollutant** | **Emission Rates (grams/hour)** | **Annual Delay Reduction (hours)** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|
| NOx | 1.341 | 125 ,000 | 167,625 | *0.1848* |
| $PM_{2.5}$ | 0.075 | | 9,375 | *0.0103* |

**Step Two:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

**Table 75. Sample Calculation of Total Emission Benefits of an Incident Management Project (Driving Time at Idle).**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| NOx | 0.1848 | 10 | *1.8477* |
| $PM_{2.5}$ | 0.0103 | | *0.1033* |

**Step Three:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

**Table 76. Sample Calculation of Cost-Effectiveness Estimates for Incident Management Project (Driving Time at Idle).**

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| NOx | 1.8477 | $400,000 | *$216,480* |
| $PM_{2.5}$ | 0.1033 | | *$3,870,656* |

### *Summary Cost-Effectiveness Estimates: Incident Management*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 77 below:

**Table 77. Median Cost-Effectiveness Estimates (Dollars per Ton) – Incident Management.**

| **Pollutant** | **Cost-Effectiveness** |
|---|---|
| $PM_{2.5}$ | $2,990,667 |
| $PM_{10}$ | $2,788,516 |
| CO | $10,718 |
| NOx | $167,771 |
| VOCs | $171,503 |

### Dust Mitigation

Dust mitigation projects are unique within this analysis, in that their sole impact is on $PM_{10}$. There are two main types of dust mitigation projects represented in the analysis: road paving, and street sweeping projects. Road paving projects center on adding a paved surface on top of dirt roads, to mitigate the level of $PM_{10}$ raised into the local troposphere by vehicle travel. Street sweeping projects center on the direct removal of foreign objects and contaminants from roadways, including $PM_{10}$. Information on both types of dust mitigation projects was identified within CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study). In all, 14 dust mitigation projects were included in the analysis.

Key inputs for the analysis of dust mitigation projects include:

- Direct estimates of daily $PM_{10}$ emission impacts (i.e., grams mitigated per day) from dust mitigation project documentation;
- Estimates of days per year of project effectiveness (both to identify annual impacts, and to compare projects after scaling for days of effectiveness);
- Estimates of per-mile $PM_{10}$ emission impacts (to compare road paving projects after scaling for distance covered by projects);
- Estimates of project lifetimes; and
- Estimates of project costs.

The steps required to conduct the analysis of dust mitigation projects include:

- Generate estimates of daily $PM_{10}$ emission impacts;
- Generate estimates of annual $PM_{10}$ emission impacts
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

***Sample Analytical Scenario: Dust Mitigation (Street Sweeping)***

As an illustrative example, consider a project involving a street sweeping project.

In this scenario, we assume the following details:

- Street sweeping reduces $PM_{10}$ emissions by 100,000 grams per day at the project level;
- The project is active 250 days per year;
- The project lifetime is 5 years; and
- The project cost is $2 million.

**Step One:** The annual emission impact is identified by multiplying daily emission impacts by the number of days per year the project is active:

**Table 78. Sample Calculation of Annual Emission Benefit of a Street Sweeping Project.**

| **Pollutant** | **Emission Impact (grams/day)** | **Days per Year Project Active** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|
| $PM_{10}$ | 100,000 | 250 | 25,000,000 | *27.56* |

**Step Two:** The estimated annual emission impact is multiplied by the project lifetime to identify project-level emission impacts:

**Table 79. Sample Calculation of Total Emission Benefit of a Street Sweeping Project.**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| $PM_{10}$ | 27.56 | 5 | *137.79* |

**Step Three:** The project cost is divided by the estimated project-level emission impact to yield the cost-effectiveness estimate:

**Table 80. Sample Calculation of Cost-Effectiveness Estimate for a Street Sweeping Project.**

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| $PM_{10}$ | 137.79 | $2,000,000 | *$14,515* |

### *Summary Cost-Effectiveness Estimates: Dust Mitigation*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 81 below:

**Table 81. Median Cost-Effectiveness Estimates (Dollars per Ton of $PM_{10}$) – Dust Mitigation.**

| **Project Type** | **Cost-Effectiveness (dollars per ton of $PM_{10}$)** |
|---|---|
| All Dust Mitigation | $262 |
| Paving | $229 |
| Street Sweeping | $1,005 |

## Natural Gas Fueling Infrastructure

Natural gas fueling infrastructure (NGFI) projects have hypothesized impacts on $PM_{2.5}$, $PM_{10}$ and VOCs, by encouraging shifts in heavy-duty vehicle travel from diesel-powered vehicles to lower-emission, natural-gas-fueled vehicles. However, MOVES2010b does not include VOC emission rates for vehicles fueled by natural gas. Hence, the analysis of NGFI projects focuses on $PM_{2.5}$ and $PM_{10}$ impacts. Furthermore, shifting travel to vehicles fueled by natural gas may lead to *increases* in NOx emissions, limiting the useful scope of NGFI projects to areas either without the need to curb NOx emissions or with projects with offsetting NOx reductions sufficient to offset NOx increases under NGFI.

