FHWA – COST EFFECTIVENESS TABLES SUMMARY

Background And Summary Finding

Introduction

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. A companion document titled 'Congestion Mitigation and Air Quality (CMAQ) Improvement Program Cost-Effectiveness Tables Development and Methodology' offers detailed information about all project type analyses conducted in the study supporting these Tables, along with supplementary analytical results.

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. The companion document titled 'Congestion Mitigation and Air Quality (CMAQ) Improvement Program Cost-Effectiveness Tables Development and Methodology' offers detailed information about all project type analyses conducted in the study supporting these Tables, along with supplementary analytical results and may be found at the following website – www.xxxxxxxxxxxxx.gov.

MAP-21

The statutory language contained in MAP-21, 23 U.S.C. Sec. 149, (i), that is relevant to the development and use of the Cost- Effectiveness (CE) Tables 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).

Key Analytical Assumptions and Limitations

Assumptions:

- 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;

- 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);

- The project cost does not differentiate between shares of funds applied to capital costs versus operation and 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.

Limitations:

- The range of analytical scenarios is not intended to cover the full range of potential outcomes within a project type, or the full range of potential projects.

  The analysis centers on a snapshot of data from the CMAQ database, which limits the range of conclusions that can be drawn. Project details in the CMAQ database often contain assumptions that carry forward into analysis of project emissions.
- The analysis incorporates estimates of technological effectiveness (i.e., per-unit emission impacts) and activity (e.g., hours of idling, vehicle miles of travel) from EPA's Diesel Emissions Quantifier (DEQ). Resulting analysis calibrated with respect to values from the DEQ is a direct function of the values entered into the DEQ.

- Difficulties in identifying representative project examples for some project types limited the range of potential projects included in the analysis. Not only is it difficult to identify key data for some candidate projects (e.g., project costs, associated travel demand), but the scope of available data was also constrained through the relative maturity of some project types. That is, some project types that have been included in previous analyses are no longer funded commonly within CMAQ. The range of project types included in the analysis is targeted at representing an informative view of the relative performance of predominant project types across the range of pollutants in the study within the recent history of the Program, rather than serving as a census of all projects eligible for CMAQ funding.

- Cost-effectiveness with respect to reducing pollutant emissions may not be the primary reason to implement a given project. Rather, there can be a wide range of benefits provided by projects. In this analysis, we are focusing on only the two central issues relevant to the CMAQ program, air quality improvement and reductions in traffic congestion.

Development and Presentation of Cost-Effectiveness Estimates

Disaggregation by Criteria Pollutant

The critical information presented here is the specification of separate cost-effectiveness estimates for each criteria pollutant and applicable precursor controlled through the CMAQ program, including (listed in order of appearance in the summary tables):

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

Previous studies have 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 analysis 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 MOVES

This analysis 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.

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
- Truck Stop Electrification
- 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).

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, about five percent for shared ride projects, and about seven percent for pedestrian and bicycle projects.

Summary Findings

Cost-effectiveness estimates for individual pollutants are 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:

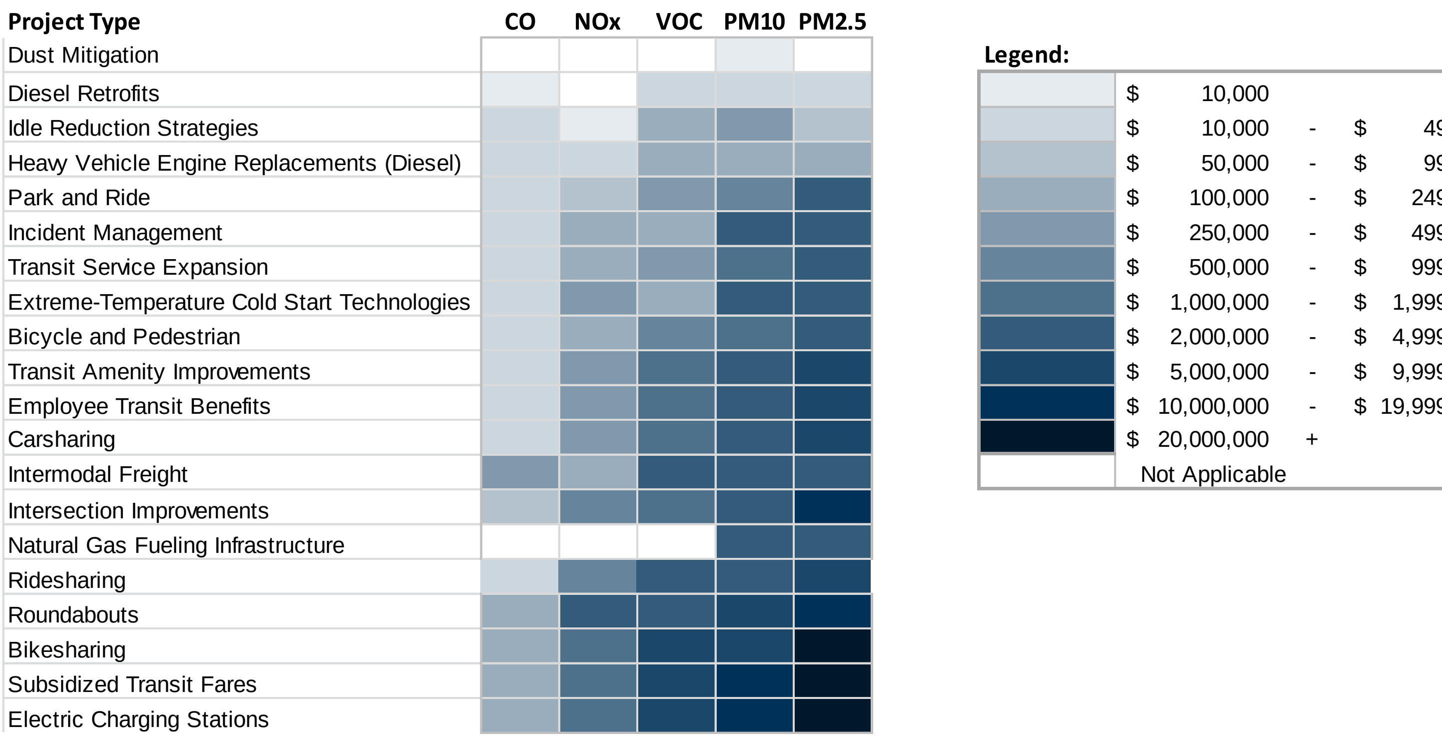


Figure 1. Median Cost-Effectiveness Estimates (Dollars per Ton of Pollutant Reduced).

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
Truck Stop Electrification	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 analysis indicates 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 demonstrates strong cost-effectiveness for reducing NOx and VOC emissions.

Diesel retrofits demonstrates strong cost-effectiveness for CO, VOCs, $PM_{2.5}$ and PM_{10}. Heavy-duty vehicle diesel engine replacements demonstrate 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 appear to provide strong cost-effectiveness in reducing CO, NOx and VOC emissions. In addition, transit service expansion demonstrate moderate cost-effectiveness with respect to $PM_{2.5}$ and PM_{10},

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

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.

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.

Roundabouts did not demonstrate strong cost-effectiveness for any of the pollutants in the study. Consequently, roundabouts generally perform 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 should 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.

Summary Cost-Effectiveness Estimates

The cost-effectiveness estimates in this section are presented in separate tables for each pollutant or applicable precursors. Cost-effectiveness is defined in these tables 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. 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.

