CONGESTION MITIGATION AND AIR QUALITY IMPROVEMENT (CMAQ) PROGRAM

2020 Cost-Effectiveness Tables Update

Office of Natural Environment
Federal Highway Administration
U.S. Department of Transportation

July 20, 2020

FOREWORD

This CMAQ Cost-Effectiveness Tables Update is intended to provide information to assist States, MPOs and other project sponsors as they make the most efficient use of their CMAQ funding to reduce vehicle emissions and traffic congestion.

This document provides information regarding the development of estimates of cost-effectiveness for a range of representative project types previously funded under the CMAQ Program. Conclusions drawn from this analysis are confined to the CMAQ Program. Topics include: the analysis process and methodology, including the use of the MOtor Vehicle Emissions Simulator (MOVES) in determining emissions rates; key limitations of the analysis process; and the selection of specific project types for analysis. The results are displayed graphically by pollutant type in increasing order of median project cost. An aggregate table of summary finding displays results for all pollutants and all project types.

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16. Abstract

The 2020 CMAQ Cost-Effectiveness Tables Update describes the cost-effectiveness of projects funded by the Congestion Mitigation and Air Quality Improvement (CMAQ) Program. State and local governments can use CMAQ funding to support projects and programs that will contribute to attainment or maintenance of the National Ambient Air Quality Standards (NAAQS). Project types were ranked based on dollars per ton of pollutant reduced and projects were characterized as having strong, weak, or mixed cost-effectiveness. Congestion impacts, measured as reductions in idle time, were also estimated for certain project types.

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CMAQ, cost-effectiveness, air quality, mobile source emissions, NOx, VOCs, PM2.5, PM10, CO

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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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORcost-effectiveness 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

Symbol	When You Know	Multiply By	To Find	Symbol
		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

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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)

EXECUTIVE SUMMARY

The 2020 CMAQ Cost-Effectiveness Tables Update compares the cost-effectiveness of projects funded by the Congestion Mitigation and Air Quality Improvement (CMAQ) Program, in accordance with 23 U.S.C. 149(i)(2). State and local governments can use CMAQ funding to support projects and programs that will reduce emissions in areas that are in non-attainment or maintenance of the National Ambient Air Quality Standards (NAAQs) for three criteria pollutants: ozone, carbon monoxide (CO), and particulate matter (PM_{10} and $PM_{2.5}$). The cost-effectiveness analysis also considers applicable precursors, namely nitrogen oxides (NOx) and volatile organic compounds (VOCs). Note that conclusions drawn from this 2020 Cost-Effectiveness Tables analysis are only applicable to the CMAQ Program.

This report updates the first set of tables completed in 2015. This version includes a revision to the project types list to reflect information from the CMAQ Public Access System (PAS), and updated emissions modeling using the U.S. Environmental Protection Agency's MOtor Vehicle Emissions Simulator (MOVES) software.

A series of tables present the cost-effectiveness, in dollars per ton of emissions reduced, of eligible CMAQ project types. The 2020 Cost-Effectiveness Tables Update includes analysis of 21 project types, which are generally consistent with the 2015 study. New project types in this study are marked with an asterisk below. This study added several categories and refined others (e.g., bicycle and pedestrian improvements). Projects types in the 2020 Update include:

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

Findings are presented in terms of median cost-effectiveness by project type and individual pollutant. Project types were rated as having strong, weak, or mixed cost-effectiveness by summing the median cost-effectiveness across all pollutants. Strong cost-effectiveness is characterized as costing less than $2.8M per ton of emissions reduced across all pollutants, mixed cost-effectiveness as costing between $2.8M and $8.8M per ton, and weak cost-effectiveness as costing $8.8M or more per ton.

Project types which demonstrate strong cost-effectiveness for PM_{10} and $PM_{2.5}$ include dust mitigation and idle reduction technologies. For example, dust mitigation projects can reduce PM pollution for less than $15,000 per ton. Electric vehicle charging stations, carsharing, transit service expansions, natural gas refueling facilities, and park and ride programs show strong cost-effectiveness for reducing CO emissions – the first three project types are also especially strong for NOx and VOCs. Most projects with strong cost-effectiveness tend to target a particular pollutant (e.g., dust mitigation) or significantly reduce vehicle miles traveled (VMT) (e.g., transit service expansions).

Projects showing the weakest cost-effectiveness include heavy-duty vehicle replacements, bikesharing, intersection improvements, and subsidized transit fare programs. In the case of heavy-duty vehicle replacements and intersection improvements, both project types change the profiles of existing emissions, but neither removes vehicle activity entirely. Heavy-duty vehicle replacements show especially low cost-effectiveness for VOCs and PM, as these vehicles emit large amounts of these pollutants regardless of fuel type. In some cases, emissions from replacement vehicles can be significantly higher for specific pollutants. For example, replacing a diesel bus with a compressed natural gas (CNG) bus will increase PM emissions despite lowering all other criteria pollutants.[1] Some project types that demonstrate weak cost-effectiveness, such as bikesharing and bicycle and pedestrian improvements, significantly reduce vehicle activity but have high start-up costs.

Along with the analysis of emission impacts, the 2020 Cost-Effectiveness Tables Update also includes an analysis of congestion impacts, measured as reductions in vehicle-hours at idle (e.g., time queuing to pass through an intersection). Three of the project types analyzed may reduce congestion, measured on the basis of travel time per hour saved: intersection improvements (e.g., left turn lanes, signalization), roundabouts, and incident management.

It is important to acknowledge that cost-effectiveness with respect to reducing pollutant emissions and congestion is not necessarily the only reason to implement a given project. Different projects can provide a wide range of benefits (e.g., reductions in fuel consumption, safety improvements) that might make them worth pursuing. For example, a new bicycle lane may bring safety benefits, in addition to air quality improvements. Cost-effectiveness should be considered alongside these other benefits when determining project priorities, noting however that CMAQ-funded projects must demonstrate emissions benefits.

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[1] Other programs, such as the EPA's Diesel Emissions Reduction Act (DERA) funding programs, also support projects that improve air quality by reducing diesel emissions. These other programs have also analyzed the effectiveness of projects similar to those funded by the CMAQ Program, using their own methods and data. As a result, they may have found different results. Readers are encouraged to consult the DERA Program for additional information: https://www.epa.gov/cleandiesel

TABLE OF CONTENTS

INTRODUCTION

This document estimates and compares the cost-effectiveness of representative projects eligible for the Congestion Mitigation and Air Quality Improvement (CMAQ) Program as required under 23 U.S.C. 149(i)(2). 23 U.S.C. 149(b) and the 2013 CMAQ Interim Guidance detail project eligibility for the CMAQ program.[2]

The 2020 Cost-Effectiveness Tables Update is organized into four parts. The first section summarizes the findings of the cost-effectiveness study. The second section describes the CMAQ program and the cost-effectiveness evaluation requirement, and summarizes related research under prior legislation. The third section describes the research objective, the CMAQ project types analyzed, and the analytical scenario methods used to calculate cost-effectiveness for each project type. This section also includes data sources and assumptions used for modeling emissions impacts for each of the evaluated project types. The final section presents the cost-effectiveness estimates by project type.

SUMMARY OF FINDINGS

This section presents summary findings from the 2020 Cost-Effectiveness Tables Update. Table 1 compares the median cost-effectiveness estimates for each project type and pollutant in the analysis, measured in dollars per ton of pollutant reduced. The shading in the table indicates the relative performance of the various project types – lighter shades indicate stronger cost-effectiveness. Blank cells indicate that the project type has negligible impact on a particular pollutant. Project types are ranked from most to least cost-effective based on overall cost-effectiveness across all criteria pollutants (i.e., “Total Cost per Ton” in Table 1). Note, however, that projects are typically chosen for their effectiveness at reducing certain pollutants, rather than their across-the-board effects. The subsequent sections on individual pollutants provide additional context.

The suite of project types was ranked by first summing the median[3] cost-effectiveness across all pollutants for each project type, and then ordering the list of project types from most to least cost-effective (dollars per ton of emissions reduced). This arrangement provides the overall cost-effectiveness of each project across all of the criteria pollutants, and this list was then divided into thirds: strong, mixed, and weak cost-effectiveness. Project types with overall strong cost-effectiveness are characterized as costing less than $2.8M per ton of emissions reduced, with overall mixed cost-effectiveness between $2.8M and $8.8M per ton, and with overall weak cost-effectiveness costing $8.8M or more per ton. The discussion of individual pollutants examines these categories more closely, indicating what distinguishes the strong, mixed, and weakly cost-effective projects from each other within each category.

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[2] The 2013 Interim Guidance details project eligibility for the CMAQ program: “CMAQ Interim Program Guidance” (US Department of Transportation Federal Highway Administration, November 2012).

[3] The median is a measure of central tendency; it is most appropriate to use when data is skewed (asymmetrical distribution) or contains outliers. The median is calculated as the middle value in a range of values ordered from smallest to largest. If there is an even number of observations, the median is the average of the two middle values. The median was chosen instead of the mean for the cost-effectiveness analysis, as many project type costs were skewed to the right or left. Skewedness can significantly distort the mean.

Table 1: Summary of Median Cost-Effectiveness Analyses[4]

Project Type	CO	NOx	VOCs	PM_{10}	$PM_{2.5}$	Total Median Cost per Ton
Dust Mitigation				A	B	$ 15,932
Idle Reduction Strategies	A	A	A	B	B	$ 58,999
Diesel Engine Retrofit Technologies	B	B	C	D	D	$ 407,684
Intermodal Freight Facilities and Programs	B	A	C	D	D	$ 494,834
Carsharing	A	B	B	D	E	$ 766,199
Incident Management	B	B	D	D	D	$ 1,071,991
Transit Service Expansion	A	C	C	E	F	$ 2,766,431
Traffic Signal Synchronization	C	D	F	D	F	$ 3,042,950
Park and Ride	A	C	D	E	F	$ 3,622,288
Natural Gas Re-Fueling Infrastructure	A	B	D	F	F	$ 3,675,107
Electric Vehicle Charging Stations	A	C	D	F	F	$ 6,380,581
Transit Amenity Improvements	B	D	D	F	G	$ 7,457,446
Rideshare Programs	B	D	D	F	G	$ 8,194,085
Roundabouts	D	D	F	G	F	$ 8,786,402
Extreme Temperature Cold-start Technologies	B	F	D	F	F	$ 10,850,034
Bikesharing	B	G	F	F	G	$ 13,834,816
Bicycle and Pedestrian Improvement Projects	B	D	E	F	H	$ 19,423,016
Intersection Improvements	D	F	F	H	H	$ 30,823,921
Employee Transit Benefits	D	F	F	H	I	$ 50,281,268
Subsidized Transit Fares	D	F	F	H	I	$ 50,281,268
Heavy-Duty Vehicle Replacements	D	D	F	I	I	$ 69,830,233

Median Cost-Effectiveness (Dollars per Ton Reduced)	
A	<10,000
B	10,000 - 50,000
C	50,000 - 100,000
D	100,000 - 500,000
E	500,000 - 1,000,000
F	1,000,000 - 5,000,000
G	5,000,000 - 10,000,000
H	10,000,000 - 20,000,000
I	>20,000,000

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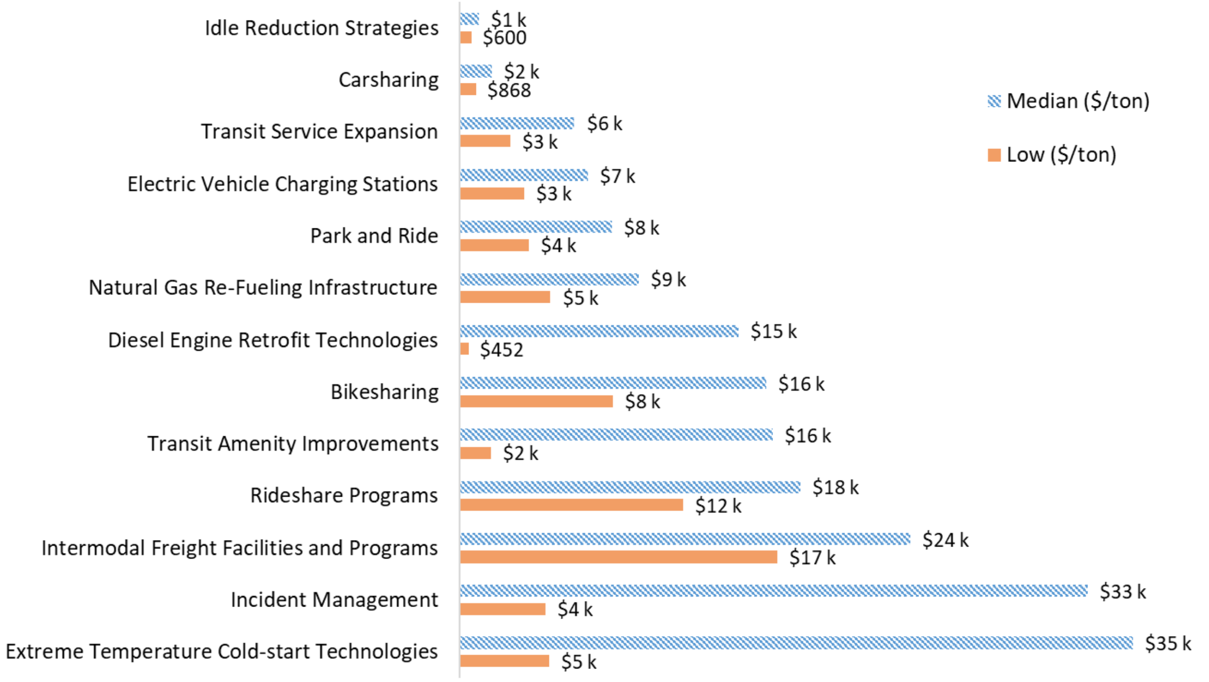
[4] Note empty (white) cells in the table indicate that those pollutants do not apply to the particular strategy (e.g., empty cells for CO, NOx, and VOCs with dust mitigation projects). The table is divided into thirds to indicate strong, mixed, and weak overall cost-effectiveness (total median cost-effectiveness across all pollutants).

Individual Pollutant Cost-Effectiveness

Please note that the charts in the following sections are split between higher and lower cost projects (two charts for each pollutant with different scales). The splitting is not the result of analysis, but purely for graphical purposes to aid nominal comparisons between projects.

Both median and low cost estimates ($/ton) are provided in the following figures; for many projects types, the lower-end estimates of cost-effectiveness are significantly lower than the median, indicating skewness in the cost data. The relevance of medians and skewness to the analysis are discussed in more detail in later sections (Assumptions and Limitations and Cost-Effectiveness by Project Type).

Carbon Monoxide



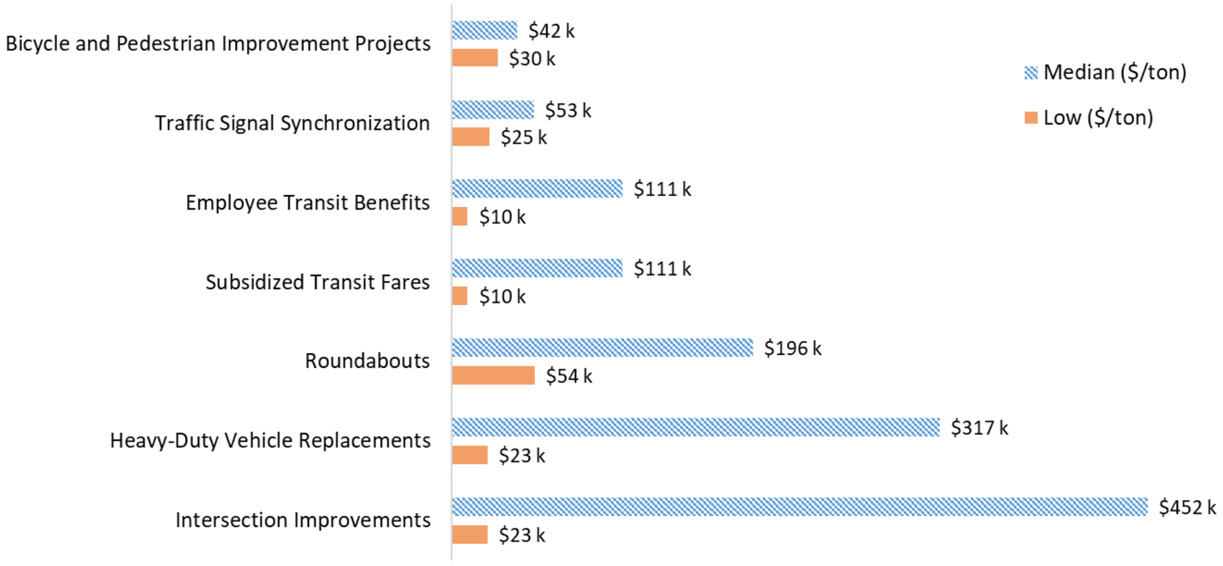


Figure 1. Median cost-effectiveness (dollars per ton reduced) for CO

Projects most effective at reducing CO reduce light-duty vehicle (LDV) activity or heavy-duty vehicle idling. The two most effective project types are diesel idle reduction strategies and carsharing. Median costs of these project types are around $1,000 to $1,500 per ton CO reduced; low-end estimates are around $600 to $850 per ton.