Information on NGFI projects was identified within project-level data from non-CMAQ project that are consistent with CMAQ funding criteria (i.e., there were no similar NGFI project within CMAQ assessment studies). In all, 40 NGFI projects were included in the analysis.

Key inputs for the analysis of NGFI projects include:

- Estimates of per-mile emission rate reductions for travel via natural-gas vehicle relative to diesel-fueled vehicle;
- Estimates of the number of vehicles using facilities provided within the project;
- estimates of annual VMT per vehicle using facilities provided within the project;
- Estimates of project lifetimes; and
- Estimates of project costs.

The steps required to conduct the analysis of NGFI projects include:

- Generate estimates of emission reductions per vehicle per year;
- Generate estimates of total emission reductions per year;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

***Sample Analytical Scenario: Natural Gas Fueling Infrastructure***

As an illustrative example, consider a project involving a new natural gas fueling station, targeted at serving local buses.

In this scenario, we assume the following details:

- Due to the presence of the facility, 30 transit buses switch from diesel to natural gas;

- switching from diesel to natural gas reduces bus emissions by 0.028 grams per mile for $PM_{10}$, and by 0.027 grams per mile for $PM_{2.5}$;

- The natural gas buses travel 45,000 miles per year (no change from prior travel using diesel);

- The project lifetime is 20 years; and

- The project cost is $20 million.

**Step One:** The annual emission impact per vehicle is identified by multiplying per-mile emission impacts per vehicle by the number of vehicles that switch to natural gas due to the project, and the number of miles traveled per vehicle per year:

**Table 82. Sample Calculation of Annual Emission Benefit of a Natural Gas Fueling Station Project.**

| **Pollutant** | **Emission Impact per Bus (grams/mile)** | **Annual VMT per Bus** | **Number of Trucks Affected per Year** | **Annual Emission Benefit (grams)** | ***Annual Emission Benefit (tons)*** |
|---|---|---|---|---|---|
| $PM_{2.5}$ | 0.027 | 45,000 | 30 | 36,450 | *0.0402* |
| $PM_{10}$ | 0.028 | | | 37,800 | *0.0417* |

**Step Two:** The estimated annual emission impact is multiplied by the project lifetime to identify project-level emission impacts:

**Table 83. Sample Calculation of Annual Emission Benefit of a Natural Gas Fueling Station Project.**

| **Pollutant** | **Annual Emission Benefit (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Benefit (tons)*** |
|---|---|---|---|
| $PM_{2.5}$ | 0.0402 | 20 | *0.8036* |
| $PM_{10}$ | 0.0417 | | *0.8333* |

**Step Three:** The project cost is divided by the estimated project-level emission impact to yield the cost-effectiveness estimate:

**Table 84. Sample Calculation of Cost-Effectiveness Estimate for a Natural Gas Fueling Station Project.**

| **Pollutant** | **Lifetime Emission Benefit (tons)** | **Project Cost** | ***Cost-Effectiveness (dollars per ton)*** |
|---|---|---|---|
| $PM_{2.5}$ | 0.8036 | $20,000,000 | *$24,888,477* |
| $PM_{10}$ | 0.8333 | | *$23,999,603* |

### *Summary Cost-Effectiveness Estimates: Natural Gas Fueling Infrastructure*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 85 below:

**Table 85. Median Cost-Effectiveness Estimates (Dollars per Ton of $PM_{10}$) – Natural Gas Fueling Infrastructure.**

| **Pollutant** | **Cost-Effectiveness (dollars per ton)** |
|---|---|
| $PM_{2.5}$ | $4,507,710 |
| $PM_{10}$ | $4,269,635 |

## Ridesharing

This section reviews the analysis of ridesharing projects. Ridesharing projects center on the support of programs designed to encourage mode shift from single-occupant light-duty vehicle to multiple-occupant vehicles (carpools and vanpools). Ridesharing projects may involve direct subsidies of drivers of shared vehicles, the purchase of vanpools, and indirect support such as ride-matching services.

In the analyses of ridesharing projects, key inputs included:

- estimates of single-occupant light-duty vehicle and van emission rates from national-average fleet-level MOVES runs across a range of travel speeds;
- estimates of travel demand impacts (i.e., reductions in single-occupant VMT and increases in multiple-occupant VMT);
- project costs; and
- project lifetimes, as identified in CMAQ assessment studies (2008 Assessment Study, 2014 Assessment Study).

The estimated emission impacts centered on shifts of travel via single-occupant vehicle to multiple-occupant vehicle. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated single-occupant vehicle trips (less incremental multiple-occupant vehicle trips), and project lifetimes. In all, 84 ridesharing projects were analyzed.

The steps required to conduct the analysis of ridesharing projects include:

- generate single-occupant and multiple-occupant light-duty vehicle per-mile emission rates for $PM_{2.5}$, $PM_{10}$, NOx, VOC and CO in MOVES2010b for the range of relevant travel speeds;
- identify estimates of single-occupant light-duty vehicle travel activity (daily and annual VMT) reduced through projects;
- identify estimates of incremental multiple-occupant light-duty vehicle travel activity (daily and annual VMT) associated with projects;
- identify estimates of project lifetimes; and
- identify estimates of project costs.