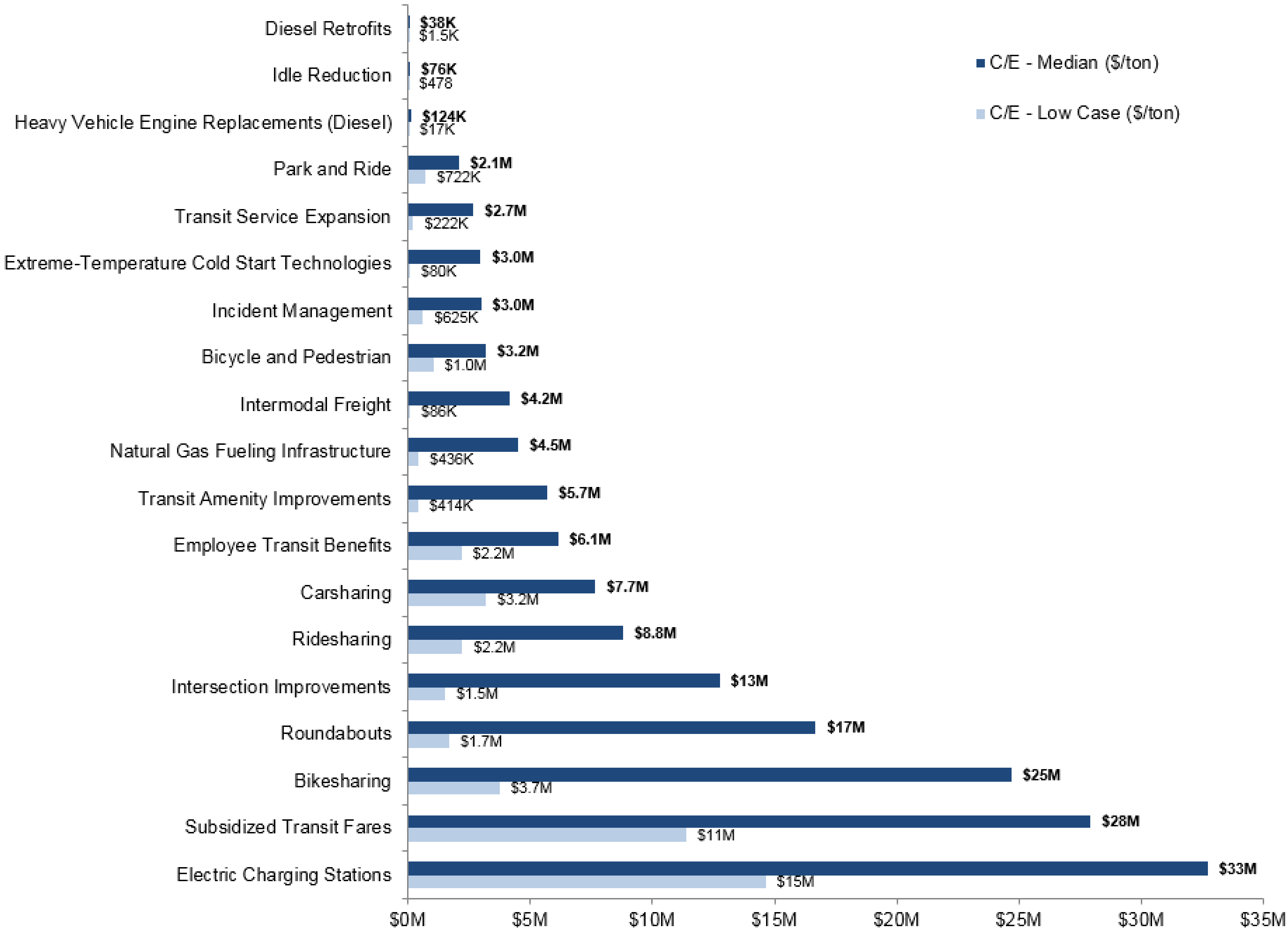
$PM_{2.5}$

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 heavy-duty diesel engine idling, one of the most polluting phases of diesel engine operation. 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. 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.



C/E - Median ($/ton)
C/E - Low Case ($/ton)
Diesel Retrofits
$38K
$1.5K
Idle Reduction
$76K
$478
Heavy Vehicle Engine Replacements (Diesel)
$124K
$17K
Park and Ride
$2.1M
$722K
Transit Service Expansion
$2.7M
$222K
Extreme-Temperature Cold Start Technologies
$3.0M
$80K
Incident Management
$3.0M
$625K
Bicycle and Pedestrian
$3.2M
$1.0M
Intermodal Freight
$4.2M
$86K
Natural Gas Fueling Infrastructure
$4.5M
$436K
Transit Amenity Improvements
$5.7M
$414K
Employee Transit Benefits
$6.1M
$2.2M
Carsharing
$7.7M
$3.2M
Ridesharing
$8.8M
$2.2M
Intersection Improvements
$13M
$1.5M
Roundabouts
$17M
$1.7M
Bikesharing
$25M
$3.7M
Subsidized Transit Fares
$28M
$11M
Electric Charging Stations
$33M
$15M
$0M
$5M
$10M
$15M
$20M
$25M
$30M
$35M

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 $PM_{2.5}$ are diesel engine technology related projects. Idle reduction curtails heavy-duty diesel engine idling, one of the most polluting phases of diesel engine operation, 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 diesel retrofit technologies 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.