A large proportion of the other project types studied also exhibit strong cost-effectiveness for reducing CO emissions. Transit service expansions, electric vehicle charging stations, park and ride, natural gas refueling infrastructure, bikesharing, ridesharing, and transit amenity improvements all had median costs less than $21,000 per ton of CO reduced. Park and ride, transit service expansion, and bicycle and transit amenity improvements encourage mode shift, thus reducing VMT and emissions. Extreme-temperature cold start technologies reduce CO emissions during vehicle starts in cold climates. Incident management projects reduce engine idling in sudden congestion, reducing per-mile CO emissions.

Weaker strategies only marginally affect vehicular travel or are not directed at reducing CO. Heavy-duty vehicle diesel engine replacements address the inefficiencies of highly polluting older diesel vehicles, while intersection improvements smooth traffic operations to reduce idling, one of the more polluting phases of engine operation.

Nitrogen Oxides

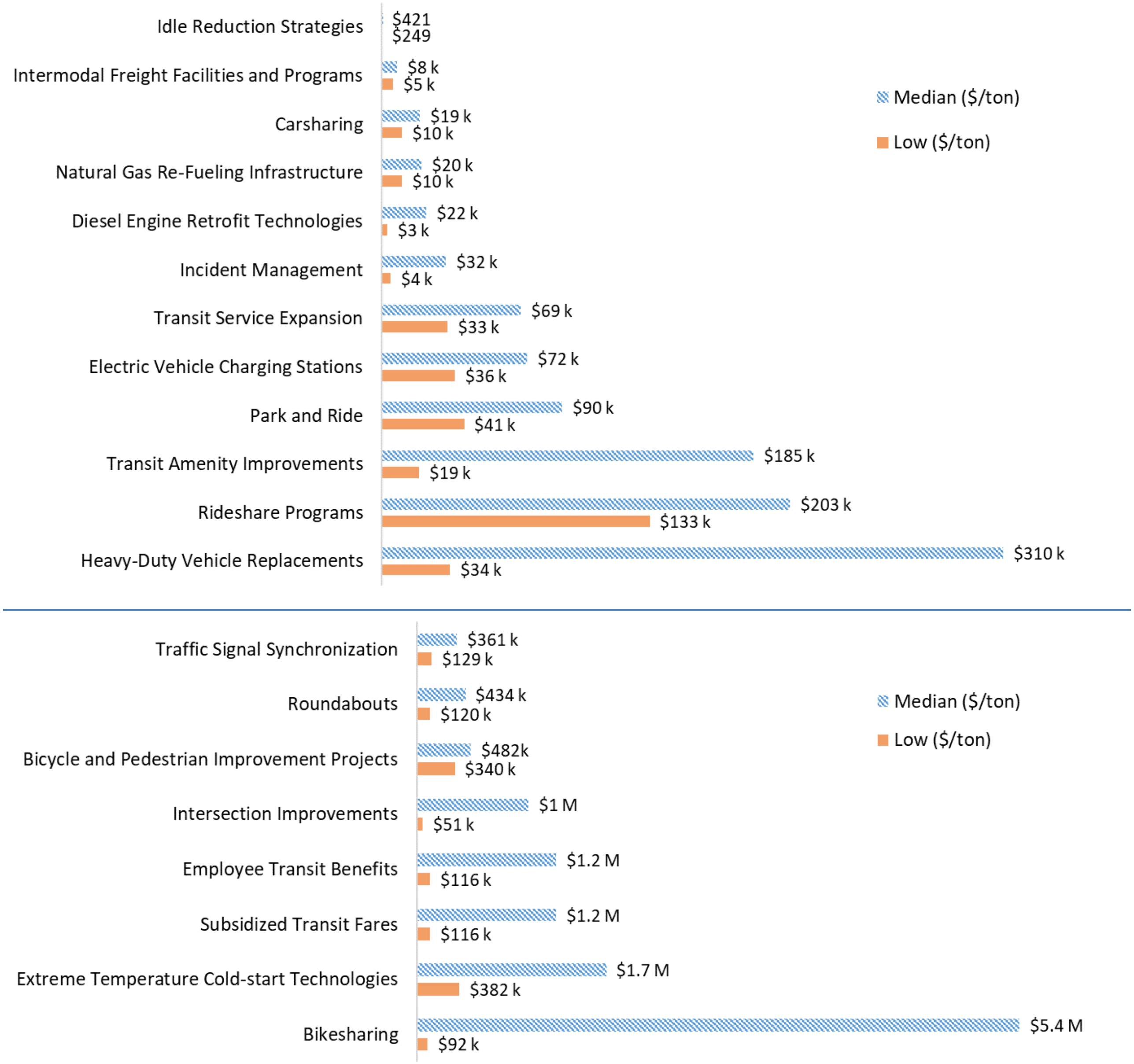


Figure 2. Median cost-effectiveness (dollars per ton reduced) for NOx

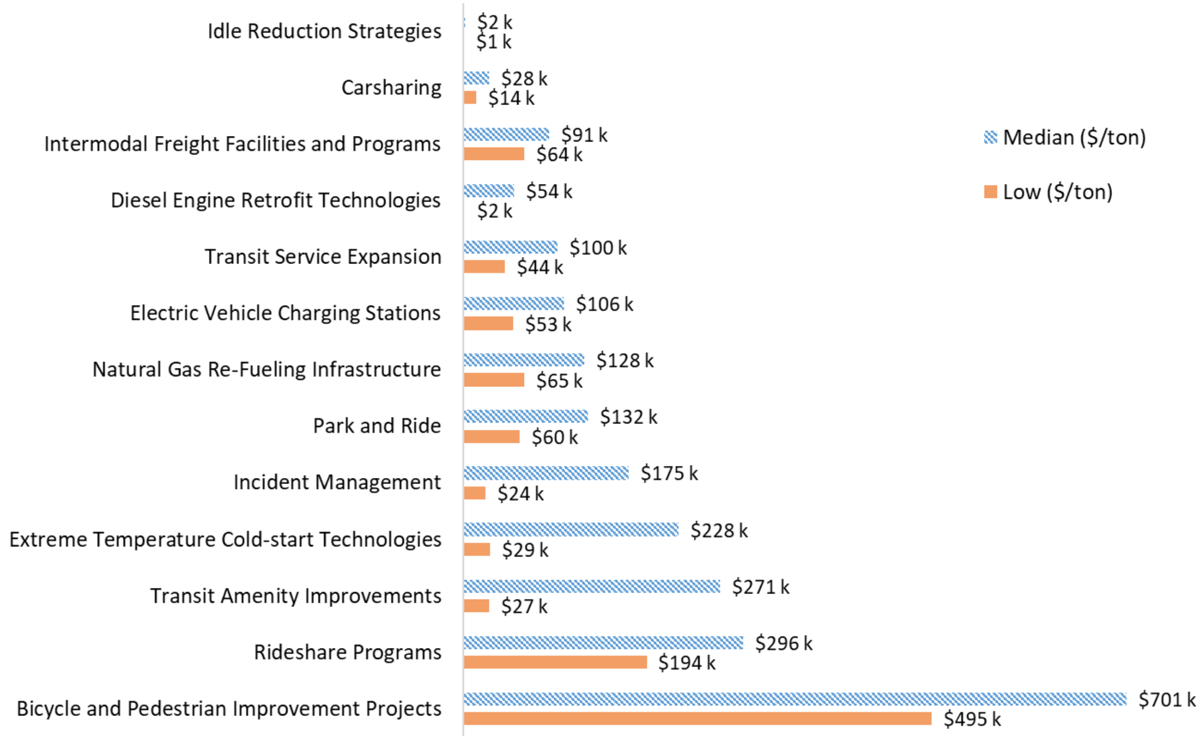
Projects that reduce engine idling show the strongest cost-effectiveness for reducing NOx. These projects include idle reduction strategies, carsharing, natural gas refueling infrastructure, and diesel engine retrofits; all of which either directly reduce diesel engine idling pollution (anti-idle strategies, natural gas, retrofits) or remove excess vehicles from the road (carsharing, intermodal freight). Incident management is also relatively cost-effective for reducing NOx. The median cost per ton of NOx reduced for these highly cost-effective projects generally is less than $30,000. Similarly, projects that generally reduce

LDV activity and idling, including electric vehicle charging stations, transit service expansion, and park and ride, are also relatively effective at reducing NOx; median costs are between $30,000 and $90,000.

Transit amenity improvements, heavy-duty replacements, ridesharing, roundabouts, transit amenity improvements, and traffic signal synchronizations show mixed cost-effectiveness for reducing NOx emissions, with median costs between about $185,000 and $480,000 per ton reduced. These projects also all reduce engine idling or LDV activity. However, they tend to be weakened by only marginal effects on travel behavior, high capital costs, or both.

Less cost-effective projects have minimal effects on vehicle activity, such as intersection improvements, transit subsidies, and bicycle and pedestrian projects. Bikesharing and bicycle and pedestrian improvements can involve expensive start-up costs that weaken their cost-effectiveness.

Volatile Organic Compounds



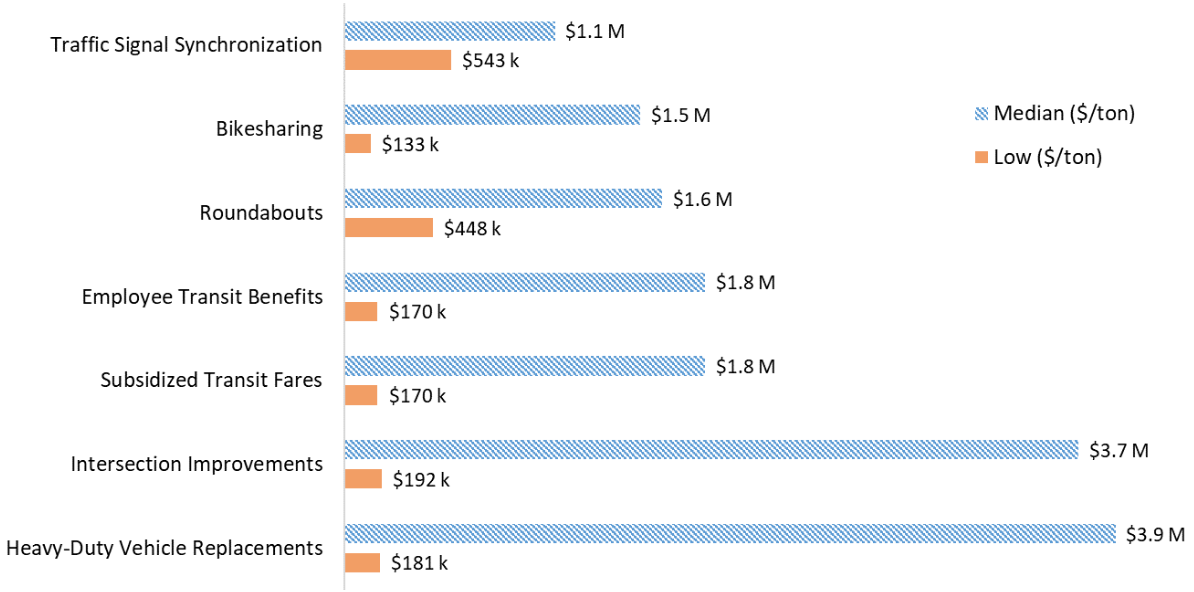


Figure 3. Median cost-effectiveness (dollars per ton reduced) for VOCs

Similar to NOx, projects with strong cost-effectiveness for VOCs include projects that reduce engine idling and fuel consumption, in addition to other strategies targeting ozone reduction (i.e., engine retrofits). Intermodal freight facilities and programs are also highly cost-effective as they shift freight operations to more fuel-efficient modes such as rail and maritime transport. The median cost for these projects is between about $2,000 and $90,000 per ton of VOCs reduced.

As with other pollutants, park and ride and incident management projects that generally reduce traffic idling on the roadway are also very effective. Transit service expansion and electric vehicle charging stations, which facilitate mode shift and a reduction in overall VMT are similarly effective. The median cost for these projects is between $100,000 and $175,000 per ton of VOCs.

Less cost-effective projects (e.g., vehicle replacements) generally have marginal effects on fuel consumption. These include projects that result in marginal effects on vehicle activity (e.g., transit amenity improvements, traffic signal synchronization, intersection improvements, and roundabouts); as with NOx, bicycle and pedestrian projects are significantly less cost-effective due to large capital costs. These less cost-effective projects have a median cost greater than $200,000, with more extreme cases costing between $1 and nearly 4 million per ton of VOCs.

Particulate Matter (d < 10 μm)

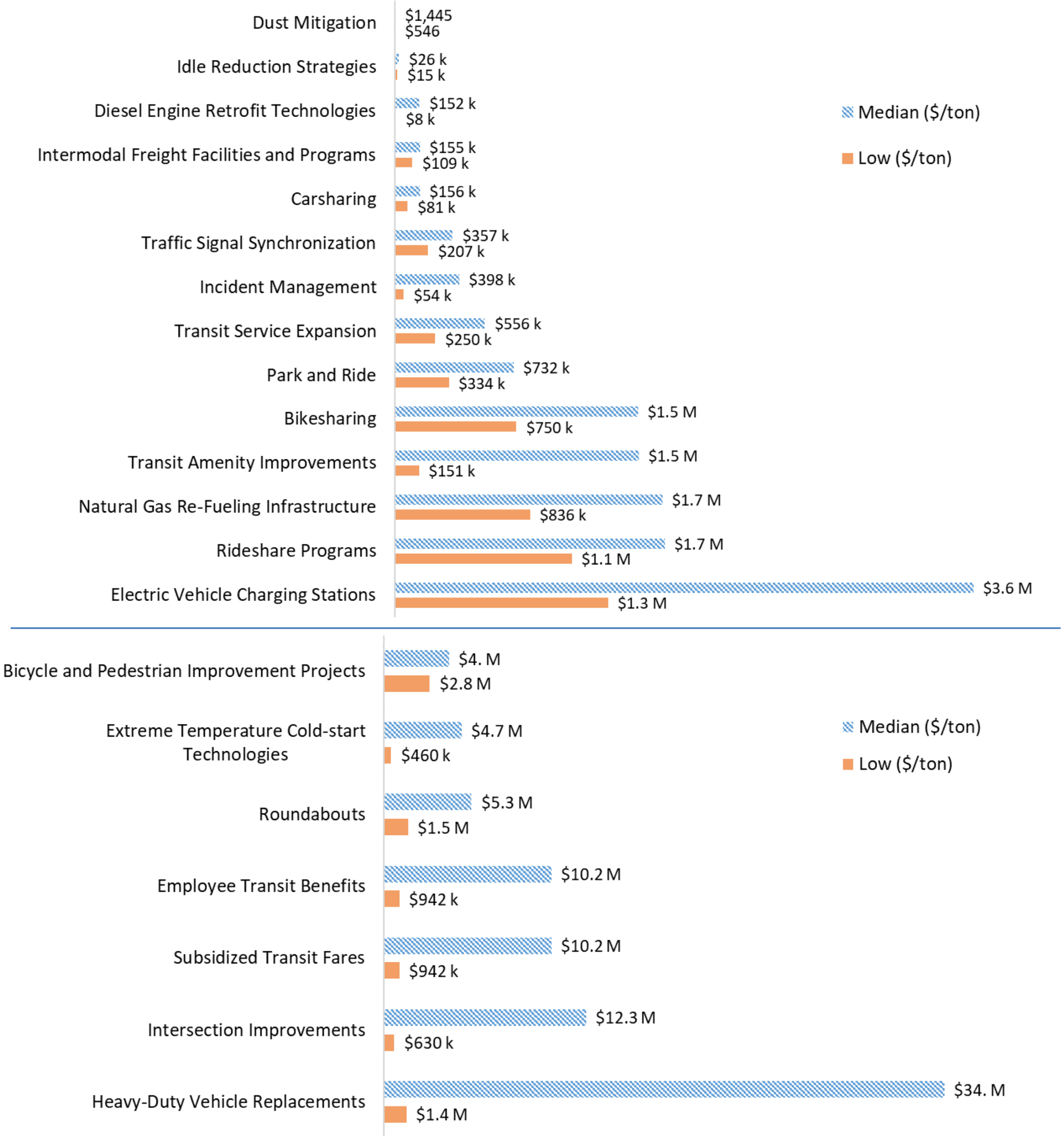


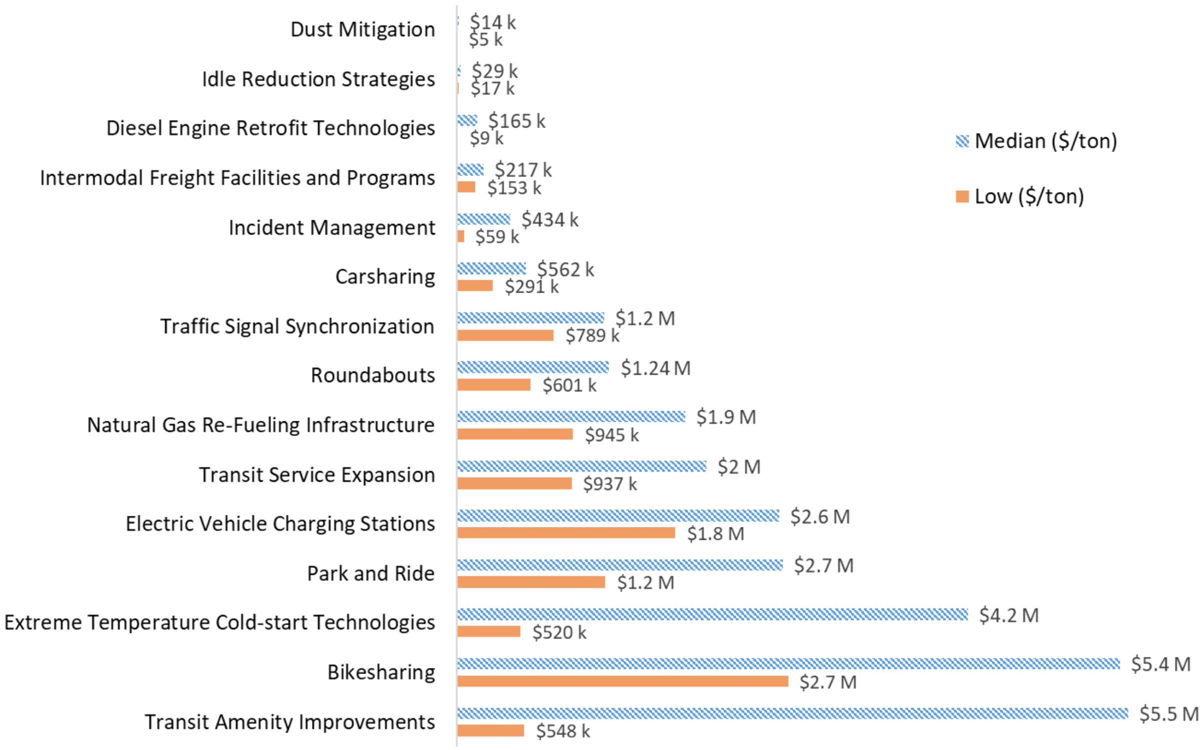
Figure 4. Median cost-effectiveness (dollars per ton reduced) for PM_{10}

Projects most cost-effective at reducing PM_{10} include those that mitigate fugitive dust. The median cost of these projects is $1,500 per ton of PM_{10}. Other very cost-effective projects include those that either substantially reduce idling or allow for cleaner fuel combustion through retrofits or vehicle replacements, especially for diesel engines. Intermodal freight facilities and programs, carsharing, traffic signal synchronization, and incident management each cost less than $400,000 per ton of PM_{10} reduced.