***Sample Analytical Scenario: Vanpool Program***

As an illustrative example consider a scenario involving a vanpool program, designed to encourage drivers of single-occupant vehicles to reduce drive-alone trips to and from work.

In this scenario, we assume the following details:

- the average travel speed for single-occupant and multiple-occupant trips is 35 miles per hour;
- the average single-occupant vehicle emission rates for travel at 35 miles per hour are 0.338 grams per mile for NOx and 0.011 grams per mile for PM2.5;
- the average passenger van emission rates for travel at 35 miles per hour are 0.636 grams per mile for NOx and 0.022 grams per mile for PM2.5;
- there is an average reduction of 8 single-occupant trips associated with each vanpool trip;
- the average distance associated with mitigated single-occupant trips is 20 miles;
- the average distance traveled in vanpool trips is 30 miles;
- under the program, there are 10 vanpool trips into and out of the target destination each workday (250 trips per year);
- the project lifetime is 5 years; and
- the project cost is $600,000.

**Step One:** Annual emission benefits are identified by multiplying per-trip single-occupant vehicle emissions by the number of mitigated trips:

**Table 86. Sample Calculation of Annual Emission Benefits from a Vanpool Program (in Grams per Mile, Average Vehicle Travel Speed of 35 mph).**

| **Pollutant** | **Light-Duty-Vehicle Emission Mitigation (grams/mile)** | **Annual Light-Duty-Vehicle VMT Reduction** | ***Annual Emission Benefit (grams)*** |
|---|---|---|---|
| NOx | 0.338 | 800,000 | *270,400* |
| $PM_{2.5}$ | 0.011 | | *8,800* |

**Step Two:** Annual emission impacts are identified by subtracting new van emissions from the annual emission benefit identified in Step One:

### Table 87. Sample Calculation of Annual Emission Impacts from a Vanpool Program (Average Vehicle Travel Speed of 35 mph).

| **Pollutant** | **Annual Emission Benefit (grams)** | **New Vanpool Emissions (grams/mile)** | **Annual New Bus VMT** | **Annual New Vanpool Emissions (grams)** | **Annual Net Emission Impact (grams)** | ***Annual Net Emission Impact (tons)*** |
|---|---|---|---|---|---|---|
| NOx | 270,400 | 0.636 | 150,000 | 95,400 | 175,000 | *0.1929* |
| $PM_{2.5}$ | 8,800 | 0.022 | | 3,300 | 5,500 | *0.0061* |

**Step Three:** Each of the estimated annual emission impacts is multiplied by the project lifetime to identify project-level emission impacts:

### Table 88. Sample Calculation of Total Emission Impacts for a New Bus Route (Average Travel Speed of 25 mph).

| **Pollutant** | **Annual Net Emission Impact (tons)** | **Project Lifetime (years)** | ***Lifetime Emission Impact (tons)*** |
|---|---|---|---|
| NOx | 0.1929 | 5 | *0.9645* |
| $PM_{2.5}$ | 0.0061 | | *0.0303* |

**Step Four:** The project cost is divided by the estimated project-level emission impacts to yield cost-effectiveness estimates:

### Table 89. Cost-Effectiveness Estimates for a New Bus Route (in Dollars per Ton, Average Travel Speed of 25 mph).

| **Pollutant** | **Lifetime Emission Impact (tons)** | **Project Cost** | ***Cost-Effectiveness ($/ton)*** |
|---|---|---|---|
| CO | 0.9645 | $600,000 | *$622,070* |
| NOx | 0.0303 | | *$19,793,127* |

### *Summary Cost-Effectiveness Estimates: Ridesharing*

The median cost-effectiveness estimates for the range of scenarios are presented in Table 90 below:

**Table 90. Median Cost-Effectiveness Estimates (Dollars per Ton of $PM_{10}$) – Ridesharing.**

| **Pollutant** | **Cost-Effectiveness (dollars per ton)** |
|---|---|
| $PM_{2.5}$ | $8,802,478 |
| $PM_{10}$ | $3,549,880 |
| CO | $47,355 |
| NOx | $367,482 |
| VOCs | $2,091,487 |

## REFERENCES AND DATA SOURCES

Allegheny County Health Department. “Air Quality Control Program: Allegheny County Diesel School Bus Retrofit Program Description.” Web. 27 May 2015. http://www.achd.net/air/pubs/pdf/School%20Bus%20Retrofit%20Program.pdf

Arlington County Commuter Services (2006). “Arlington Carshare Program: 2006 Report.” Division of Transportation, Department of Environmental Services.

Annotti, J. and Ballard, J. (2013). “2013 DERA Ports Projects Analysis.” United States Environmental Protection Agency Working Paper.

Arizona Department of Transportation. “CMAQ Detailed Project Listing Report (FY 2011).” AZDOT. Web. 24 April 2015. http://azdot.gov/docs/default-source/planning/cmaq2011.pdf?sfvrsn=2

Atlanta Regional Commission. CMAQ Calculator.