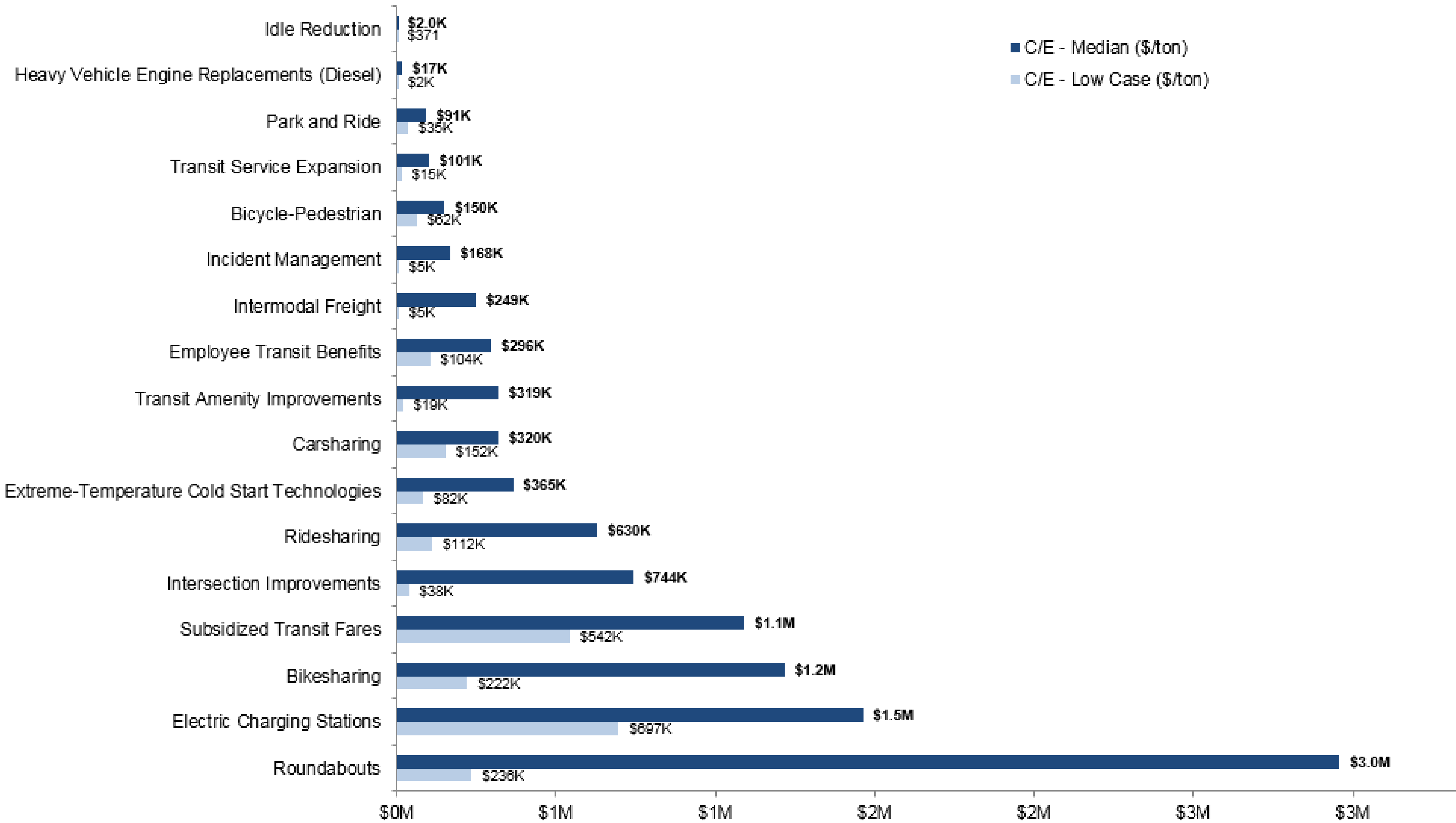


Figure 3. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of NOx Emission Reductions.

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 curtails heavy-duty diesel engine idling, one of the most polluting phases of diesel engine operation. Extreme-temperature cold start technologies address the inefficiencies of starting vehicles under unusually low levels of ambient heat. 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.