The group showing the next strongest cost-effectiveness for reducing this category of emissions included transit service expansion, park and ride, roundabouts, bikesharing, natural gas refueling, and ridesharing. These projects all cost between about $500,000 and $1.7 million. Each of these projects only marginally impacts engine idling or other dust suppression activities, though they do have impact to some extent.

In general, less cost-effective projects (e.g., transit benefits) do not focus on reducing heavy-duty idling or other dust suppression activities. These include bikesharing, extreme-temperature cold-start technologies, and intersection improvements. The median cost of these projects ranges from $4 to in excess of $30 million.

Particulate Matter (d < 2.5 µm)



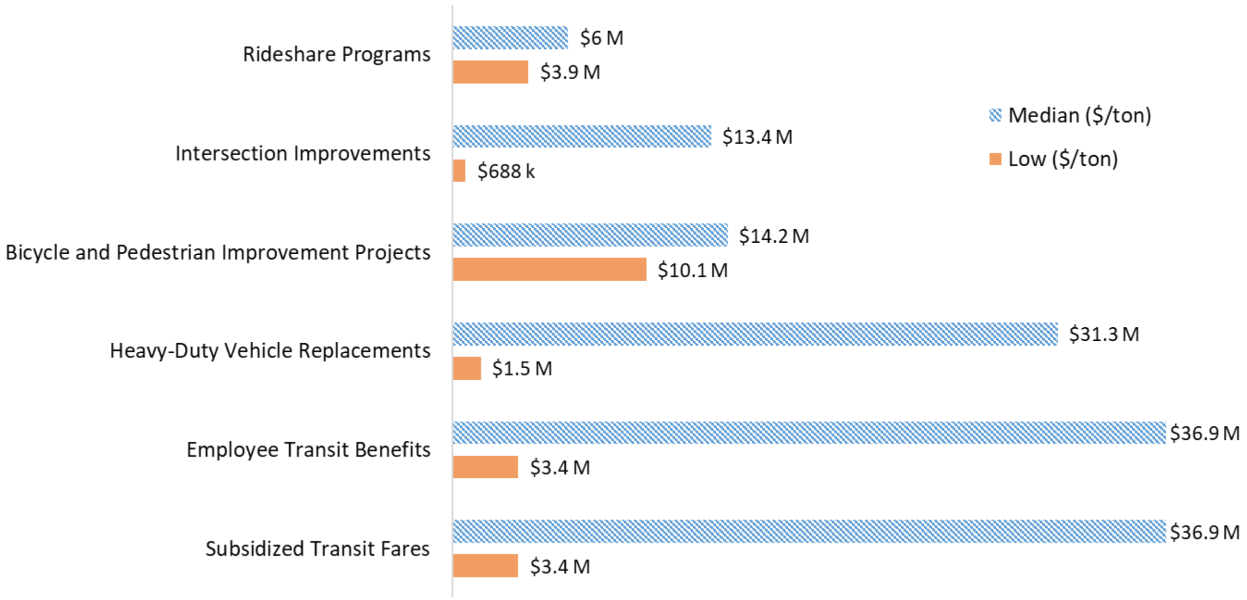


Figure 5. Median cost-effectiveness (dollars per ton reduced) for PM2.5

As with PM_{10}, projects most cost-effective at reducing $PM_{2.5}$ include projects that mitigate fugitive dust and those that either reduce idling or involve retrofits strategies. Incident management, carsharing, and intermodal freight projects are also very effective at reducing PM emissions, with median cost of these projects being less than $600,000 per ton of $PM_{2.5}$.

The next most cost-effective group of projects includes traffic signal synchronization, roundabouts, natural gas refueling, and transit service expansion, where the median cost of these projects ranges between $1.2 and $2 million.

As a rule, projects showing weaker cost-effectiveness do not focus on these activities (traffic flow improvements, transit service expansion, etc.). Programs such as bikesharing, transit amenity improvements, extreme-temperature cold-start technologies, intersection improvements, and transit fare subsidies can cost between $6 and $37 million per ton of $PM_{2.5}$ reduced.

Projects with Strong Cost-Effectiveness

The analysis indicates that certain projects are particularly cost-effective for reducing the CMAQ pollutants and precursors across the board (overall cost-effectiveness):

Table 2: Projects with Strong Cost-Effectiveness

Project Type	Pollutants
Dust Mitigation	PM
Idle Reduction Strategies	All pollutants
Diesel Engine Retrofit Technologies	CO, NOx, VOCs
Intermodal Freight Facilities and Programs	CO, NOx, VOCs
Carsharing	CO, NOx, VOCs
Incident Management	CO, NOx
Transit Service Expansion	CO, NOx, VOCs

In particular, dust mitigation reduces PM pollution for less than $15,000 per ton (CO, NOx, and VOCs emissions were not quantified for dust mitigation projects, which in practice have no effect on CO, NOx, or VOCs). Idle reduction strategies are also cost effective for reducing PM, while also contributing to substantial reductions in CO, NOx, and VOCs.

Diesel engine retrofits are particularly cost effective in reducing CO, NOx, and VOCs, and also lead to considerable reductions in PM. Car sharing and transit service expansions also strong cost-effectiveness across the board, as these projects reduce the number of light-duty vehicles on the road and may include use of alternative fuel transit vehicles.

Intermodal freight projects are especially cost-effective for reducing NOx and VOCs. These projects are generally cost-effective for reducing other pollutants as well, though the emphasis on heavy-duty freight increases the effect for NOx and VOCs.

Projects with Weak Cost-Effectiveness

Several project types demonstrated weak cost-effectiveness overall. These project types include:

Table 3: Projects with Weak Cost-Effectiveness

Project Type	Pollutants
Extreme Temperature Cold-start Technologies	NOx, PM
Bikesharing	NOx, VOCs, PM
Bicycle and Pedestrian Improvements	PM
Intersection Improvements	NOx, VOCs, PM
Subsidized Transit Fares/Employee Transit Benefits	NOx, VOCs, PM
Heavy-Duty Vehicle Replacements	VOCs, PM

Two major themes apply to these projects. First, most are associated with large capital expenditures that dampen the overall effectiveness of the project, even where emissions savings are large. For example, bikesharing and bicycle/pedestrian infrastructure projects shift motorized trips to non-motorized trips, effectively reducing those substituted emissions to zero. However, the high start-up cost to construct the infrastructure obscures benefits in this analysis framework. This illustrates a limitation of using direct cost as the basis for evaluating investments such as CMAQ projects: it prioritizes "one-shot" approaches with large effects in a single investment, rather than more distributed effects that are difficult to attribute or that accumulate variably over time. This high capital cost theme is true of extreme-temperature cold-start programs for a similar reason, in that few places in the U.S. require such a deployment – they are primarily limited to the State of Alaska.

Second, most of the projects demonstrating weak cost-effectiveness do not affect existing activity, and thus have marginal effects on emissions. For example, a subsidized transit fare program may only encourage the marginal traveler who lives in an area with high transit accessibility to switch to transit. There is no overall change to the transit service provided, so the majority of the polluting activity and related travel behavior remain after the program is implemented. This is also true of intersection improvements, which make similarly marginal changes to travel speed or drive cycle, and of vehicle replacements: in the grand scheme, both have an effect on existing emissions, but neither are as effective as removing polluting vehicle trips from the road.

Heavy-duty vehicle replacements show extremely low cost-effectiveness for VOCs and PM. This can be attributed to the fact that heavy-duty vehicles emit large amounts of these pollutants, regardless of fuel type. In some cases, emission rates for replacement vehicles (e.g., replacing a diesel transit buses with a CNG bus) can be significantly higher for specific pollutants.[5] Simply replacing the vehicle with a newer model year or different fuel type may change the emissions profile and cause some reductions, but is comparatively less effective because it does not reduce heavy-duty emitting activity.

Projects with Mixed Cost-Effectiveness

The remaining project types demonstrated competitive cost-effectiveness for at least some pollutants in the analysis (

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[5] For example, for purposes of this analysis based on MOVES estimated emissions rates, a 2019 model year CNG transit bus produces 84% more kilograms per mile of CO and 33% more kilograms per mile of VOCs than a diesel bus. Conversely, the same CNG bus produces 76% fewer kilograms per mile of $PM_{2.5}$.

Table 4). Despite strong cost-effectiveness for some categories (see Table 1), the higher costs per ton in other categories lowered the overall cost-effectiveness for the project type.

Table 4: Projects with Mixed Cost-Effectiveness

Project Type	Strong Cost-Effectiveness	Mixed Cost-Effectiveness	Weak Cost-Effectiveness
Traffic Signal Synchronization	CO	NOx, VOCs, PM_{10}, $PM_{2.5}$	-
Park and Ride	CO, NOx	VOCs, PM_{10}	$PM_{2.5}$
Natural Gas Re-Fueling Infrastructure	CO, NOx	VOCs, PM_{10}, $PM_{2.5}$	-
Electric Vehicle Charging Stations	CO, NOx	VOCs, PM_{10}, $PM_{2.5}$	-
Transit Amenity Improvements	CO	NOx, VOCs, PM_{10}	$PM_{2.5}$
Rideshare Programs	CO	NOx, VOCs, PM_{10}	$PM_{2.5}$
Roundabouts	-	CO, NOx, VOCs, $PM_{2.5}$	PM_{10}

Several of these project types had strong cost-effectiveness for some pollutants. Electric vehicle charging stations are especially cost-effective for CO and NOx, but have comparatively weak cost-effectiveness at reducing PM emissions. Similarly, park and ride projects and natural gas refueling facility projects both have strong cost-effectiveness in reducing CO and NOx emissions, but display weak cost-effectiveness in reducing PM and VOCs emissions.

The most effective way to reduce emissions is to remove vehicles entirely from the road. Projects that simply modify the way vehicles pollute will have much less of an effect. For example, park and ride facilities are constructed to facilitate at least partial mode shift to commuter transit service. In this case, light-duty vehicle travel is removed from the roads, and the amount of transit travel likely remains the same. While replacing light-duty VMT results in reductions for some pollutants, the pollution profile of heavy-duty transit vehicles is fundamentally different. Therefore, these projects will only be successful for reducing emissions from light-duty vehicles, while still having significant emissions related to heavy-duty vehicles.

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.[6] Some project types may not have any impact on reducing congestion (e.g., diesel retrofit projects). Three of the project types analyzed demonstrated estimated impacts on congestion: intersection improvements (e.g., left turn lanes, signalization), roundabouts, and incident management. The common measure of effectiveness across these project types is reduction of delay. There are other CMAQ-eligible projects that may also reduce congestion not analyzed here.

Congestion impacts were estimated as vehicle-hours of delay reduced by projects that minimize stop-and-go driving behaviors and smooth traffic flow. For projects that primarily reduce delays (e.g., time spent queuing to pass through an intersection), reductions were measured in vehicle-hours spent at idle. For projects principally focused on smoothing driving behaviors along a corridor (e.g., signal synchronization), congestion impacts were measured using changes in average speed and, thus, travel

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[6] Some projects eligible for CMAQ funding have the effect of reducing roadway congestion, such as incident management and intermodal freight facilities. However, 23 U.S.C 149 specifies that project eligibility is confined to transportation projects in non-attainment or maintenance areas that are likely to contribute to attainment or maintenance of a NAAQS.

time. Cost-effectiveness in reducing congestion was estimated by dividing project cost by project lifetime delay reductions, i.e., dollars per each vehicle-hour of delay reduced (Table 5).

Table 5: Median Cost-Effectiveness of Project Congestion Reduction

Project Type	Median Delay Reduction (hours)	Median Project Cost (dollars)	Median Cost-Effectiveness (cost per hour of delay mitigated)
Intersection Improvements	369,000	$920,000	$2.49
Roundabouts	1,091,000	$1,250,000	$1.15
Incident Management	120,000	$300,000	$2.50

Note that the congestion mitigation cost-effectiveness of these projects in the 2020 Update differs from the 2015 analysis, as the 2020 Update's findings rely on the CMAQ Emissions Calculator Toolkit's (CMAQ Toolkit) Traffic Flow Improvements modules for delay calculations. For consistency with the emissions analyses in this report and across the CMAQ Program, this report used the CMAQ Toolkit's delay reduction estimates where possible.

The US DOT's 2018 value of time guidance indicates an all-purpose value of $16.10 per person-hour (2017 US dollars).[7] Multiplying person-hours by an average vehicle occupancy value of 1.13 persons per vehicle yields a value of time per vehicle-hour of $18.19.[8] All three projects' congestion reduction cost-effectiveness fall well below this threshold, suggesting that each would result in substantial social benefits on the basis of congestion relief alone, above and beyond their relative emissions benefits.

The analysis does not account for long-term changes in travel behavior. For example, there can be a rebound effect after installation of a new roundabout: traffic flow improvements may accrue early in the presence of existing travel behavior, but these improvements will decline and ultimately extinguish as travelers accommodate them into their travel patterns.

Roundabouts demonstrated the strongest cost-effectiveness for reducing delay, almost double that of the other two project types.[9] These effects are likely specific to delay reduction during peak hours, which was calculated at nearly 40 seconds saved per vehicle in the median analytical scenario; off-peak savings varied between 0-9 seconds, depending on the approach to the roundabout.

The following section discusses the approach used to generate the cost-effectiveness estimates summarized above, including an outline of data sources and a description of the process used to generate analytical scenarios. Key assumptions and limitations of the cost-effectiveness analysis are also discussed.

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[7] "Benefit-Cost Analysis Guidance for Discretionary Grant Programs" (Office of the Secretary, US Department of Transportation, December 2018).

[8] "NHTS 2009: Average Vehicle Occupancy by Mode and Purpose" (US Bureau of Transportation Statistics, 2009), https://nhts.ornl.gov/tables09/fatcat/2009/avo_TRPTRANS_WHYTRP1S.html.

[9] Note that this analysis examined a three-legged roundabout, the representative median scenario based on PAS data.

CMAQ COST-EFFECTIVENESS ANALYSIS

CMAQ Overview and Cost-Effectiveness

The Clean Air Act Amendments of 1990 expanded efforts by the U.S. to improve air quality by making the National Ambient Air Quality Standards (NAAQS) more stringent, and by requiring additional control measures in areas that failed to meet the NAAQS. In pursuit of national air quality improvement goals, the Intermodal Surface Transportation Efficiency Act 1991 (ISTEA) created the Congestion Mitigation and Air Quality Improvement (CMAQ) Program. Reauthorized in every successive transportation authorization, Congress has charged the CMAQ program with supporting transportation projects and programs that reduce emissions and roadway congestion.[10]

State and local governments can use CMAQ funding to support projects and programs that contribute to the attainment or maintenance of NAAQS in both current and former nonattainment and maintenance areas for carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$) and ozone (O_3).