Baker, M. (2010). “Northern Transportation and Air Quality Summit (NTAQS).” Pennsylvania DOT. Presentation. Cambridge, MA, August 24-26, 2010.

California Department of Transportation. “FFY 2002-2003 CMAQ Obligations Annual Report.” Caltrans. Web. 24 April 2015. http://www.caltrans.ca.gov/hq/transprog/federal/cmaq/2002-03_AnnualReport.pdf

California Energy Commission (2009). “City of Lemoore Grant for the CNG Fueling Station City of Lemoore Project.” DRIVE. Web. 31 December 2014. http://www.energy.ca.gov/drive/projects/ARV-09-019.html

California Energy Commission (2010). “San Diego Metropolitan Transit System Grant for CNG Fueling Station Upgrades.” DRIVE. Web. 31 December 2014. http://www.energy.ca.gov/drive/projects/ARV-10-018.html

California Environmental Protection Agency Air Resources Board (2014). “Verification Procedure – Currently Verified.” Web. http://www.arb.ca.gov/diesel/verdev/vt/cvt.hrm.

Cervero, R., Golub, A. and Nee, B. (2006). “San Francisco City CarShare: Longer-Term Travel-Demand and Car Ownership Impacts.” Prepared for City of San Francisco, Department of Transportation & Parking.

Chilukuri, V., Smith, S., Trueblood, M., Ryan, T. (2011) “Diverging Diamond Interchange Performance Evaluation (I-44 and Route 13).” MDOT. February 2011. Web. 30 December 2014. http://library.modot.mo.gov/RDT/reports/TRyy1013/or11012.pdf

City of Dubuque. “Dubuque Intermodal Transportation Center: Cost/Benefit Analysis.” Web. 27 May 2015. http://www.cityofdubuque.org/DocumentCenter/Home/View/3675

City of Louisville Kentucky. “Appendix L – List of High and Low Cost Bicycle Facility Improvements.” Web. 24 April 2015. http://louisvilleky.gov/sites/default/files/parks/planning_and_design/16appendixllistofhighandlowcostbicyclefacilityimprovements.pdf

City of Long Beach California. “Shoreline Pedestrian Bikepath.” LongBeach, Parks, Recreation and Marine. Web. 30 December 2014. http://www.longbeach.gov/park/recreation/sports/bike_paths.asp

Commonwealth of Virginia Department of Transportation. “Adaptive Traffic Signal Technology.” VDOT. Web. 30 December 2014. http://www.route29solutions.org/learn_more/5._adaptive_technology.asp

Commonwealth of Virginia Department of Transportation. “Augusta County – Route 612 and Route 792 Intersection Improvements.” VDOT. Web. 30 December 2014. http://www.virginiadot.org/projects/staunton/augusta_county_--_route_612_and_route_792_intersection_improvements.asp

Commonwealth of Virginia Department of Transportation (2013). “Average Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial, and Primary Route.” Web. 22 December 2014. http://www.virginiadot.org/info/resources/Traffic_2013/AADT_PrimaryInterstate_2013.pdf

Commonwealth of Virginia Department of Transportation (2013). “I-64 Interchange at Route 15, Zion Crossroads.” Web. 22 December 2014. http://www.virginiadot.org/projects/culpeper/zioncrossroads.asp

Commonwealth of Virginia Department of Transportation. “Rio Road Intersection” VDOT. Web. 30 December 2014. http://www.route29solutions.org/learn_more/2._rio_road_intersection.asp

Commonwealth of Virginia Department of Transportation. “Rockingham County – Route 340 and Route 253 Intersection Improvements.” VDOT. Web. 30 December 2014. http://www.virginiadot.org/projects/staunton/rockingham_county_8211_route_340_and_route_253_intersection_improvements.asp

Commonwealth of Virginia Department of Transportation. “Route 221/Route 668 Intersection Improvements – Bedford County.” VDOT. Web. 30 December 2014. http://www.virginiadot.org/projects/salem/route_221-route_668_intersection_improvements_-_bedford_county.asp

"Cost Benefits." Diverging Diamond Interchange. 2014. Web. 30 December 2014. http://divergingdiamond.com/benefits.html

Dao, Thi (2014). "Ohio City Starts CNG Fueling Station Construction." Government Fleet Top News. 16 April 2014. Web. 31 December 2014. http://www.government-fleet.com/news/story/2014/04/ohio-city-starts-cng-fueling-station-construction.aspx

Department of Public Works, City of Indianapolis. "County Line Road and Morgantown Road Intersection Improvement Project." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/Fact%20Sheet/CoLineRdMorgantownRdFS.pdf

Department of Public Works, City of Indianapolis. "County Line Road and Railroad Road Intersection Improvement Project." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/Fact%20Sheet/CoLineRdRailroadRdFS.pdf

Department of Public Works, City of Indianapolis (2014). "Edgewood Avenue and Gray Road Intersection Improvements." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/0752-1274%20EdgewdGrayFactSheet07.29.14pdf.pdf