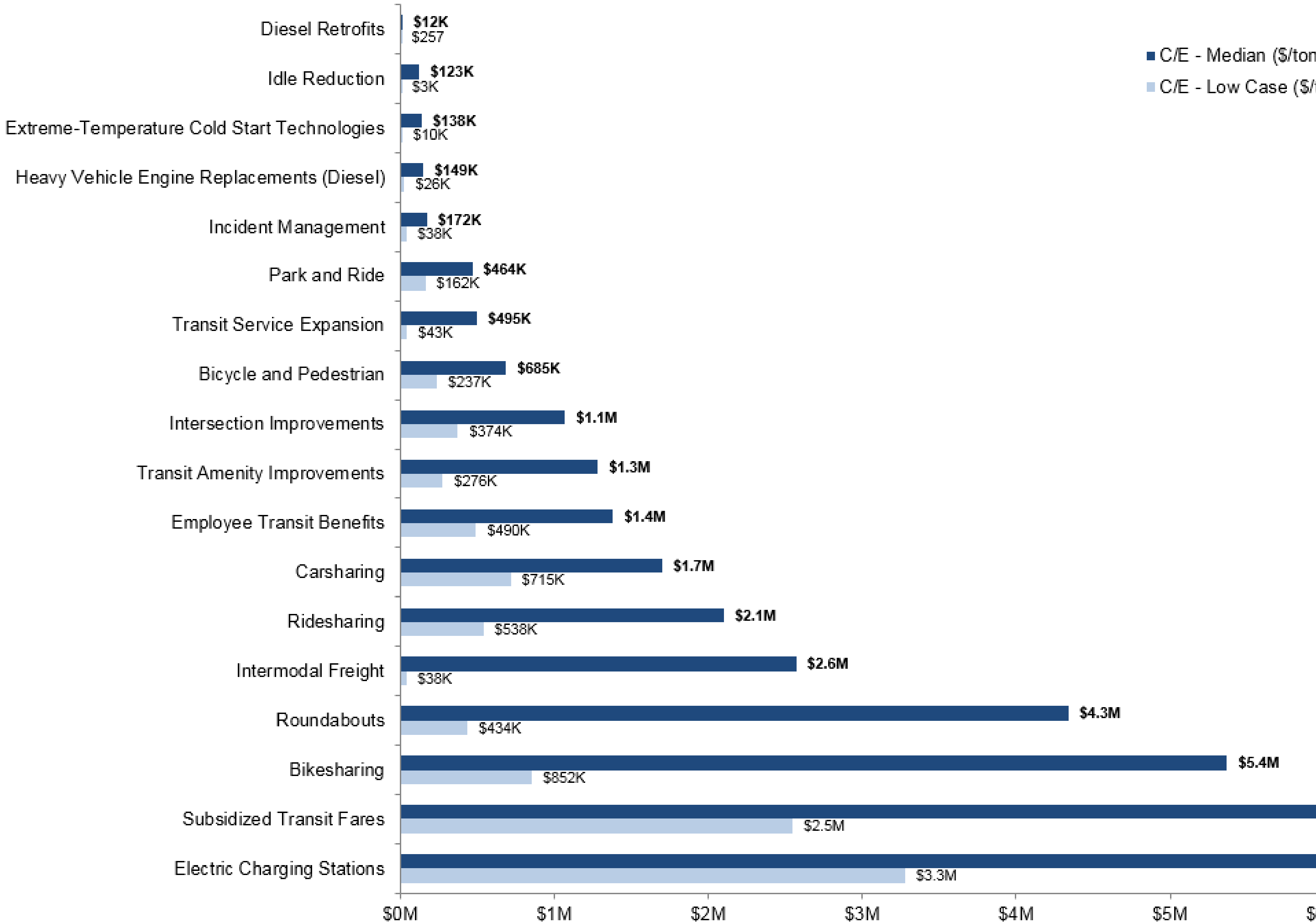

C/E - Median ($/ton
C/E - Low Case ($/
Diesel Retrofits
$12K
$257
Idle Reduction
$123K
$3K
Extreme-Temperature Cold Start Technologies
$138K
$10K
Heavy Vehicle Engine Replacements (Diesel)
$149K
$26K
Incident Management
$172K
$38K
Park and Ride
$464K
$162K
Transit Service Expansion
$495K
$43K
Bicycle and Pedestrian
$685K
$237K
Intersection Improvements
$1.1M
$374K
Transit Amenity Improvements
$1.3M
$276K
Employee Transit Benefits
$1.4M
$490K
Carsharing
$1.7M
$715K
Ridesharing
$2.1M
$538K
Intermodal Freight
$2.6M
$38K
Roundabouts
$4.3M
$434K
Bikesharing
$5.4M
$852K
Subsidized Transit Fares
$2.5M
Electric Charging Stations
$3.3M
$0M
$1M
$2M
$3M
$4M
$5M