Cost-Effectiveness Reporting

Under 23 USC 149(i), the Secretary, in consultation with EPA, 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 CMAQ funding. Under section 149(i)(2)(C), States and MPOs shall consider the information in this table when selecting projects.

The CMAQ program was last reauthorized in the *Fixing American's Surface Transportation Act* (FAST Act). The FAST Act modified certain eligibilities within the program by:

- Adding eligibility for verified non-road vehicle and engine technologies that are used in port-related freight operations located in ozone, PM_{10}, or $PM_{2.5}$ nonattainment or maintenance areas funded through 23 U.S.C. or 49 U.S.C. 53.
- Making eligible the installation of vehicle-to-infrastructure communications equipment.
- Continuing eligibility for electric vehicle and natural gas vehicle infrastructure, and added priority for infrastructure located on the corridors designated under 23 U.S.C. 151.
- Amending the eligible uses of CMAQ funds set aside for $PM_{2.5}$ nonattainment and maintenance areas. $PM_{2.5}$ set-aside funds may be used to reduce fine particulate matter emissions in a $PM_{2.5}$ nonattainment or maintenance area, including:

    - Diesel retrofits;
    - Installation of diesel emission control technology on non-road diesel equipment, or on-road diesel equipment operated for highway construction projects; and
    - The most cost-effective projects to reduce emissions from port-related landside non-road or on-road equipment operated within the boundaries of the area.

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[10] "Congestion Mitigation and Air Quality Improvement (CMAQ) Program" (US Federal Highway Administration, n.d.), https://www.fhwa.dot.gov/environment/air_quality/cmaq/.

To address the requirement to develop cost-effectiveness tables, FHWA considered the following when developing the 2020 Update and prior cost-effectiveness tables:

- 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 to assess how these projects mitigate congestion and improve air quality;
- 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).

Objective and Project Types

CMAQ cost-effectiveness is measured as dollars per ton of pollutant reduced, based on median cost values. A set of cost-effectiveness tables for CMAQ-funded projects was developed in 2015. The 2020 Cost-Effectiveness Tables Update uses the same basic format as the 2015 version, with some changes in project types and methodology. The following sections highlight where the 2020 cost-effectiveness approach diverges from the methodology used in the development of the 2015 Cost-Effectiveness Tables.

The 2020 Cost-Effectiveness Tables Update analyzed 21 project types, generally consistent with the 2015 study. New project types in this study are marked with an asterisk below. This study added several categories and refined others (e.g. bicycle and pedestrian improvements). Projects studied include:

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

Methodology

The approach taken to complete the 2020 Cost-Effectiveness Tables Update is largely consistent with the 2015 analysis. The following sections provide an overview of the project cost data and associated emission rates represented through the use of MOVES2014b. Additional data elements described include travel demand, emission intensity, and project lifetimes.

CMAQ Public Access System

The 2020 Cost-Effectiveness Tables Update relied primarily on the CMAQ Public Access System (PAS) to establish the range of costs for each project type, with publicly-available or third party data regarding infrastructure and program costs supplementing those findings. The 2015 Cost-Effectiveness Tables did not utilize the PAS.

The following data sources were used to develop cost estimates by project type for the 2019 Cost-Effectiveness Tables Update:

- CMAQ Public Access System (PAS): The PAS is a read-only public interface that displays details about CMAQ-funded projects with their associated financial information and emission benefits.[11] The 2020 Cost-Effectiveness Tables Update primarily relied on the PAS for establishing the cost components of the analysis. This more closely aligns with actual reported data for approved projects. The 2020 Update only represents projects that have already received CMAQ funding, not projects that could potentially be funded. For cost-effectiveness analyses, records were sorted by project type and project description in order to determine which project category listed above applied to each. The capital, operating, and total project costs were then analyzed for each relevant project type to determine a typical cost range for CMAQ projects, given what was known about the scope of each project type. The analysis included an assessment of the minimum, median, maximum costs for each project type. The sections below describe the analysis process for each individual project type.
- Publicly Available Project Cost Data. While the PAS contains project specific cost data, the cost-effectiveness scenarios were developed with supplemental cost, scope, and usage data that ensures their representativeness. Sources for this supplemental information consisted of publications from State and local governments, including State departments of transportation, metropolitan planning organizations (MPOs), and transit authorities. Documents included information available on websites, press releases, and other publications. Examples include reports and memos related to signal retiming and roundabout construction.
- Third Party Cost and Use Data. Research used in developing the cost-effectiveness scenarios included broader research on relevant infrastructure and program costs, in addition to the direct individual project cost data. Sources included publications by academics, trade groups, and other professional organizations involved in publicizing certain transportation projects. Examples include daily parking utilization rates and fees, and research findings by the Transit Cooperative Research Program (TCRP). Data from these sources helped calibrate the project type scenarios.

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[11] "CMAQ Public Access System" (US Federal Highway Administration, n.d.), https://fhwaapps.fhwa.dot.gov/cmaq_pub/.

MOVES Analysis and Emissions Rates

This research utilizes the US Environmental Protection Agency's **MO**tor **V**ehicle **E**missions **S**imulator version 2014b (MOVES2014b or MOVES) to estimate emissions impacts by criteria pollutant and applicable precursors. MOVES was developed by the EPA for modeling emissions resulting from on-road and some non-road motor vehicle activity. MOVES allows users to specify their own inputs for many fleet-level variables, including vehicle type, age, fuel, road type.

MOVES users may conduct fine-scale modeling with custom inputs. As part of the cost-effectiveness analysis, MOVES default values were used to estimate national-scale emissions rates in tons per mile or per hour. These were multiplied by estimates of lifetime project level activity impacts (e.g., VMT impacts, travel speeds) identified through separate research to yield estimated emission impacts for a given project type.

MOVES can model composite emissions rates for the entire vehicle fleet (e.g., for traffic flow improvements, which affect the general roadway), or can disaggregate by any of its variables. Separate emission rates for different vehicle types were estimated for vehicle replacement projects, and further disaggregated by fuel type as necessary. Where the distribution of vehicle age was relevant, as for scenarios involving vehicle replacement and engine retrofit technologies, separate emissions rates were estimated by model year (with reference to 2019).

In addition, MOVES can estimate emissions rates with respect to speed in order to evaluate changes in travel time or drive cycle. These data matter especially for projects whose potential emissions benefits depend on changes in travel speed, such as for intersection improvements and incident management projects. Scenarios in this analysis related to travel conditions use travel speeds identified from real-world projects, and were allowed to vary across meaningful ranges for sensitivity analysis.

In several cases, MOVES emissions rates were applied using the CMAQ Toolkit, a suite of emissions calculators for users to determine emissions benefits for CMAQ-eligible projects without independently developing their own models.[12] Containing pre-loaded national-default MOVES2014b emissions rates for a given project type, the CMAQ Toolkit is a consistent reference for emissions reduction calculations associated with CMAQ-eligible projects. This report relied on Toolkit project modules where possible, and makes specific reference to cost-effectiveness analyses that rely on the Toolkit

Assumptions and Limitations

Key assumptions for the cost-effectiveness analysis include:

- Discounting. Emission impacts are not discounted across project lifetimes. For example, a ton of emissions reduced in the first year of a project is equivalent to the same ton of emissions reduced in the last year. The purpose of this assumption is to treat all cohorts experiencing emission impacts (e.g. model years of heavy-duty trucks) the same, rather than favoring groups in particular time periods.

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[12] For more information on the CMAQ Toolkit, please visit the Toolkit website: https://www.fhwa.dot.gov/environment/air_quality/cmaq/toolkit/

- Independent Pollutant Impacts. The cost-effectiveness of a project with respect to one pollutant is independent of the project's impacts on other pollutants. Variations in the relative impacts of pollutants in different circumstances make selecting one nationally-applicable weighting system impractical. Moreover, as some projects target reductions in individual pollutants, weighting systems can obscure the relative effectiveness of different strategies at reducing different pollutants. Therefore, total project costs were assigned to each pollutant category.

- Representativeness. 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 eligible for receiving CMAQ funding.

- CMAQ Share of Project Costs. All reported or estimated project costs are included in calculations of cost-effectiveness measures, rather than the share of project costs receiving CMAQ funding. This assumption was imposed to allow for direct comparison across scenarios. Ultimately, cost-effectiveness estimates should reflect how effectively a given project type achieves reductions in pollutant emissions; representing only the share of CMAQ funds associated with individual project examples would result in estimates that may inappropriately attribute all pollutant reductions to CMAQ funds while ignoring pollutant reductions attributable to other funding sources.

- Project Costs Assigned to First Year. 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, to be consistent with CMAQ project reporting requirements). This represents the timing of the obligation of funds from the CMAQ program toward projects. This assumption means that the result reflects the cost-effectiveness of the total project cost. The full project cost is also assumed to incorporate all relevant costs (i.e., capital and/or operating). The estimates of project costs do not generally differentiate between capital costs versus operation assistance; the corresponding assumption of funds being applied to all project costs was selected for consistency with the data.

- All Types of Costs. The project cost represents all types of reported or estimated costs to which funds would be applied (e.g., capital costs and operating costs).

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

- Median Estimates. Median estimates are the selected measures to compare cost-effectiveness across project types. The median indicates the middle value of a set and is not subject to the influence from outliers as with average values. Other approaches, such as best-case scenarios or mean value calculations, may be distorted by very successful or very weak projects, and thus overstate the relative effectiveness of a project type. For example, diesel retrofits of relatively old long-haul trucks may have a larger benefit on average compared with retrofitting newer model years, but old long-haul trucks may represent a very small share of vehicles available for retrofits under a given project. Analyzing the best case effects of retrofitting a diesel long-haul truck would focus on the absolute oldest, i.e. most polluting model years, and thus bias the results of the analysis. By using the median value, cost-effectiveness estimates in this report more closely represent the typical project.

- Base Year. The base year for all projects is 2019.
- Scenario Building. There are several assumptions related specifically to scenario building for the 2019 update. Every scenario analyzed represents a real project from the PAS. The range of scenarios included in the analysis excluded cases that were either considerable outliers in terms of cost (high or low) or those with overly vague descriptions. As a result, the analysis assumes that the range of scenarios includes both best-case scenarios and scenarios that may be less effective for a given project type.
- Emission Rates. The emissions rates used in this analysis are based on the assumptions built into the MOVES2014b model. Key assumptions include the relative proportions 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, etc.), the appropriate drive cycles 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 vs. national average). Refer to the MOVES documentation for further details of its methodology and assumption.

Potential Sources of Bias

The analysis presented herein is not intended to cover the full range of potential outcomes within a project type, nor the full range of potential projects. The range of project types included in the analysis represents an informative view of the relative performance of predominant project types across the range of pollutants in the study. It is not a census evaluation of all projects eligible for CMAQ funding, and difficulties identifying representative project examples in the PAS and in literature for some project types limited the range of potential projects included in the analysis.

As discussed above, the analysis assumes that the estimated project costs cover the full extent of capital costs, and operating assistance. If projects include 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), cost-effectiveness estimates would be biased upwards (i.e., higher cost per ton).

In addition, the costs for project types involving user-specific technologies or policies (e.g., diesel retrofits, employee transit passes) are represented as per-unit costs, rather than total cost for an entire project (e.g., 50 retrofits), and do not include administration and installation fees. Therefore, the estimated cost-effectiveness for such project types may be considered a conservative estimate, and any administration and installation costs would raise the cost per ton reduction of a given pollutant.

The CMAQ PAS database presented some challenges to identifying representative costs for each project type evaluated. The PAS data is self-reported by funding recipients, and does not include much detail about individual projects. Therefore, particularly with projects that may involve purchasing multiple units (e.g., vehicle replacements), it is difficult to know the contents of a project and, crucially, why a project may have cost what was reported. The authors attempted to verify costs noted in the PAS with third-party data, but the analysis primarily focused on PAS data, as this is the best estimate of project costs funded by the CMAQ program.

The analysis assumes constant annual impacts across project lifetimes, unless variable information across years was available (i.e., changes in expected emission rates calculated using MOVES2014b). For example, consider the construction of a bicycle lane. Travel behavior towards more bicycling would be expected to ramp up in the first several years as people adapt to the new availability of the facility, and new motorized vehicle trips would likely take their place in the long run, absent other mode choice constraints. However, for purposes of this analysis, those travel behavior changes and the accompanying emissions benefits of less motorized travel are assumed to occur in the first year of implementation without collateral long-run effects, and remain constant for the life of the project. Conversely, congestion relief from intersection improvements such as roundabouts or new signals would likely have larger impacts earlier in the project's lifetime, but the delay reductions would be expected to diminish as drivers become accustomed to a new configuration.

Assuming constant annual impacts across project lifetimes likely results in lower cost per ton estimates if impacts would be expected to decrease over time, and vice versa. 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 important to acknowledge that cost-effectiveness with respect to reducing pollutant emissions and congestion is not necessarily the only reason to implement a given project. Different projects can provide a wide range of benefits (e.g., reductions in fuel consumption, safety improvements) that might make them worth pursuing. For example, a new bicycle lane may bring improved safety benefits, in addition to air quality improvements. Cost-effectiveness should be considered alongside these other benefits when determining project priorities, noting however that CMAQ-funded projects must produce emissions benefits.

The cost-effectiveness estimates only account for the two eligibility criteria relevant to the CMAQ program: air quality improvements and reductions in traffic congestion.

Cost-Effectiveness Calculations

The 2020 Cost-Effectiveness analysis represents the cost of the entire CMAQ-eligible *project*, independent of the relative share of CMAQ *funds* that a given project receives. This approach mirrors prior cost-effectiveness table reports, which analyzed total project costs within individual cost-effectiveness measures without differentiating by funding source.

In addition to project costs, a key input in the development of the scenarios is related to the project lifetimes. 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 timeframes, consider Table 6 below[13], which offers a summary of project lifetimes specified in a CMAQ study under SAFETEA-LU:

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[13] FHWA 2008, op. cit., p. 55.

Table 6. 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	5 – 20
Intermodal Freight Facilities and Programs	20
Engine Retrofits	Varies by classification

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., PAS, literature review). 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 equal 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 one-year (project lifetime), $10,000 project that reduces annual passenger vehicle-miles traveled (VMT) by 50,000, at a prevailing average travel speed of 35 mph at an estimated carbon monoxide (CO) emission rate of three grams per mile. To estimate the cost-effectiveness of the project with respect to CO, divide the project cost by the estimated reduction in CO emissions:

Equation 1: General Equation for Cost-Effectiveness

$$Cost - effectiveness = \frac{Project\ Cost}{Emissions\ Reduction * Project\ Lifetime}$$

$$Cost - effectiveness = \frac{Project\ Cost}{\Delta VMT * CO\ Emissions\ per\ Mile * Project\ Lifetime}$$

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).

$$Cost - effectiveness = \frac{\$10{,}000}{50{,}000\ mi * 0.003\ kg/mi * 1\ year}$$

$$Cost - effectiveness = \frac{\$10{,}000}{150\ kg} = \frac{\$10{,}000}{0.16535\ tons} = \$60{,}479\ per\ ton$$

When information was not available for a given scenario, representative values from related cases or the literature filled in missing values. For example, if a given infrastructure project lacked a specific lifetime, and if literature noted a common project lifetime for related projects, the common value was used in the cost-effectiveness analysis.

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 a range of 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 breadth 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 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 varying the associated travel speed (e.g., representing congested arterials, uncongested arterials, and uncongested highways). This process was repeated as appropriate to vary factors including vehicle age (e.g., for diesel retrofits), vehicle use impacts (e.g., to test differing demand sensitivities), and road types (e.g., urban versus rural arterials or highways).

The number of scenarios varied by project type based on available data and configurations. However, to ensure statistical validity, all project analyses used a reasonable minimum of twenty scenarios where possible. The general analysis structure links key inputs from external sources (e.g., projects from the PAS, other projects consistent with CMAQ proposals) to emission estimates from analysis in MOVES2014b. Key inputs in the generation of estimates of cost-effectiveness (measured in dollars per ton of pollutant reduced) are shown in the table below.

Table 7. 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 accompanying sensitivity range quantify the impact of a given project type on travel demand by vehicle type. Technological effectiveness measures represent the share of pollutant emissions that would be captured over a given volume of travel demand or engine use (e.g., operating hours). Representative travel speeds and road types are used to link specific emission rate estimates from MOVES2014b 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.

COST-EFFECTIVENESS BY PROJECT TYPE

The remainder of the document reviews each project type included in the analysis. For each project type, the discussion outlines the steps and methodology that FHWA followed 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, based on the range of inputs identified for the analysis. For each project type, the discussion concludes with a summary table of median cost-effectiveness estimates identified in the analysis.

This section includes descriptions of the skewness of cost data. Skewness is a statistical concept referring to how the data is distributed across its range. If a distribution has several outlier data points larger than the bulk of the cases, this distribution is said to “skew to the right”. In the opposite case, where extreme outliers are less than the bulk of the cases, the distribution is said to “skew to the left”.

Park and Ride

Park and ride projects focus on providing new park and ride lots to encourage transfers from LDVs to public transit, resulting in an emission reduction. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated LDV trips (less any additional bus emissions), and project lifetimes.