Department of Public Works, City of Indianapolis (2014). "Edgewood Avenue and McFarland Road Intersection Improvements." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/0752-141%20EdgewdMcFarlndFactSheet07.22.14.pdf

Department of Public Works, City of Indianapolis (2013). "Five Points Road and Thompson Road Intersection Improvements." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/0752-1335%20FivePoints-ThompsonFS07.13.pdf

Department of Public Works, City of Indianapolis (2013). "German Church Road Intersection Improvements at 42nd and 46th Streets." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/0752-1334%20GermanChurch-42ndFS07.13.pdf

Department of Public Works, City of Indianapolis (2013). "Spring Mill Road and 91st Street Intersection Improvements." Rebuild Indy. Web. 30 December 2014. http://www.indy.gov/eGov/City/DPW/RebuildIndy/Projects/Documents/Roundabouts/0752-1336%20SpringMill-91stFS11-13.pdf

Editor, Bluffton News (2014). Bluffton News. 16 July 2014. Web. 30 December 2014. http://www.blufftonnews.com/ground-breaks-new-section-bluffton-bike-path

Editor, Los Angeles Department of Transportation Bike Blog (2011). “Bike Path Projects: What is Being Built and Where.” LADOT Bike Blog. 22 June 2011. Web. 30 December 2014. https://ladotbikeblog.wordpress.com/bike-path-projects-2/

Environmental Protection Agency (2006). “Diesel Retrofit Technology: An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits.” Office of Transportation and Air Quality, Document No. EPA-420-S-06-002.

Environmental Protection Agency (2010). “Diesel Emissions Quantifier Default Values.” Document No. EPA-420-B-10-035.

Environmental Protection Agency (2012). “Motor Vehicle Emissions Simulator (MOVES): User Guide for MOVES2010b.” Document No. EPA-420-B-12-001b.

Environmental Protection Agency (2014). “Diesel Retrofits: Quantifying and Using Their Emission Benefits in SIPs and Conformity: Guidance for State and Local Air and Transportation Agencies.” Transportation and Climate Division, Office of Transportation and Air Quality. Document No. EPA-420-B-14-007, February 2014.

Environmental Protection Agency (2014). “National Clean Diesel Campaign (NCDC): Verification: Verified Technology List.” Web. 6 June 2014. http://www.epa.gov/cleandiesel/verification/verif-list.htm

Environmental Protection Agency, Region 7 (2014). “Region 7 Clean School Bus Program.” Web. 6 June 2014. http://www.epa.gov/region7/citizens/cleanschoolbus/index.htm

Federal Highway Administration (2006). “Multi-Pollutant Emissions Benefits of Transportation Strategies.” Publication No. FHWA-HEP-07-004.

Federal Highway Administration (2006). “The Congestion Mitigation and Air Quality (CMAQ) Improvement Program under the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users: Program Guidance.” https://www.fhwa.dot.gov/environment/air_quality/cmaq/policy_and_guidance/cmaq06gm.cfm

Federal Highway Administration (2008). “SAFETEA-LU 1808: CMAQ Evaluation and Assessment. Phase 1 Final Report.” Document No. FHWA-HEP-08-019. https://www.fhwa.dot.gov/environment/air_quality/cmaq/research/safetea-lu_phase_1/safetealu1808.pdf

Federal Highway Administration (2013). “The Congestion Mitigation and Air Quality (CMAQ) Improvement Program Under the Moving Ahead for Progress in the 21st Century Act: Interim Program Guidance.”

https://www.fhwa.dot.gov/environment/air_quality/cmaq/policy_and_guidance/2013_guidance/cmaq2013.pdf

Federal Highway Administration (2015). “Air Quality and Congestion Mitigation Measure Outcomes Assessment Study: Final Technical Report.” Document No. FHWA-HEP-15-002. https://www.fhwa.dot.gov/environment/air_quality/cmaq/research/outcomes_assessment/technical_report/airqual_final.pdf

Georgia Department of Transportation (2010). “HO Lane Briefing.” Web. 9 January 2015. http://www.dot.ga.gov/travelingingeorgia/expresslanes/I85expresslanes/Documents/HOLaneBriefing-22APR10.pdf

Government Fleet (2014). “Arizona City to Build Its First CNG Station.” Natural Gas – Conversions, Vehicles and Technology. 19 September 2014. Web. 31 December 2014. http://www.government-fleet.com/channel/natural-gas/news/story/2014/09/ariz-city-to-build-its-first-cng-station.aspx

Government Fleet (2014). “California City Expands CNG Fueling Station.” Government Fleet Top News. 19 November 2014. Web. 31 December 2014. http://www.government-fleet.com/news/story/2014/11/calif-city-expands-cng-fueling-station.aspx

Government Fleet (2014). “Colorado Approves $30M for Natural Gas Infrastructure.” Government Fleet Top News. 7 January 2014. Web. 31 December 2014. http://www.government-fleet.com/news/story/2014/01/colo-approves-30m-for-natural-gas-infrastructure.aspx

Government Fleet (2014). “Florida City’s CNG Plan to Save $2.9M in Fuel Costs.” Natural Gas – Conversions, Vehicles and Technology. 29 September 2014. Web. 31 December 2014. http://www.government-fleet.com/channel/natural-gas/news/story/2014/09/report-10-year-roi-projected-for-fla-city-cng-investment.aspx

Gresham Smith and Partners (2010). “Diverging Diamond Interchange: Bessemer Street/ US 29 Bypass.” City of Alcoa. Web. 30 December 2014. http://www.cityofalcoa-tn.gov/content/download/2305/9452/file

Hampton Roads Transportation Planning Organization (2010). “Hampton Roads CMAQ/RSTP: Project Selection Process.” Document No. T10-03.