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 the inefficiencies of 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 roundabouts. With the exception of roundabouts, these projects center on modal shift and associated reductions in VMT. Roundabouts 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.

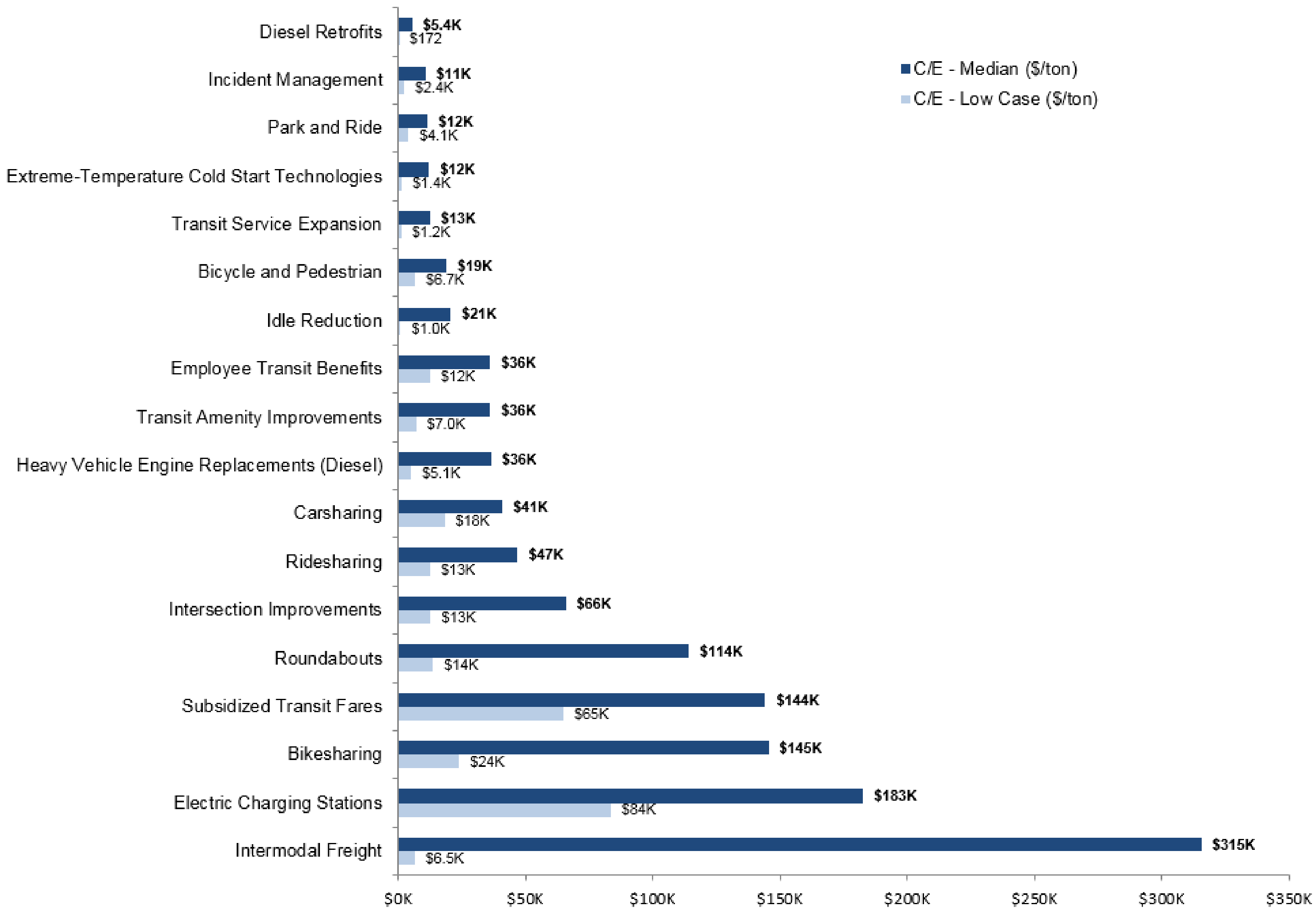


Figure 5. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of CO Emission Reductions.