This analysis included the following steps:

- Generate light-duty and bus per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for the range of relevant travel speeds;
- Identify LDV travel activity estimates (daily and annual VMT) reduced through projects;
- Identify new bus travel activity estimates (daily and annual VMT) associated with projects;
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains 25 park and ride projects from 2015 and 2016 identified for analysis.[14] The median project cost was approximately $984,000. The distribution of projects costs are shown in Figure 6 below.

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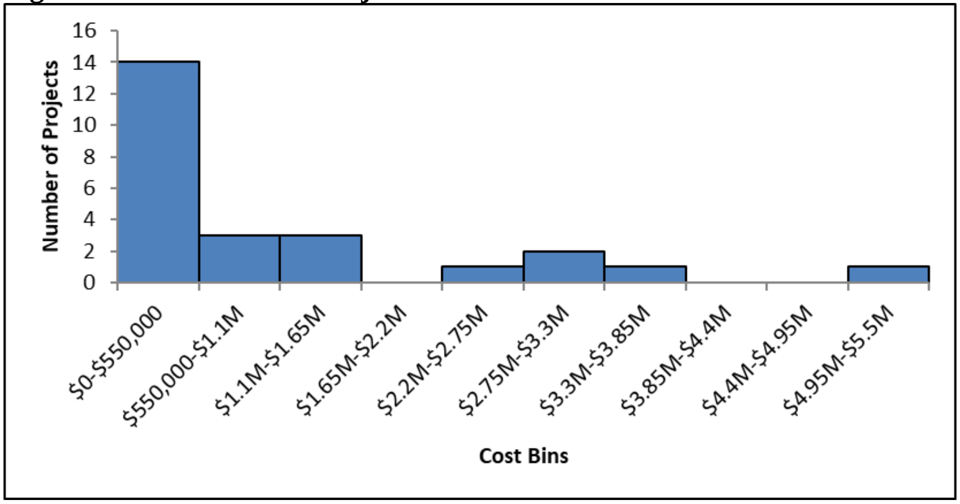
[14] 2016 was chosen as it was the most recent year with full available data.

Figure 6: Park and Ride Project Cost Distribution



Project costs are skewed to the right with the majority of the projects costing less than $1 million each, and just two projects costing over $3 million. This cost range was taken into consideration when constructing the range of project costs in the analytical scenarios.

Scenario Building

Twenty analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized transit projects.

For the purposes of the analysis, it was assumed that the park and ride lots were used exclusively on work days (250 times per year), and that the useful life of the lots was twenty years. Additionally, it was assumed that travelers who utilized the park and ride lot reduced their LDV use by an average of 24 miles (twelve miles each way in the morning and afternoon). Finally, it was assumed that the transit vehicles already operated from the park and ride lot, and therefore no additional transit vehicle emissions were incurred.

Three inputs varied across the twenty scenarios (

Table 8). The facility and utilization assumptions were based on projects publicized by State DOTs, transit agencies, and local governments.[15] The cost data was based on publicized data as well as PAS data.

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[15] Agencies included Virginia DOT, Sound Transit (WA), the Delaware Transit Corporation, and the Lee County (FL) Board of County Commissioners.

Table 8: Park and Ride Scenarios

Parameter	Value Range
Number of Spaces	100 to 650 spaces
Utilization Rate	40% to 100%
Days per Year	250 days
Daily Miles Reduced (per Vehicle)	24 miles
Project Lifetime	20 years
Project Cost	$200,000 to $3.3M

Methodology

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

In this scenario, the following assumptions were used:

- The average light-duty emission rates are 0.369 grams per mile for NOx and 0.012 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 75 percent, for 250 days per year;
- The average LDV 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 twenty years; and
- The project cost is $2,000,000.

Step One: Identify annual emissions impacts by multiplying per-trip emissions by the number of affected trips:

Table 9. Sample Calculation of Annual Emission Benefit from a Park-and-Ride Project

Pollutant	LDV Emissions Reduced (grams/mile)	Daily VMT Reduction	Annual VMT Reduction	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	0.369	9,000	2,250,000	829,622	0.915
$PM_{2.5}$	0.012			28,076	0.031

Step Two: Identify project-level emission impacts by multiplying each of the estimated annual emissions benefits by the project lifetime:

Table 10. Sample Calculation of Total Emission Impacts from a Park-and-Ride Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	0.915	20	18.290
$PM_{2.5}$	0.031		0.619

Step Three: Calculate cost-effectiveness estimates by dividing the project cost by the estimated project-level emission impacts:

Table 11. Sample Calculation of Cost-Effectiveness Estimates for a Park-and-Ride Project

Pollutant	Total Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	18.290	$2,000,000	$109,349
$PM_{2.5}$	0.619		$3,231,141

Cost-Effectiveness

The median cost-effectiveness estimates for the range of park and ride project scenarios are presented in Table 12 below:

Table 12. Median Cost-Effectiveness Estimates (dollars per ton) – Park and Ride Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Park and Ride	$2,660,225	$732,201	$7,986	$90,028	$131,848

Rideshare Programs

Ridesharing projects encourage mode shift from single-occupant LDV 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.

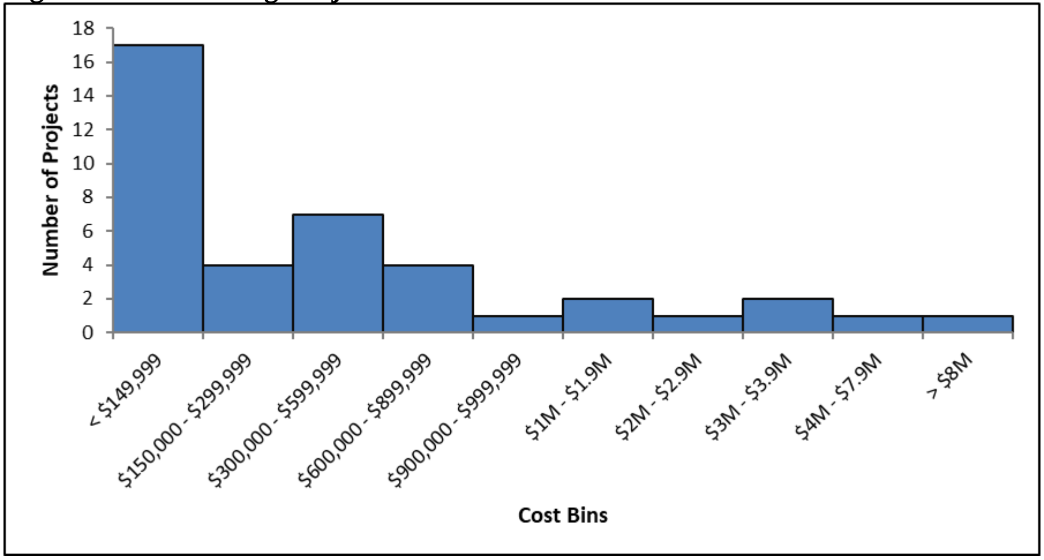
This analysis included the following steps:

- Generate single-occupant and multiple-occupant light-duty per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for relevant travel speeds for travel affected by the project;
- Identify estimates of single-occupant and multiple-occupant light-duty travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

Cost Analysis

The PAS contains 40 ridesharing projects identified for this analysis, with a wide variety of purposes: marketing and outreach, operation assistance, pooling of low emission vehicles, and vanpools startup and replacement. The distribution of project costs is shown in Figure 7 below. As mentioned in the previous section, ridesharing projects may involve direct subsidies of drivers of shared vehicles, the purchase of vanpools and indirect support such as ride-matching services. Restricting the subtypes from the PAS based on this definition, the average is about $431,000.

Figure 7: Ridesharing Project Cost Distribution



In addition, information on ridesharing projects was identified through a review of ridesharing project documentation.[16] Using the 2019 operating and capital budget for the Ann Arbor Area Transit Authority's VanRide service as a representative example, vehicle replacement including components averages about $350,000 per year. This cost range was taken into consideration when constructing the range of project costs in the analytical scenarios.

Scenario Building

Nine analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above)
- A review of ridesharing project documentation and supporting literature.

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[16] "About TheRide," n.d., https://www.theride.org/AboutUs.

For purposes of this analysis, it was assumed that the average reduction in single-occupant trips associated with each rideshare trip is eight (i.e. half of a van's capacity)[17]. The rideshare trip distance traveled was allowed to vary between 20-40 miles.

Table 13: Ridesharing Scenarios

Parameter	Value Range
Average reduction of single occupant trips associated with ridesharing	8 trips
Average total distances associated with ridesharing	160, 240, 320 miles
Workdays per Year	250 days
Project Lifetime	5 years
Project Cost	$350K, $400K, $450K

Methodology

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

In this scenario, the following assumptions were used:

- Average light-duty emission rates are 0.3716 grams per mile for NOx and 0.0126 grams per mile for $PM_{2.5}$;
- Each vanpool trip is associated with an average reduction of eight single-occupant vehicle trips;
- The average round-trip distance associated with mitigated single-occupant trips is 240 miles;
- Under the program, there are rideshare trips into and out of the target destination each workday (250 trips per year);
- The project lifetime is five years; and
- The project cost is $400,000.

Step One: Identify annual emissions impacts by multiplying per-trip emissions by the number of affected trips.

Table 14: Sample Calculation of Annual Emission Benefit of a Vanpool Program

Pollutant	Emissions Reduced (grams/mile)	Annual VMT Reduction	Annual Emission Benefit (tons)
NOx	0.3716	960,000	0.393
$PM_{2.5}$	0.0126		0.013

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[17] http://www.kitsaptransit.com/faqs/vanpool-frequently-asked-questions/how-many-people-does-it-take-to-form-a-vanpool-this-is-not-a-joke

Step Two: Identify project-level emission impacts by multiplying each of the estimated annual emission impacts by the project lifetime.

Table 15: Sample Calculation of Annual Emission Benefit of a Vanpool Program

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	0.393	5	1.97
$PM_{2.5}$	0.013	5	0.07

Step Three: Calculate cost-effectiveness estimates by dividing the project cost by the estimated project-level emission impacts.

Table 16: Median Cost-Effectiveness Estimates for a Vanpool Program

Pollutant	Lifetime Emission Benefit (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	1.97	400,000	$203,417
$PM_{2.5}$	0.07		$6,010,024

Cost-Effectiveness

The median cost-effectiveness estimates for the range of scenarios are presented in Table 17 below:

Table 17: Median Cost-Effectiveness Estimates (dollars per ton) – Ridesharing Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Ridesharing	$6,010,024	$1,667,035	$17,901	$203,417	$295,708

Employee Transit Benefits

For purposes of this report and the CMAQ program, employee transit benefits are functionally identical to subsidized transit fares. Both programs reduce the cost of transit to incentivize its use, thereby diverting LDV trips to transit. Since employee transit benefits are a type of subsidized transit benefit and the methodologies for assessing the cost-effectiveness of such programs are essentially the same, please refer to the subsidized transit fares section of this report for the cost-effectiveness analysis.

Carsharing

Carsharing projects offer access to vehicles owned and maintained by third parties (e.g., cities) for intermittent trips best served by LDVs (LDVs). Shared vehicles provide alternatives to reduce household LDV, and in some cases enable households to own fewer cars, both of which may result in decreases in VMT through eliminating some discretionary trips and mode shift to public transit).

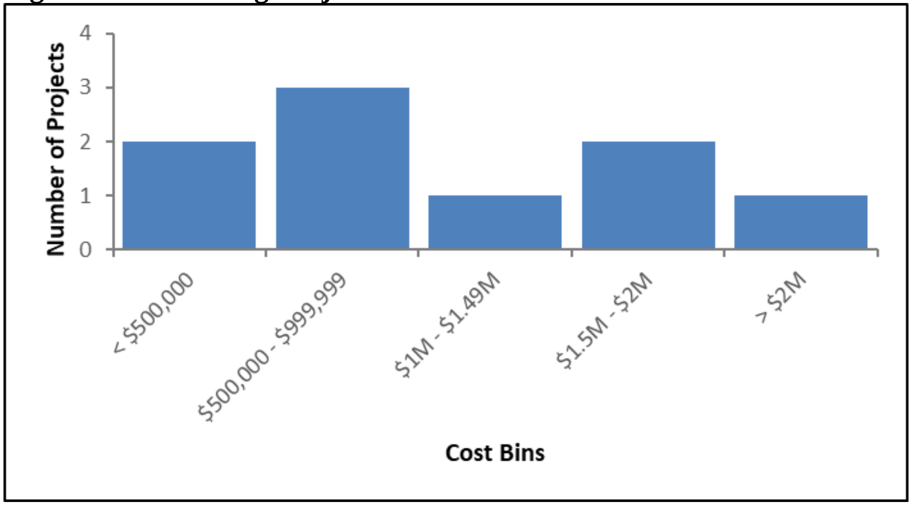
This analysis included the following steps:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for relevant travel speeds for travel affected by the project;
- Identify estimates of travel activity (daily and annual VMT) affected by the project (such as estimates of reductions in LDV usage for each user through the use of carsharing and estimates of participation rates in carsharing projects);
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains eight carsharing projects prior to 2016 identified for analysis. The average was approximately $974,794. The distribution of project costs is shown in Figure 8 below.

Figure 8: Carsharing Project Cost Distribution



As shown above, the majority of projects cost between $900,000 and $1,500,000. In addition this, information on carsharing projects was identified through a review of carsharing project documentation and supporting literature.[18]

Scenario Building

Nine analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- A review of carsharing project documentation and supporting literature.

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[18] R Cervero, A Golub, and B Nee, “City CarShare: Longer-Term Travel Demand and Car Ownership Impacts,” *Transportation Research Record: Journal of the Transportation Research Board,* 2007, 70–80; Amanda Suutari, “Flexcar: A Model of For-Profit Carsharing” (The Eco-Tipping Point Project, 2006), http://www.ecotippingpoints.org/our-stories/indepth/usa-portland-flexcar-carsharing.html.

For purposes of this analysis, it was assumed that each shared vehicle is used by fifteen owners of light duty vehicles[19], fleet size of 500, and each participant reduces net annual VMT by 2500 to 4500[20] with average travel speed of 35 mph. Additionally, the useful life of the project is assumed to be five years. Across the nine scenarios, two inputs varied: the annual VMT reduction per person and project costs.

Table 18: Carsharing Project Scenarios

Parameter	Value Range
Number of Owners Sharing LDV	11
Number of LDV (Fleet Size)	500
Annual VMT Reduction per person (one way)	2,500; 3,500; 4,500
Travel Speed	35
Project Lifetime	5 years
Project Cost	\$1M, \$1.5M; \$2M

Methodology

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

In this scenario, the following assumptions were applied:

- The project includes the purchase and maintenance of 500 LDVs;
- Each shared vehicle is used by eleven owners of LDVs;
- Each participant reduces net annual VMT by 5,000 (2 way);
- The average travel speed for offset travel is 35 miles per hour;
- The average fleet-level emission rates for travel at 25 miles per hour are 0.372 grams per mile for NOx and 0.0126 grams per mile for $PM_{2.5}$;
- The project lifetime is five years; and
- The project cost is \$1 million.

Step One: Identify annual emissions impacts by multiplying per-miles emissions by the number of affected trips.

Table 19: Sample Calculation of Annual Emission Benefit of a Carsharing Project

Pollutant	Emission Rates (grams/mile)	Annual VMT Reduction	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	0.372	27.5M	10,220,222	11.27
$PM_{2.5}$	0.0126	27.5M	345,916	0.38

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

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[19] Laura Bliss, "Here's How Many Cars This Car-Sharing Service Killed," *CityLab*, July 20, 2016, https://www.citylab.com/transportation/2016/07/car2go-car-ownership-vmt-ghg/491825/.

[20] Elliot Martin and Susan Shaheen, "The Impacts of Car2go on Vehicle Ownership, Modal Shift, Vehicle Miles Traveled, and Greenhouse Gas Emissions: An Analysis of Five North American Cities" (Transportation Sustainability Research Center - UC Berkeley, July 2016), http://innovativemobility.org/wp-content/uploads/2016/07/Impactsofcar2go_FiveCities_2016.pdf.

Table 20: Sample Calculation of Total Emission Benefits of a Carsharing Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Lifetime Emission Benefit (tons)
NOx	11.27	5	56.3
$PM_{2.5}$	0.38	5	1.91

Step Three: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 21: Sample Calculation of Cost-Effectiveness Estimates for a Carsharing Project

Pollutant	Lifetime Emission Benefit (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	56.3	$1,000,000	19,020
$PM_{2.5}$	1.91	$1,000,000	561,976

Cost-Effectiveness

The median cost-effectiveness estimates for the range of scenarios are presented in Table 22 below:

Table 22: Median Cost-Effectiveness Estimates (dollars per ton) – Carsharing Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Carsharing	$561,976	$155,879	$1,674	$19,020	$27,650

Bikesharing

Bikesharing projects involve providing incentives to shift travel mode from LDV 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.