Houston-Galveston Transportation Management Area (2013). “Transit Bus Expansion Program.” Web. 27 May 2015. http://www.h-gac.com/taq/commitees/TPC/2013/09-sep/docs/ITEM%2011A%281%29--%20Transit%20Bus%20Expansion%20Program.pdf

I-15 CORE Traffic Team; Rasband, E.; Forbush, T.; Ash, K. (2012) “UDOT Diverging Diamond Interchange (DDI) Observations and Experience.” Web. 30 December 2014. http://www.udot.utah.gov/main/uconowner.gf?n=10172614219775523

Imperial County, California (2010). “Retrofit of Heavy Duty Vehicles in Mexicali (TAA07-003): Final Report.”

Kentucky Transportation Cabinet (2014). “Congestion Mitigation and Air Quality Improvement Program Projects As of June 30, 2014.” KY Transportation. Web. 24 April 2015. http://transportation.ky.gov/Program-Management/2015%20Draft%20STIP%20Book/A-8.pdf

Litman, T. (2015). “Evaluating Public Transit Benefits and Costs: Best Practices Guidebook.” Victoria Transport Policy Institute. http://www.vtpi.org/tranben.pdf

Lombardo, M. and LaForte (2011). “Memorandum to the Citizens Advisory Committee: Action – Adopt a Motion of Support for the Award of a Contract to City CarShare, in an Amount Not to Exceed $1,700,000, for the eFleet: Carsharing Electrified Project and Authorization for the Executive Director to Negotiate Terms and Conditions.” January 26, 2011.

MacDougall and Associates. “Nawiliwili to Anahola Bike/Pedestrian Path.” Kauai. Web. 30 December 2014. http://www.kauai.gov/Government/Departments/PublicWorks/BuildingDivision/Projects/BikePathProject/tabid/335/Default.aspx

Manzo IV, F. (2014). “Highway Construction Costs: How Does Illinois Compare?” Illinois Economic Policy Institute. ILEPI Economic Commentary #7.

Martin, E. and Shaheen, S. (2011). “The Impact of Carsharing on Public Transit and Non-Motorized Travel: An Exploration of North American Carsharing Survey Data.” *Energies*, Vol. 4, pp.2094-2114.

Martin, E., Shaheen, S.A., and Lidicker, J. (2010). “Impact of Carsharing on Household Vehicle Holdings: Results from North American Shared-Use Vehicle Survey.” *Transportation Research Record*, Vol. 2143, pp. 150-158.

Massachusetts Bay Transit Authority, “MBTA Capital Investment Program FY2009 – FY2013.” MBTA. Web. 30 December 2014. http://www.mbta.com/uploadedFiles/About_the_T/Financials/CIP%20FY09-FY13.pdf

Massachusetts Bay Transit Authority. “GLX Green Line Extension.” MBTA. Web. 30 December 2014. http://greenlineextension.org/

Matthews, Cara (2014). “Lower Hudson Pedestrian and Bike Path Projects Get More than $8 Million in Funding.” Tax Watch. 15 January 2014. Web. 30 December 2014.

http://taxes.lohudblogs.com/2014/01/15/lower-hudson-pedestrian-bike-path-projects-get-8-million-funding/

Metropolitan Transit Authority (2013). “MTA Capital Program 2010-2014, Amendment.” July 2013. Web. 31 December 2014. http://web.mta.info/capital/pdf/Board_2015-2019_Capital_Program.pdf

Metropolitan Transit Authority (2014). “MTA Capital Program 2015-2019.” 24 September 2014. Web. 31 December 2014. http://web.mta.info/capital/pdf/Board_2015-2019_Capital_Program.pdf

Millard-Ball, A. (2009). “Truck Stop Electrification and Carbon Offsets: Issues Paper.” Prepared for Climate Action Reserve.

Minnesota Pollution Control Agency (2011). “Electric Vehicle Charging Station Infrastructure Development.”

Municipality of Anchorage (2006). “Assembly Memorandum No. AM-526-2006.”