PM_{10}

Emission control practices most cost-effective at controlling 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 curtails 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 address transportation mode selection and 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.

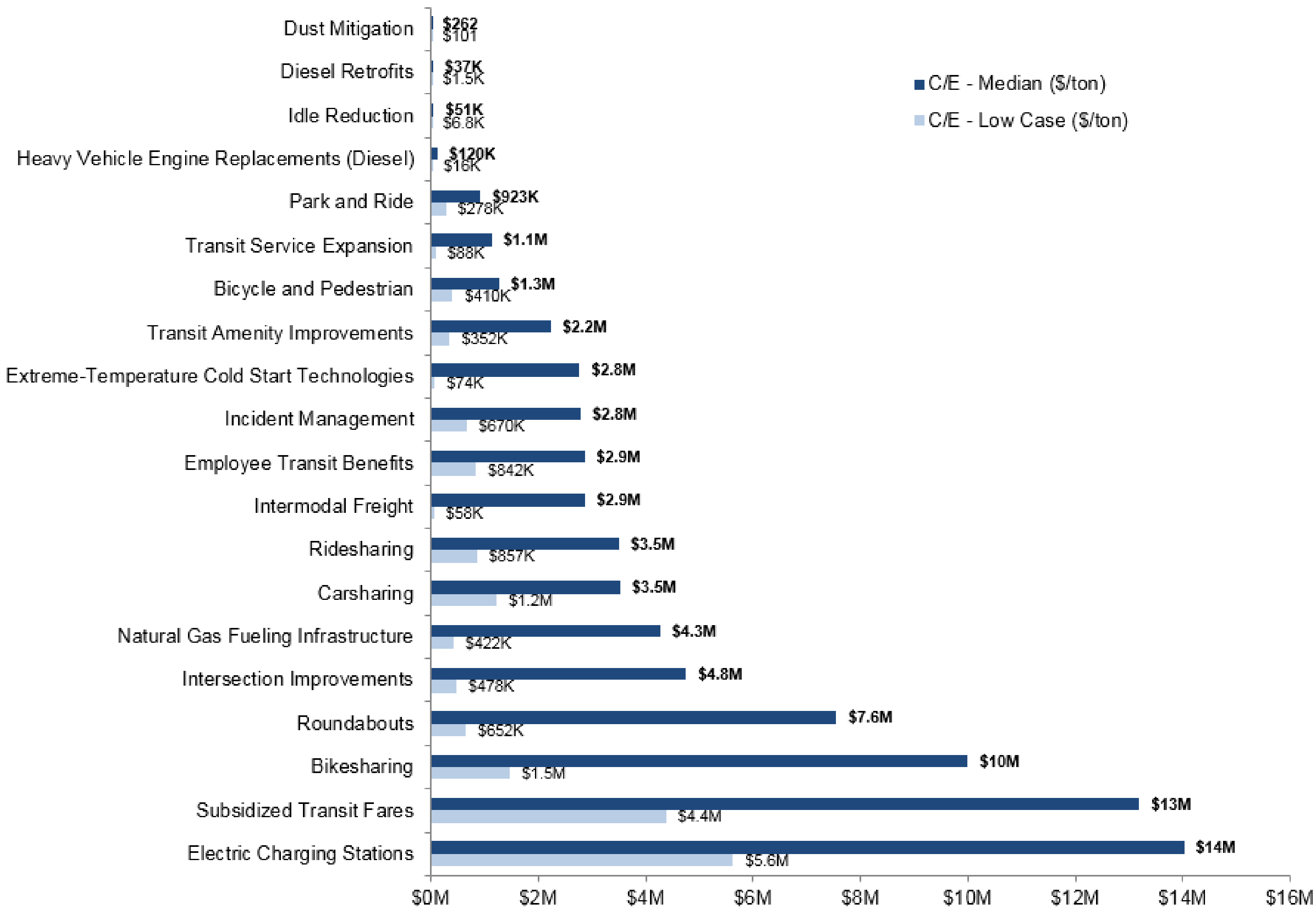


Figure 6. Chart. Median Cost-Effectiveness Estimates (Cost per Ton Reduced) of PM_{10} Emission Reductions.