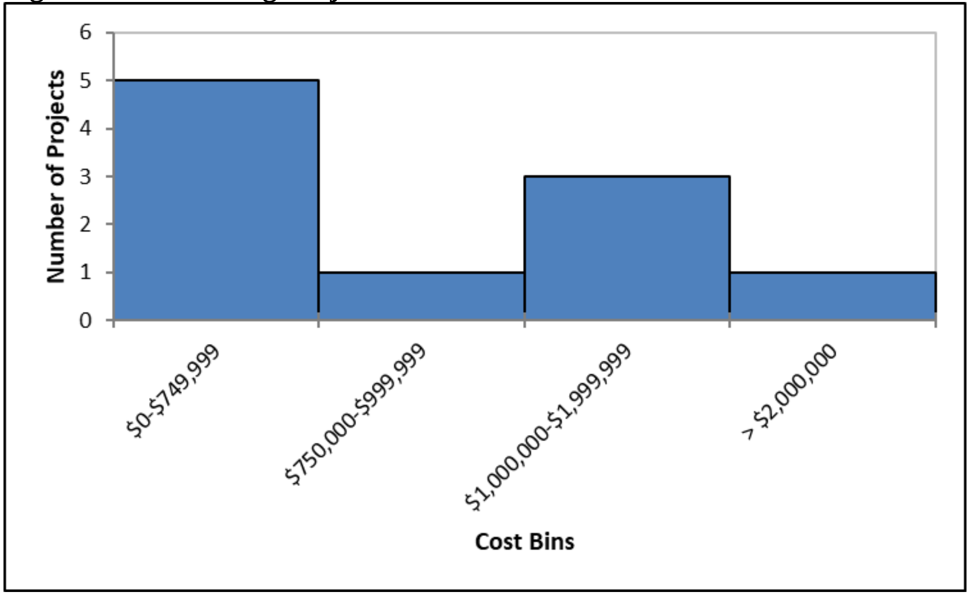
This analysis included the following steps:

- Generate light-duty per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for relevant travel speeds for travel affected by the project;
- Generate estimates of travel demand reduced for each user per trip through mode shift to shared bicycle;
- Generate estimates of participation rates (users and annual trips) in bikesharing projects;
- Identify project lifetime estimates; and
- Identify project cost estimates, including adjustment factors accounting for revenue recovery.

Cost Analysis

The PAS contains ten bikesharing projects identified for analysis from 2016. The median project cost was $1,150,793. The distribution of project costs is shown in Figure 9 below.

Figure 9: Bikesharing Project Cost Distribution



The project costs are slightly bimodal, with the majority of the projects costing less than $1 million and/or between $1-2 million.

Starting a bike share program requires substantial capital.[21] Including the cost of fixed infrastructure such as docking stations, systems typically cost about $4,000 to $5,000 per bike. With a typical city funding up to 35 docking stations and about 350 bicycles, total capital investment can reach $1,575,000.[22] This cost range was taken into consideration when building and analyzing cost-effectiveness scenarios.

Scenario Building

Nine analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized transit projects.

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[21] Rebecca Beitsch, "Despite Popularity, Bike Share Programs Often Need Subsidies" (Pew Charitable Trusts, March 24, 216AD), https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2016/03/24/despite-popularity-bike-share-programs-often-need-subsidies.

[22] Economic and Planning Systems, Inc., "Draft Report: City of Santa Monica Bicycle Sharing Analysis" (The City of Santa Monica, CA, October 25, 2012), https://www.smgov.net/uploadedFiles/Departments/PCD/Plans/Bike-Action-Plan/SantaMonicaBikeShare%20cost%20and%20revenue%20estimates.pdf.

For purposes of this analysis, it was assumed that annual ridership ranges from 1,000,000 to 2,000,000 (e.g., annual ridership for Capital Bikeshare in Washington DC is at the high end at 2,000,000)[23] and that the average net impact of each trip by shared bicycle is a reduction in travel by light duty vehicle of two miles at 35 miles per hour.[24] Additionally, useful life of the project is assumed at five years. Across the nine scenarios, two inputs varied: the number of trips per year via shared bicycle and project cost.

Table 23: Park and Ride Scenarios

Parameter	Value Range
Travel Length	2 miles
Annual Ridership	1,000,000; 1,500,000; 2,000,000
Annual VMT Reduction	200,000; 300,000; 400,000
Project Lifetime	5 years
Project Cost	$750,000; $1,000,000; $1,500,000

Methodology

As an illustrative example, consider a project involving a new bikesharing project. In this scenario, the following assumptions were used:

- 1,000,000 annual ridership;
- The average net impact of each trip by shared bicycle is a reduction in travel by light duty vehicle of two miles (the average impact accounts for cases of users switching from transit and pedestrian activity, in which there is no impact on LDV use)
- The average fleet-level emission rates for travel at 35 miles per hour are 0.3716 grams per mile for NOx and 0.0126 grams per mile for $PM_{2.5}$;
- The project lifetime is five years; and
- The project cost is $750,000.

Step One: Identify Annual Emission Benefit by multiplying per-trip emissions by the number of affected trips.

Table 24: Sample Calculation of Annual Emission Benefit of a Bikesharing Project

Pollutant	Emission Rates (grams/mile)	Annual VMT Reduction	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	0.3716	2,000,000	743,289	0.81934
$PM_{2.5}$	0.0126	2,000,000	25,158	0.02773

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

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[23] "Capital Bikeshare: System Data," n.d., https://www.capitalbikeshare.com/system-data.

[24] "NHTS 2009" (US Bureau of Transportation Statistics, n.d.), https://nhts.ornl.gov/.

Table 25: Sample Calculation of Total Emission Benefits of a Bikesharing Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Lifetime Emission Benefit (tons)
NOx	0.81934	5	4.09668
$PM_{2.5}$	0.02773	5	0.13866

Step Three: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 26: Sample Calculation of Cost-Effectiveness Estimates for Bikesharing Project

Pollutant	Lifetime Emission Benefit (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	4.09668	$ 750,000	183,075.18
$PM_{2.5}$	0.13866	$ 750,000	5,409,021.27

Cost-Effectiveness

The median cost-effectiveness estimates for the range of scenarios are presented in Table 27 below:

Table 27: Median Cost-Effectiveness Estimates (dollars per ton) – Bikesharing Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Bikesharing	$ 5,409,021.27	$ 1,500,331.46	$ 16,110.94	$ 5,409,021.27	$ 1,500,331.46

Electric Vehicle Charging Stations

These projects involve the provision of electric vehicle charging infrastructure (EVCI) to support the use of electric vehicles in place of conventional LDVs. As with other CMAQ analyses, it was assumed that there are no operational emissions associated with the use of electric vehicles other than brakewear and tirewear as PM.

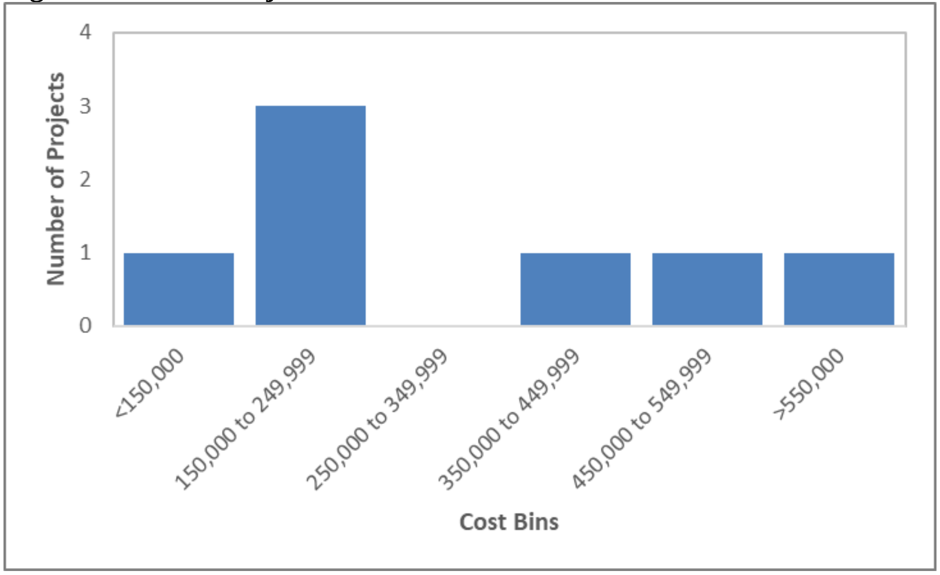
This analysis included the following steps:

- Generate emission rates estimates for offset conventional LDV trips from national-average fleet-level MOVES2014b runs for a range of relevant travel speeds;
- Identify estimates of offset travel demand via conventional LDVs;
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

Information on EVCI projects within the PAS was scant: seven EVCI projects were identified between 1992 and 2016. The median project cost was $312,287 (Figure 10). Note that this analysis does not differentiate between different electric-vehicle charging types (e.g., DC fast charging, Level 2), because information of different charging types was not available.

Figure 10: EVCI Project Cost Distribution



Project costs are slightly skewed to the left, with majority of the projects costing between $150,000 and $249,999. This range does not deviate far from the costs found in published EVCI projects where basic Level 2 charging stations costs $25,000 for the equipment, plus $15,000 installation cost.[25] With an average of 5-6 charging stations per parking garage, the typical total cost would lie somewhere between $150,000 and $249,999. This cost range was considered when constructing cost-effectiveness scenarios.

Scenario Building

Nine analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above)
- Internet research of publicized transit projects.

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[25] "Public Electric Vehicle Charging Infrastructure" (Sustainable Jersey, June 2017), http://www.sustainablejersey.com/actions-certification/actions/?type=1336777436&tx_sjcert_action%5BactionObject%5D=521&tx_sjcert_action%5Baction%5D=getPDF&tx_sjcert_action%5Bcontroller%5D=Action&cHash=e136260b594094a98ecb6f78df43448a; Energetics Incorporated, Clean Communities of Central New York, and Ithaca-Tompkins County Transportation Council, "Tompkins County Plug-in Electric Vehicle Infrastructure Plan" (New York State Energy Research and Development Authority, November 2016), http://tompkinscountyny.gov/files2/itctc/projects/EV/Tompkins%20EVSE%20Site%20Suitability%20FINAL.pdf.

For purposes of this analysis, it was assumed that trip length on average is twenty miles, with average travel speeds of 35 mph. Additionally, useful life of the project is assumed to be seven years.[26] Different charging station types will be able to charge vehicles at different rates, different configurations will accommodate different numbers of vehicles, and project cost will correspondingly vary as well. Across the nine scenarios, two inputs varied: the number of trip offsets per day due to the presence of EVCI project, which varied between 75 to 150 trips per day; and project cost, which was allowed to vary between $150,000 and $250,000.

Methodology

As an illustrative example, consider a new EVCI project.

In this scenario, the following assumptions were used:

- The EVCI project offsets 100 one-way trips per day (250 weekdays per year) by conventional LDVs;
- Each offset conventional LDV trip would have covered twenty miles;
- The average travel speed for offset travel is 35 miles per hour;
- The average fleet-level $PM_{2.5}$ emission rate for EV travel is 1.20665E-5 grams per mile;
- The average fleet-level emission rates for equivalent travel by standard LDVs are 0.0048 grams per mile for $PM_{2.5}$ and 0.3577 grams per mile for NOx;
- The project lifetime is seven years; and
- The project cost is $200,000.

Step One: Annual emissions benefits are identified by multiplying per-mile emission rates by the number of affected trips under the relevant travel speed, and subtracting the remaining brakewear and tirewear PM:

Table 28: Sample Calculation of Annual Emission Benefit of EVCI

Pollutant	**Emissions Reduced (grams/mile)**		**Annual VMT Reduction**	**Annual Emission Benefit (grams)**	**Annual Emission Benefit (tons)**
NOx	0.3577		1,000,000	357,665.68	0.3943
$PM_{2.5}$	0.0048	1.20665E-5	1,000,000	7,267.94	0.008

Step Two: Multiply each of the estimated annual emission benefit by the project lifetime to calculate project-level emission impacts.

Table 29: Sample Calculation of Total Emission Benefits of ECVI

Pollutant	**Annual Emission Benefit (tons)**	**Project Lifetime (years)**	**Lifetime Emission Impact (tons)**
NOx	0.3943	7	2.7598
$PM_{2.5}$	0.008	7	0.0561

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[26] Daniel Chang et al., “Financial Viability of Non-Residential Electric Vehicle Charging Stations” (UCLA Luskin Center for Innovation, August 2012), https://luskin.ucla.edu/sites/default/files/Non-Residential%20Charging%20Stations.pdf.

Step Three: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 30: Sample Calculation of Cost-Effectiveness Estimates for EVCI

Pollutant	Lifetime Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	2.7598	$ 200,000	$72,468.71
$PM_{2.5}$	0.0561	$ 200,000	$ 3,566,287.73

Cost-Effectiveness

The median cost-effectiveness estimates for the range of scenarios are presented in Table 31 below:

Table 31: Median Cost-Effectiveness Estimates (dollars per ton) – EVCI

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Electric Vehicle Charging Infrastructure	$3,566,287.73	$2,628,699.98	$6,742.11	$72,468.71	$106,381.99

Idle Reduction Strategies

Idle reduction strategy projects focus on providing technologies or instituting polices or procedures the reduce vehicle idling emissions. These strategies include truck stop electrification (TSE), retrofitting vehicle power management systems or otherwise upgrading vehicles, and instituting policies in traditionally high-idling areas, such as school or airport drop-off/pick-up areas. Emission impacts were identified as the product of idling emission rates, number of trucks impacted by the reduction strategies, and project lifetimes.

The analyses of scenarios were conducted using outputs from the FHWA CMAQ Emissions Calculator Toolkit, as well as project-level inputs from CMAQ projects and various State Departments of Transportation.[27] Emissions benefits were determined using the CMAQ Toolkit. Note this project category and related analysis focus on heavy-duty trucks and do not address passenger vehicles.

This analysis included the following steps:

- Generate idle time emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in the Toolkit;
- Identify approximate number of heavy-duty trucks impacted by funding;
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

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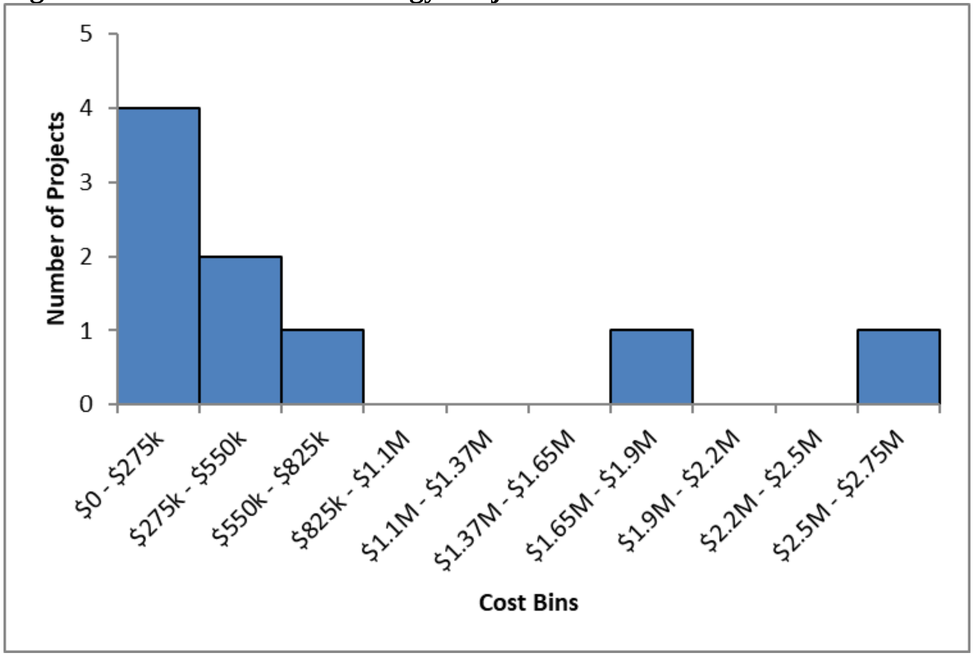
[27] CMAQ project data from the PAS was queried and analyzed. A sample of recent intersection improvement projects was collected from State DOTs through internet research. These data were used to calibrate the analytical scenarios tested.

The PAS contains nine idle reduction strategy projects from 2013 through 2016.[28] The median project cost was approximately $704,000. The distribution of projects costs are shown in Figure 11 below.

Figure 11: Idle Reduction Strategy Project Cost Distribution



The small number of identified projects shows a slight skew to the right with the majority of projects costing less than $700,000. Two larger projects cost $1.9 million and $2.5 million respectively. This cost range was taken into consideration when constructing cost-effectiveness scenarios.

Scenario Building

Twenty analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized projects.

For the purposes of the analysis, it was assumed that the idle reduction strategies were used exclusively on work days (250 times per year), and that the useful life of the projects was ten years. Additionally, it was assumed that each project would impact a range of trucks, but that the primary power units impacted would use diesel fuel. The cost data was based on publicized data as well as PAS data.

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[28] 2016 was chosen as it was the most recent year with full available data.

Table 32: Idle Reduction Strategy Scenarios

Parameter	Value Range
Number of Trucks Annually Impacted	Distributed Range: 150 to 1,000
Project Lifetime	10 years
Project Cost	$100,000 to $1.75M

Methodology

As an illustrative example, consider a scenario involving an idle reduction strategy that upgrades vehicles and reduces idle emissions rates.