Natural Gas Vehicle Global News (2014). “New Jersey Natural Gas Files to Build NGV Refueling Stations.” NGV Global News. 17 June 2014. Web. 31 December 2014. http://www.ngvglobal.com/new-jersey-natural-gas-files-to-build-ngv-refueling-stations-0617

Natural Gas Vehicle Global News (2014). “School Bus Fleet Converts to CNG in Missouri.” NGV Global News. 05 August 2014. Web. 31 December 2014. http://www.ngvglobal.com/school-bus-fleet-converts-to-cng-in-missouri-0805

Natural Gas Vehicles Today. “Posts Tagged Central Arkansas Transit Authority.” NGV Today. Web. 31 December 2014. http://ngvtoday.org/tag/central-arkansas-transit-authority/

New York City Department of Transportation (2013). “Pulaski Bridge, Pedestrian and Bicycle Improvements.” 17 December 2013. Web. 30 December 2014. http://www.nyc.gov/html/dot/downloads/pdf/2013-12-pulaski-bridge-bicycle-path.pdf

New York City Economic Development Corporation. “Seaport Modernization: Rehabilitating Port Infrastructure at the South Brooklyn Marine Terminal in Brooklyn, NY.” Web. 27 May 2015. https://www.dot.ny.gov/recovery/sponsors/tiger/repository/NYCEDC%20SBMT%20Application.pdf

North Carolina Department of Transportation. “I-95 Diverging Diamond Interchange in Lumberton.” Web. 30 December 2014. http://www.ncdot.gov/projects/I95InterchangeLumberton/

Oklahoma Department of Environmental Quality. “Diesel Frequently Asked Questions.” Web. 6 June 2014. http://www.deq.state.okus/aqdnew/cleandiesel/faq.html

Oregon Department of Transportation. “Project Descriptions.” Web. 24 April 2015. http://www.oregon.gov/ODOT/HWY/ITS/PDFs/ITSDocuments/VASTITSPlan/project_descriptions.pdf

Parsons Brinkerhoff (2012). “Compressed Natural Gas (CNG) Fueling Station and Facility Modifications to Accommodate CNG Fueled Vehicles.” Central Arkansas Transit Authority. Web. 31 December 2014. http://www.cat.org/wp-content/uploads/CATA-CNG-Final-Rept-20121022.pdf

Riverside County Transportation Department. “Mecca Roundabout Project.” RCProjects. Web. 19 December 2014. http://rcprojects.org/meccaroundabout/

Robinson, David (2014). “Two Projects for Fueling Natural Gas Vehicles Get Grants.” The Buffalo News. 28 April 2014. Web. 31 December 2014. http://www.buffalonews.com/business/two-projects-for-fueling-natural-gas-vehicles-get-grants-20140428

Sacramento Area Council of Governments (2008). “George Washington Boulevard Class 2 Bike Lane Project.” Web. 24 April 2015. http://www.sacog.org/regionalfunding/fundingprograms/pdf/2008/01/07/BikePedApplicants/01%20Sutter%20Co%20George%20Washington%20doc%201.pdf

San Bernardino Associated Governments (2013). “SB Valley Coordinated Traffic Signal System Plan.” Web. 10 July 2014. http://www.sanbag.ca.gov/projects/subr_traffic-signal.html

San Joaquin Council of Governments (2006). “California Inter-Regional Intermodal System (CIRIS): Implementation Plan Executive Summary.”

San Joaquin Valley Unified Air Pollution Control District (2007). “Appendix Q: Supporting Documents for SIP Creditability.” 30 April 2007. Web. 24 April 2015. http://www.valleyair.org/Air_Quality_Plans/docs/AQ_Ozone_2007_Adopted/34%20Appendix%20Q%20April%202007.pdf

Sharp, John (2012). “Roundabout Project Centers on 5th District.” Journal Star. 22 May 2012. Web. 19 December 2014. http://www.pjstar.com/article/20120522/News/305229881

State of Montana Department of Transportation (2013). “Re-Evaluation of Montana's Air Quality Program.” Document No. FHWA/MT-13-006/8220.

Transportation Works for Kansas, “Intersection Improvement.” Kansas Department of Transportation. Web. 19 December 2014. http://kdotapp.ksdot.org/TWorks/Projects/Info/KA-

0047-01?keyword=roundabout&chks=Y,N,PRESERVE,MODERNIZE,ENHANCE,LOCALPART,NPUBTRANS,NAVIATION,NRAIL,NBIKEPED&p=CurrentProjects

Transportation Works for Kansas. "Roundabout Construction in Wellington (Sumner County)." Kansas Department of Transportation. Web. 19 December 2014. http://kdotapp.ksdot.org/TWorks/Projects/Info/KA-0844-01?keyword=roundabout&chks=Y,N,PRESERVE,MODERNIZE,ENHANCE,LOCALPART,NPUBTRANS,NAVIATION,NRAIL,NBIKEPED&p=CurrentProjects

Transportation Works for Kansas, "Safety Project on US-56 in Marion County." Kansas Department of Transportation. Web. 19 December 2014. http://kdotapp.ksdot.org/TWorks/Projects/Info/KA-2770-02?keyword=roundabout&chks=Y,N,PRESERVE,MODERNIZE,ENHANCE,LOCALPART,NPUBTRANS,NAVIATION,NRAIL,NBIKEPED&p=CurrentProjects

Broward Metropolitan Planning Organization. (2010). "HOV/HOT Lane Project." SheetsWeb. 9 January 2015. http://www.browardmpo.org/userfiles/files/03-%20Project%20Sheets.pdf