Congestion Impacts

Included with the analysis of emission impacts was 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 improving capacity, in turn 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:

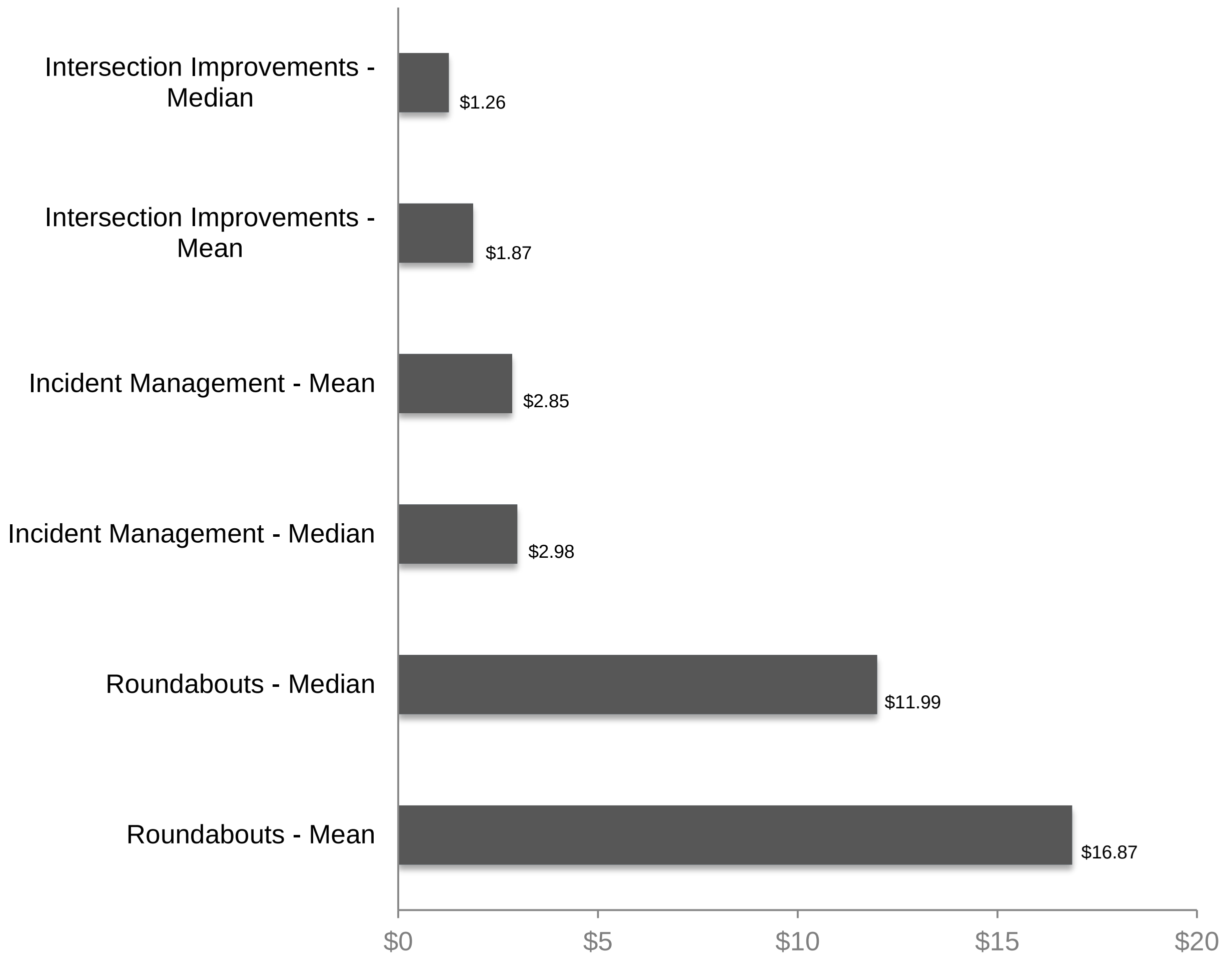


Figure 7. Median and Mean Cost-Effectiveness Estimates (Cost per Vehicle-Hour of Delay Reduced) of Congestion Reductions.

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.