In this scenario, we assume the following:

- The idle reduction strategy technology was installed on 400 diesel trucks;
- The project lifetime is ten years; and
- The project cost is $400,000.

Step One: Identify annual emissions impacts by multiplying per-trip emissions by the number of affected trips.

Table 33. Sample Calculation of Annual Emission Benefit from an Idle Reduction Strategy

Pollutant	Idle Emissions Reduced (kilograms/day)	Annual Reduction	Annual Emission Benefit (kilograms)	Annual Emission Benefit (tons)
NOx	389.007	400 Trucks	97,251	107.202
$PM_{2.5}$	5.565		1,391	1.534

Step Two: Identify project-level emission impacts by multiplying each of the estimated annual emissions benefits by the project lifetime.

Table 34. Sample Calculation of Total Emission Impacts from an Idle Reduction Strategy Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	107.202	10	1,072
$PM_{2.5}$	1.534		15

Step Three: Calculate cost-effectiveness estimates by dividing the project cost by the estimated project-level emission impacts:

Table 35. Sample Calculation of Cost-Effectiveness Estimates for an Idle Reduction Strategy Project

Pollutant	Total Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	1,072	$400,000	$373
$PM_{2.5}$	15		$26,082

Cost-Effectiveness

The median cost-effectiveness estimates for the range of idle reduction strategy project scenarios are presented in Table 36 below:

Table 36. Median Cost-Effectiveness Estimates (dollars per ton) – Idle Reduction Strategy Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Idle Reduction Strategies	$29,450	$26,187	$1,017	$421	$1,924

Bicycle and Pedestrian Improvement Projects

Bicycle and pedestrian projects provide infrastructure facilitating walking and bicycling in place of travel by LDVs. Sample projects include constructing sidewalks, crosswalks, on-street bikeways, and separated bicycle and walking paths. Cost-effectiveness estimate scenarios assumed no associated public transit service modifications and thus no emission impacts involving public transit: both additional public transit person-trips chained to new bicycle and walking trips and changes from transit to non-motorized trips were assumed to have a negligible effect on transit vehicle emissions.

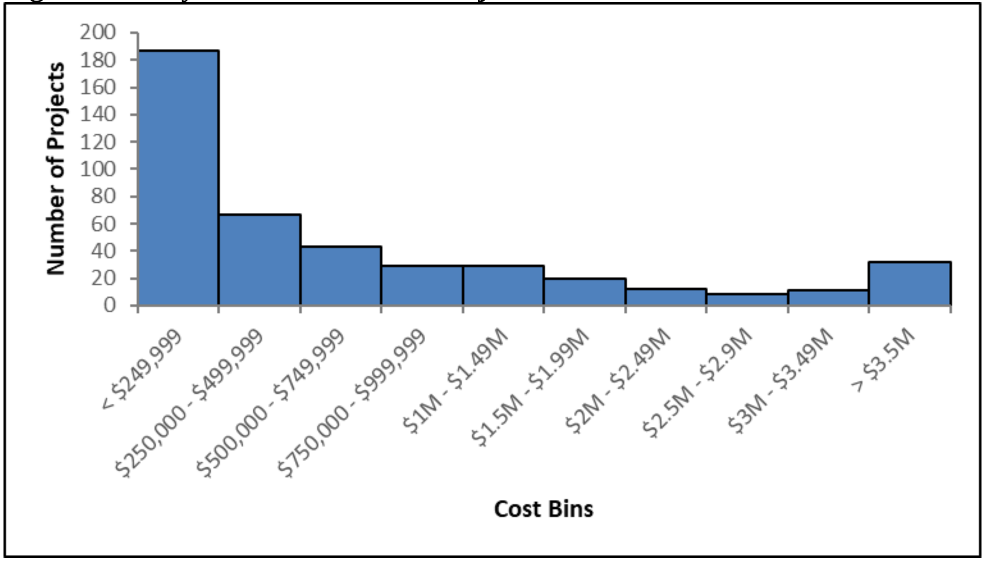
This analysis included the following steps:

- Generate emission rates estimates for offset LDV trips from national-average fleet-level MOVES2014b runs for a range of relevant travel speeds.
- Estimates of the volume of offset light-duty driving from previous CMAQ assessment studies and some other sources
- Project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains 354 bicycle and pedestrian projects identified for analysis from 2016. The median project cost was approximately $299,251. The distribution of project costs is shown in Figure 12 below.

Figure 12: Bicycle and Pedestrian Project Cost Distribution



Project costs are skewed to the left, with the majority of the projects costing less than $250,000 each. This compares with national surveys of bicycle and pedestrian infrastructure costs, which find that the average cost of bicycle lanes and multiuse paths is $228,760 per mile.[29] This cost range was taken into consideration when constructing cost-effectiveness scenarios.

Scenario Building

Nine analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above),
- Estimates of the volume of offset light-duty driving from CMAQ assessment studies and published work.

For the purposes of this analysis, it was assumed that average travel speed is at 35 mph, the facilities are used about 250 times per year, and the useful life was at fifteen years. A single round-trip distance of 0.9 miles was assumed based on an analysis of the 2017 National Household Travel Survey (NHTS). [30] This value represents the mean one-way trip distance of the middle 50% of trips taken by walking or bicycling, multiplied by two. This method removed extreme outliers and provides a representative typical trip.

Three inputs varied across the nine scenarios. The daily volume of offset light-duty trips varied between 325, 375, and 425. The 2015 CMAQ assessment study reported an estimated average increase of 374

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[29] Max Bushell et al., “Costs for Pedestrian and Bicyclist Infrastructure Improvements” (University of North Carolina - Chapel Hill: UNC Highway Safety Research Center, October 2013).

[30] Federal Highway Administration. (2017). 2017 National Household Travel Survey, U.S. Department of Transportation, Washington, DC. Available online: https://nhts.ornl.gov.

bike/walk trips per day due to infrastructure.[31] Buehler and Pucher reported that modal shifts for 90 large cities in the US was 352 trips per day.[32]

Table 37: Bicycle and Pedestrian Improvement Project Scenarios

Parameter	Value Range
Trip shifts from LDV to Bike/Ped	325; 375; 425
Days Used Per Year	250
Typical Round-Trip Distance	0.9 miles
Annual VMT Reduction	162,500; 187,500; 212,500
Travel Speed	35 mph
Project Lifetime	15 years
Project Cost	\$200,000; \$250,000; \$300,000

Methodology

As an illustrative example, consider a new bicycle lane along an existing roadway. In this scenario, the following assumptions were applied:

- The existence of a bicycle lane will shift 375 trips per day from LDVs to bicycle or walking.
- The path will be used 250 days per year.
- The average light-duty emission rates for travel at 35 miles per hour are 0.3716 grams per mile for NOx and 0.0126 for $PM_{2.5}$.
- The project lifetime is fifteen years;
- The project cost per mile is $250,000.

Step 1: Identify annual emission benefit by multiplying per-trip emissions by the number of affected trips.

Table 38: Sample Calculation of Annual Emission Benefit from a Bicycle Path Project

Pollutant	Emissions Reduced (grams/mile)	Annual VMT Reduction	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	0.3716	84,375	31,357.5	0.0346
$PM_{2.5}$	0.0126		1061.3	0.0012

Step 2: Multiply each of the estimated annual emission benefit by the project lifetime to calculate project-level emission impacts.

Table 39: Sample Calculation of Total Emission Impacts from a Bicycle Path Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime	Lifetime Emission Impact (tons)
NOx	0.0346	15	0.5185

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[31] Battelle and Texas A&M Transportation Institute, “Air Quality and Congestion Mitigation Measure Outcomes Assessment Study: Final Technical Report” (Washington DC: US Federal Highway Administation, September 2014), https://www.fhwa.dot.gov/environment/air_quality/cmaq/research/outcomes_assessment/technical_report/index.cfm.

[32] R Buehler and J Pucher, “Cycling to Work in 90 Large American Cities: New Evidence on the Role of Bike Paths and Lanes,” *Transportation* 39, no. 2 (2012): 409–32.

$PM_{2.5}$	0.0012		0.0176

Step 3: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 40: Cost-Effectiveness Estimates for a Bicycle Path Project

Pollutant	**Lifetime Emission Impact (tons)**	**Project Cost**	**Cost-Effectiveness (dollars per ton)**
NOx	0.5185	$ 250,000	$482,173
$PM_{2.5}$	0.0176		$14,245,981

Cost-Effectiveness

The median cost-effectiveness estimates for the range of scenarios are presented in Table 41 below:

Table 41: Median Cost-Effectiveness Estimates (dollars per ton) – Bicycle and Pedestrian Projects

Project Type	**$PM_{2.5}$**	**PM_{10}**	**CO**	**NOx**	**VOCs**
Bike and Pedestrian Projects	$14,245,981	$3,951,490	$42,432	$482,173	700,938

Intermodal Freight Facilities and Programs

Freight and intermodal projects focus on providing new options at port facilities for reducing heavy-duty truck trips and encouraging the transfer to rail or other modes, resulting in an emission reduction and also increased capacity and time-savings and more efficient port operations. Emission impacts were identified as the product of per-mile emission rates and activity totals across mitigated heavy-duty-vehicle trips and project lifetimes. Note that this analysis does not include the contribution of emissions from the new mode (e.g., rail or barge), in line with the 2015 cost-effectiveness study. The increase in rail miles or rail hours (or corresponding barge activity) from an intermodal project is difficult to estimate based on the CMAQ Public Access Database. Project sponsors typically report emissions benefits based solely on the number of truck trips diverted and do not subtract emissions from the replacement mode.

In addition, intermodal freight projects may use existing rail lines and vessels to move products and may not require purchase of a new locomotive or marine engine. Therefore, the amount of truck VMT diverted was assumed to provide a reasonable estimate of emission benefits for the analysis. This methodology can potentially be refined given more detailed CMAQ reporting data and mode shift data.

Heavy-duty truck vehicles simulated in this analysis are all assumed to use diesel fuel; on-road vehicle types simulated include both short- and long-haul single-unit and combination trucks. Total emissions and cost-effectiveness comparisons are based on total tonnage and dollars per ton bases.

This analysis included the following steps:

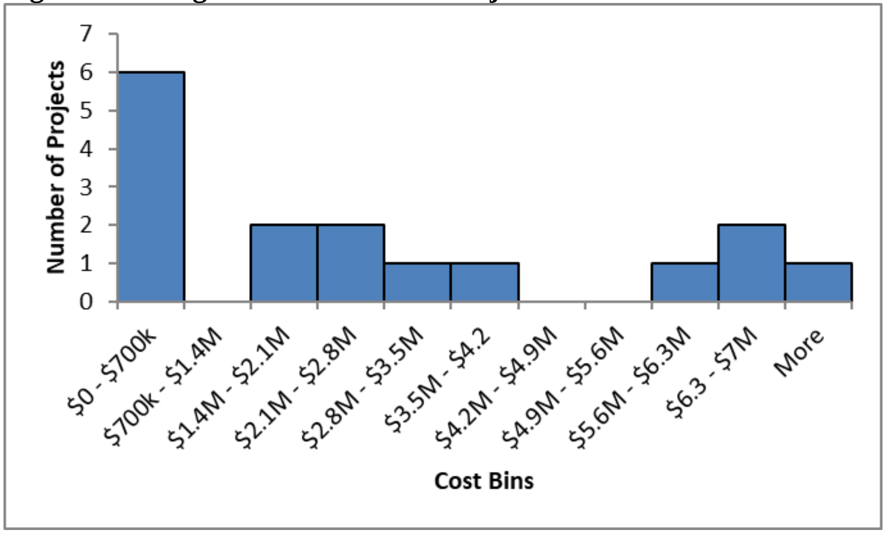
- Generate heavy-duty truck per-mile and rail per-hour emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO;

- Identify heavy-duty vehicle travel activity estimates (daily and annual VMT) reduced through projects;
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The CMAQ Public Access Database contains sixteen freight and intermodal projects from 2014 through 2016.[33] The median project cost was approximately $3.1 million. Fifteen of the sixteen projects were under $7 million in total cost, and one large project was undertaken for $12.5 million. The distribution of projects costs are shown in Figure 13 below.

Figure 13: Freight and Intermodal Project Cost Distribution



As shown above, project costs are slightly skewed to the right. While a number of projects were under $700,000, a wide range of projects exists. This is based on the wide range of activities within this project type, which range from crane rehabilitations to major infrastructure construction. This cost range was taken into consideration when building and analyzing the scenarios, which focused on rail infrastructure projects.

Scenario Building

Twelve analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of relevant publicized projects.

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[33] 2016 was chosen as it was the most recent year with full available data.

For the purposes of the analysis, it was assumed that the port facilities where the freight and intermodal projects occurred operate year round and the activity is therefore dispersed over 365 days. Additionally it was assumed that the useful life of the projects was twenty years.

Several inputs varied across the twenty scenarios (Table 42). The activity rate assumptions were based on anticipated port operations. The cost data was based on public data as well as PAS data.

Table 42: Intermodal and Freight Scenarios

Parameter	Value Range
Annual Truck Trips Reduced	Distributed Range:
Annual Truck VMT Reduced	Distributed Range:
Days per Year	250 days
Project Lifetime	20 years
Project Cost	\$800,000 to \$1.9M

Methodology

As an illustrative example, consider a scenario involving a rail track and switch addition to a port that will encourage transfers from heavy-duty trucks to rail.

In this scenario, we assume the following:

- The average heavy-duty truck emission rates, which combine running, starts, idling, and hotelling emissions, are 5.605 grams per mile for NOx and 0.198 grams per mile for $PM_{2.5}$;
- There average rail emissions rates are 127.272 grams per hour for NOx and 13.955 grams per hour for $PM_{2.5}$;
- The truck trips diverted span 25 miles on average, and there are expected to be 60,000 truck trips diverted per year, for a total annual VMT diversion of 1.5 million miles;
- The project lifetime is twenty years; and
- The project cost is \$1,000,000.

Step One: Identify annual emissions impacts by multiplying per-trip emissions by the number of affected trips:

Table 43: Sample Calculation of Annual Emission Impacts from a Freight and Intermodal Project

Pollutant	Heavy-Duty-Vehicle Emission Mitigation (grams/mile)	Annual VMT Reduction	Annual Emission Impact (grams)	Annual Emission Impact (tons)
NOx	5.605	1,500,000	8407823.915	8.807
$PM_{2.5}$	0.198		296328.9471	0.276

Step Two: Identify project-level emission impacts by multiplying each of the estimated annual emission impacts by the project lifetime:

Table 44: Sample Calculation of Total Emission Impacts from a Freight and Intermodal Project

Pollutant	Annual Emission Impact (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	8.807	20	184.871
$PM_{2.5}$	0.276		6.515

Step Three: Calculate cost-effectiveness estimates by dividing the project cost by the estimated project-level emission impacts (heavy-duty vehicle emissions reduced):

Table 45: Sample Calculation of Cost-Effectiveness Estimates for a Freight and Intermodal Project

Pollutant	Total Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	184.871	$1,000,000	$5,409
$PM_{2.5}$	6.515		$153,487

Cost-Effectiveness

The median cost-effectiveness estimates for the range of freight and intermodal project scenarios are presented in Table 46 below:

Table 46: Median Cost-Effectiveness Estimates (dollars per ton) – Freight and Intermodal Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Freight and Intermodal	$217,360	$154,839	$23,677	$7,661	$91,297

Subsidized Transit Fares

Subsidized transit fare programs seek to stimulate 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 (e.g., ozone action days). The estimated emission impacts centered on travel shifts from LDV to transit. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated LDV trips (less additional bus emissions), and project lifetimes.

This analysis included the following steps:

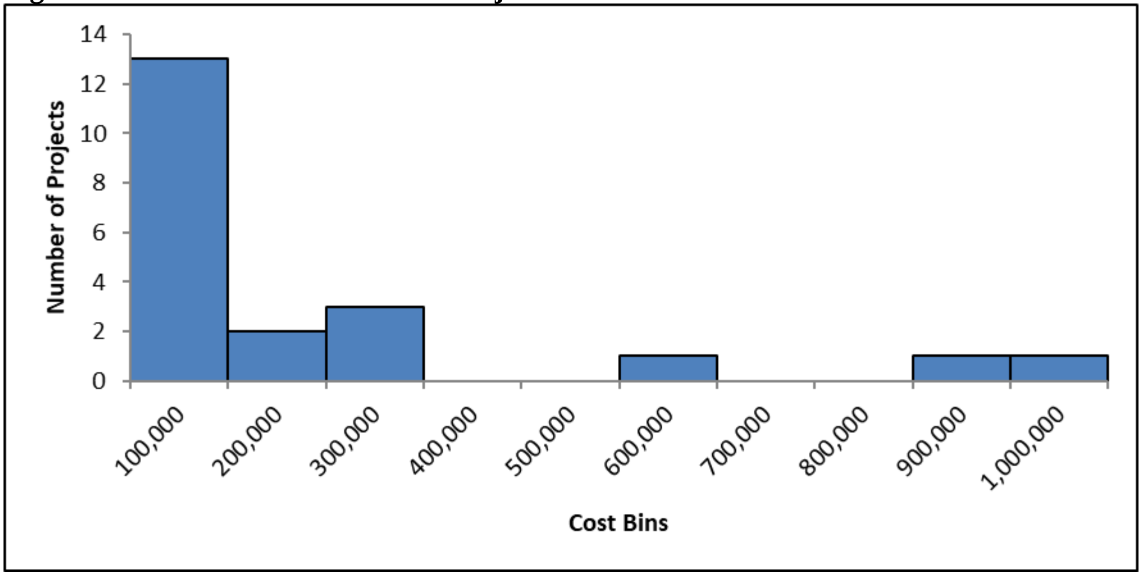
- Generate light-duty and bus per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for the range of relevant travel speeds;
- Identify estimates of LDV travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of new bus travel activity (daily and annual VMT) associated with projects;
- Identify Project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains 21 subsidized transit fare projects identified for analysis from 2016, with a median project cost of approximately $204,000 (

Figure 14).[34]

Figure 14: Subsidized Transit Fare Project Cost Distribution



Project costs are clearly skewed to the right, with the majority of the projects costing less than $200,000 each. Most fare subsidy programs are relatively low in cost compared to other transit projects. The determined cost range was taken into consideration when building and analyzing the scenarios.