United States Department of Transportation (2014). "I-95 HOV/HOT Lanes, Northern Virginia." 9 September 2014. Web. 9 January 2015. http://www.dot.gov/policy-initiatives/build-america/i-95-hovhot-lanes-northern-virginia

United States Department of Transportation (2015). "The Value of Travel Time Savings: Departmental Guidance for Conducting Economic Evaluations: Revision 2 (2015 Update)" Office of the Secretary of Transportation. 29 April 2015. http://www.transportation.gov/sites/dot.gov/files/docs/Revised%20Departmental%20Guidance%20on%20Valuation%20of%20Travel%20Time%20in%20Economic%20Analysis.pdf

Utah Department of Transportation (2013). Press Release. "UDOT Reconstructing Busy I-15 Interchange in Brigham City." Cache Valley Daily. 8 November 2013. Web. 30 December 2014. http://www.cachevalleydaily.com/news/local/article_4a6f0dc6-48d6-11e3-8e0d-0019bb30f31a.html

Vermont Energy Investment Corporation (2014). "Transportation Reference Manual: Guide to Characterize the Savings, Benefits, and Costs of Transportation Efficiency Measures."

Virginia Department of Environmental Quality (2003). "Report to the General Assembly on Remote Sensing of Vehicle Emissions in Virginia." 1 October 2003. Web.  14 January 2015. http://www.deq.state.va.us/Portals/0/DEQ/LawsAndRegulations/remotesensing.pdf

Wasatch Front Regional Council. "CMAQ Projects Submitted for Consideration for the 2015-2020 Congestion Mitigation/Air Quality Program." Web. 24 April 2015.

Washington State Department of Transportation. “Bicycle, Pedestrian and Accessibility Investments.” Web 30 December 2014. http://www.wsdot.wa.gov/projects/bike/map/

Washington State Department of Transportation (2005). “Pedestrian and Bicycle and Safe Routes to Schools Grants Programs 2005-2007 Prioritized Project List and Program Update.” December 2005. Web. 24 April 2015. http://www.wsdot.wa.gov/NR/rdonlyres/937E33EF-8ECE-48FA-9A27-3EE8577F139F/0/2005LegislatureReport.pdf

Washington State Department of Transportation. “SR 243 – Intersection Improvements.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/sr243/intersectionimprovements/

Washington State Department of Transportation. “SR 26 – SR 24 – Othello Intersection Improvement – Stage 2.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/sr26/othellointersectionstage2/

Washington State Department of Transportation. “SR 510 – SE of Reservation Rd. – Intersection Improvements – Complete August 2014.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/sr510/reservationintersection

Washington State Department of Transportation. “SR 542/Everson Goshen Rd Vic to SR 9 Vic.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/sr542/eversongoshensr9widening/

Washington State Department of Transportation. “SR 9 – 32nd St. SE and 84th St. NE Safety Improvements.” Web. 30 December 2014. http://www.wsdot.wa.gov/Projects/SR9/84thRoundabout

Washington State Department of Transportation. “SR 92 – 99th Ave NE and 113th Ave NE – Roundabouts – Complete November 2013.” Web. 19 December 2014. http://www.wsdot.wa.gov/projects/sr92/99throundabout/

Washington State Department of Transportation. “SR 971 – S Lakeshore Rd – Intersection Illumination – Complete April 2010.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/sr971/intersectionillumination/

Washington State Department of Transportation, “US - Stevens Pass – Variable Message Signs.” Web. 24 April 2015. http://www.wsdot.wa.gov/projects/us2/stevensvms/

Washington State Department of Transportation. “US 2 – Safety Improvements – Rice Road and Fern Bluff Road.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/us2/riceroadsafety/

Washington State Department of Transportation. “US 395 – Lind Rd Vicinity – Intersection Improvements.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/us395/lindrdintersection/

Washington State Department of Transporation. “US 97- Cameron Lake Road – Intersection Improvement – Complete December 2013.” Web. 30 December 2014. http://www.wsdot.wa.gov/projects/us97/cameronlakerdintersection/

Wheeler, Timothy B. (1995). “Emissions Test Sputtering at Start.” Baltimore Sun. 4 January 1995. Web. 14 January 2015. http://articles.baltimoresun.com/1995-01-04/news/1995004078_1_rickert-vehicle-emissions-emissions-program

Wiggins, Shannon (2014). “Construction to Start Soon for CNG Fueling Station.” WALB. 8 March 2014. Web. 31 December 2014. http://www.shalemarkets.com/construction-to-start-soon-for-cng-fueling-station-201403049038/

Wisconsin Department of Transportation. “Bicycle-Pedestrian Projects Funded by WisDOT (1993-2014).” Web. 30 December 2014. http://dot.wi.gov/localgov/docs/bike-ped-projectlist.pdf

Yasis, D. (2012). “Diverging Diamond Interchange in Minnesota.” MN APWA Conference. 15 November 2012. Web. 30 December 2014. http://www.apwa-mn.org/userfiles/ckfiles/files/DivergingDiamondInterchangeMN.pdf