Scenario Building

Twenty analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized transit projects.

For the purposes of the analysis, it was assumed that travelers who converted to transit reduced their LDV use by, on average, ten miles (five miles each way during the morning and afternoon commutes). Additionally, it was assumed that he programs were funded and operated for three years.

Across the twenty scenarios, three inputs were varied. The number of travelers who converted to transit varied between 4,000 and 6,250 riders. The program was assumed to operate ten days per year, and the project cost was assumed to vary between $50,000 and $900,000.

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[34] 2016 was chosen as it was the most recent year with full available data.

These assumptions were based on projects publicized by transit agencies (including TriMet and Los Angeles County MTA). Table 47 below shows the scenario parameters and value ranges.

Table 47: Subsidized Transit Fare Scenarios

Parameter	Value
Daily Shift to Transit	4,000 to 6,250 riders
Days per Year	10 days
Daily Miles Reduced (per Vehicle)	10 miles
Project Lifetime	3 years
Project Cost	$50,000 to $900,000

Methodology

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

In this scenario, the following assumptions were used:

- The fare-free program leads to 4,500 additional riders per day;
- There are an average of ten ozone action days per year covered by the project;
- The average LDV miles avoided by new passengers is ten miles and assumes the average work trip occupancy is 1.13;
- There are no additional bus emissions associated with the new passengers;
- The average light-duty emission rates are 0.369 grams per mile for NOx and 0.012 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; and
- The total project cost is $550,000.

Step One: Identify annual emissions benefits by multiplying per-trip emissions by the number of affected trips:

Table 48. Sample Calculation of Annual Emission Benefit from a Subsidized Transit Fare Project

Pollutant	Emissions Reduced (grams/mile)	Annual VMT Reduction	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	0.369	398,230	146,836	0.162
$PM_{2.5}$	0.012		4,969	0.005

Step Two: Multiply each of the estimated annual emissions benefits by the project lifetime to calculate project-level emission impacts:

Table 49. Sample Calculation of Total Emission Benefits from a Subsidized Transit Fare Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	0.162	3	0.332
$PM_{2.5}$	0.005		0.016

Step Three: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates:

Table 50. Cost-Effectiveness Estimates for a Subsidized Transit Fare Project

Pollutant	Lifetime Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	0.332	$550,000	$1,132,675
$PM_{2.5}$	0.016		$33,469,232

Cost-Effectiveness

Table 51 presents the median cost-effectiveness estimates for the range of subsidized transit fare project scenarios:

Table 51. Median Cost-Effectiveness Estimates (dollars per ton) – Subsidized Transit Fare Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Subsidized Transit Fares	$36,926,797	$10,163,738	$110,850	$1,249,687	$1,830,196

Transit Service Expansion

Transit service expansion projects encourage mode shift to public transit by increasing the availability of transit service in a given region. Consistent with the full range of projects in the analysis, the entire range of relevant costs were considered when evaluating transit service projects, rather than focusing solely on the subset representing CMAQ funding. The estimated emission impacts reflect modal shifts from LDV to transit. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated LDV trips (less additional bus emissions), and project lifetimes.

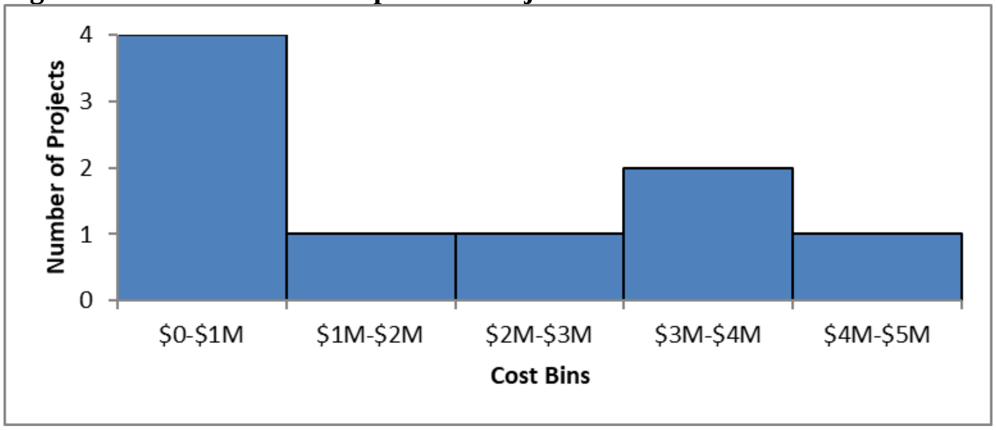
This analysis included the following steps:

- Generate light-duty and bus per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for the range of relevant travel speeds;
- Identify estimates of LDV travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of new bus travel activity (daily and annual VMT) associated with projects;
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains nine projects identified for analysis from 2016.[35] The median project cost was approximately $1.8 million (Figure 15).

Figure 15: Transit Service Expansion Project Cost Distribution



Project costs are skewed to the right, with the majority of the projects costing less than $1 million each. However, despite the small sample there is a clear range of project costs, up to approximately $5 million. The determined cost range was taken into consideration when building and analyzing the scenarios.

Scenario Building

Twenty analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized transit projects.

For the purposes of the analysis, it was assumed that two types of service expansion projects occurred: new transit service bus routes, and increased capacity on existing transit service bus routes. In these scenarios, users would convert to transit exclusively on work days (250 times per year). Light rail projects were not included in the service expansion category.

Five inputs varied across the twenty scenarios (Table 52). For the ten new transit service bus route scenarios, the range of daily travelers shifting to transit was 3,000 to 6,600 riders. The assumed daily LDV miles traveled avoided was 25 miles. The assumed new daily transit bus vehicle miles traveled ranged from 250 to 400. The increase in transit bus vehicle emissions was subtracted from the avoided light-duty emissions. The assumed project lifetime that the expanded service would be funded and operated was five years. The assumed project costs ranged from $1 million to $3.2 million.

For the ten increased capacity scenarios, the range of daily travelers shifting to transit was 1,000 to 1,900 riders. The assumed daily LDV miles traveled avoided was twenty. The assumed project lifetime that the

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[35] 2016 was chosen as it was the most recent year with full available data.

increased capacity would be funded and operated was three years. The assumed project costs ranged from $500,000 to $950,000.

These assumptions were based on projects publicized by State DOTs (including Louisiana DOT), transit agencies (including Nova Transit), and local governments (including Athens-Clarke County, Georgia).

Table 52: Transit Service Expansion Scenarios.

Parameter	Value
Daily Shift to Transit	3,000 to 6,600 riders for new routes 1,000 to 1,900 riders for increased capacity
Days per Year	250 days
Daily Miles Reduced (per Vehicle)	25 miles for ne555w routes 20 miles for increased capacity
Daily New Bus VMT	350 to 500 miles traveled for new routes 0 miles traveled for increased capacity
Project Lifetime	5 years for new routes 3 years for increased capacity
Project Cost	$1M to $3.2M for new routes $500,000 to $950,000 for increased capacity

Methodology

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

In this scenario, the following assumptions were used:

- The new route operates approximately 14 runs (in both directions) each weekday (250 days per year);
- The route covers 25 miles round-trip;
- Average daily ridership on the route is 3,000 people;
- Each transit trip offsets an average of ten miles by LDV (per transit passenger);
- The average light-duty emission rates are 0.369 grams per mile for NOx and 0.012 grams per mile for $PM_{2.5}$;
- The average emission rates for the new bus service are 6.138 grams per mile for NOx and 0.154 grams per mile for $PM_{2.5}$;
- The funding for the new route covers a period of five 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 $1,000,000.

Step One: Identify gross annual emissions benefits by multiplying per-trip LDV emissions by the number of offset trips:

Table 53. Sample Calculation of Gross Annual Emission Benefit from a New Bus Route

Pollutant	Emissions Reduced (grams/mile)	Annual LDV VMT Reduction	Annual Emission Benefit (grams)
NOx	0.369	16,592,920	6,118,157
$PM_{2.5}$	0.012		752,261

Step Two: Identify net annual emissions benefits by subtracting new annual bus emissions from the gross annual emissions benefits from Step One:

Table 54. Sample Calculation of Gross Annual Emission Benefit from a New Bus Route

Pollutant	Annual Emission Benefit (grams)	New Bus Emissions (grams/mile)	Annual New Bus VMT	Annual New Bus Emissions (grams)	Annual Net Emission Impact (tons)
NOx	**6,118,157**	**6.138**	**87,500**	**537,064**	**6.152**
$PM_{2.5}$	**752,261**	**0.154**		**13,487**	**0.213**

Step Three: Calculate project-level emission impacts by multiplying estimated annual emissions benefits by the project lifetime:

Table 55. Sample Calculation of Total Emission Impacts for a New Bus Route

Pollutant	Annual Net Emission Impact (tons)	Project Lifetime (years)	Lifetime Emission Impact (tons)
NOx	6.152	5	30,761
$PM_{2.5}$	0.213		1.067

Step Four: Estimate cost-effectiveness by dividing the project cost by the estimated project-level emission impacts:

Table 56. Cost-Effectiveness Estimates for a New Bus Route

Pollutant	Lifetime Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
CO	30.761	$1,000,000	$32,509
NOx	1.067		$937,344

Cost-Effectiveness

Table 57 presents the median cost-effectiveness estimates for the range of transit service expansion project scenarios analyzed:

Table 57. Median Cost-Effectiveness Estimates (dollars per ton) – Transit Expansion Projects

Project Type	$PM_{2.5}$	PM_{10}	**CO**	**NOx**	**VOCs**
Transit Service Expansion	$2,035,198	$556,301	$6,029	$69,251	$99,652

Transit Amenity Improvements

Transit facility and amenity improvement projects focus on enhancing the experience of transit users, in turn shifting travel demand to public transit. Emission impact scenarios modeled the substitution of LDV trips for transit. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated LDV trips (less the additional bus emissions), and project lifetimes.

This analysis included the following steps:

- Generate light-duty and bus per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES2014b for the range of relevant travel speeds;
- Identify estimates of LDV travel activity (daily and annual VMT) reduced through projects;
- Identify estimates of new bus travel activity (daily and annual VMT) associated with projects;
- Identify Project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains twenty transit amenity improvement projects from 2016, with project costs averaging approximately $24.9 million (

Figure 16).[36]

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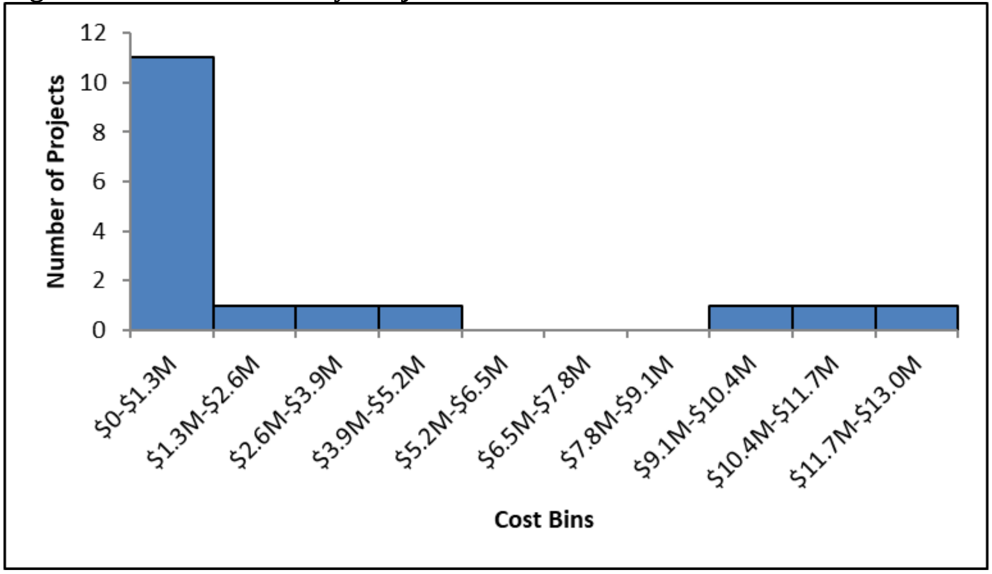
[36] 2016 was chosen as it was the most recent year with full available data.

Figure 16: Transit Amenity Project Cost Distribution



Project costs are skewed to the right, with the majority of projects costing less than $1 million each. However, there is a very wide range of project costs, with several projects costing over $10 million and two projects costing over $100 million. The two large projects included major vehicle overhauls and installing bus rapid transit facilities. However, since typical amenity improvement projects are less ambitious and therefore cost less, these outliers were not considered when building and analyzing cost-effectiveness scenarios.

Scenario Building

Fifteen analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized transit projects.

For the purposes of the analysis, it was assumed that three types of amenity improvement projects occurred: bus stop rehabilitation, improved fare collection systems, and enhanced bicycle and pedestrian connections. These scenarios assume that users would convert to transit exclusively on work days (250 times per year), and that the useful life of the amenities was fifteen years.[37] Additionally, it was assumed that travelers who converted to transit and utilized the amenities reduced their LDV use by an average of ten miles (five miles each way in the morning and afternoon).[38] Finally, transit vehicles operating with the enhanced amenities were assumed to already be in use, and therefore incurred no additional emissions.

Across the fifteen scenarios, two input were varied: the number of users who shifted, on average, to transit and the project costs (Table 58). For the bus stop rehabilitation scenarios, it was assumed that a

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[37] “Minimal Asset Useful Life Standards for FTA Grants” (Virginia Department of Rail and Public Transportation, November 30, 2015), https://olga.drpt.virginia.gov/documents/forms/DRPT%20Asset%20Useful%20Life%20Chart.pdf.

[38] This assumption relied on a similar analysis of the 2017 NHTS as used in the Bicycle and Pedestrian Improvement Projects section, focused instead on transit trips.

range of 100 to 200 users converted to transit per day, at a cost ranging from $140,000 to $500,000. For the improved fare collection systems scenarios, it was assumed that a range of 200 to 300 users converted to transit per day at a cost ranging from $500,000 to $1 million. For the enhanced bicycle and pedestrian connection scenarios, it was assumed that a range of 300 to 400 users converted to transit per day at a cost ranging from $750,000 to $1.4 million. These assumptions were based on available transit literature (Table 58).

Table 58: Transit Amenity Scenarios

Parameter	Value
Daily Shift to Transit	100 to 200 riders for bus stop rehabilitation 200 to 300 riders for improved fare collection 300 to 400 riders for enhanced connections
Days per Year	250 days
Daily Miles Reduced (per Vehicle)	10 miles
Project Lifetime	10 years
Project Cost	$140,000 to $500,000 riders for bus stop rehabilitation $50,000 to $1M riders for improved fare collection $750,000 to $1.4M riders for enhanced connections

Methodology

As an illustrative example, consider a scenario involving the installation of a new traveler information system, which would improve users' abilities to time their transfers and make connections.

In this scenario, we assume the following details:

- The average light-duty emission rates are 0.369 grams per mile for NOx and 0.012 grams per mile for $PM_{2.5}$;
- The project stimulates the shift of 300 LDV trips per day to public transit for 250 days each year, and assumes the average work trip vehicle occupancy is 1.13;
- There are no changes in transit service provided, only increases in utilization;
- The average LDV round trip replaced by a public transit trip is ten miles;
- The project lifetime is ten years; and
- The project cost is $750,000.

Step One: Identify Annual emissions benefits by multiplying per-trip emissions by the number of affected trips:

Table 59. Sample Calculation of Annual Emission Benefit from a Transit Amenity Project

Pollutant	Emissions Reduced (grams/mile)	Daily VMT Reduction	Annual VMT Reduction	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	0.36872095	2,655	663,717	244,726	0.270
$PM_{2.5}$	0.01247836			8,282	0.009

Step Two: Identify project-level emission impacts by multiplying annual emissions benefits by the project lifetime:

Table 60. Sample Calculation of Total Emission Impacts from a Transit Amenity Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	0.270	15	4.046
$PM_{2.5}$	0.009		0.137

Step Three: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 61. Sample Calculation of Cost-Effectiveness Estimates for a Transit Amenity Project

Pollutant	Total Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	4.046	$750,000	$185,347
$PM_{2.5}$	0.137		$5,476,783

Cost-Effectiveness

Table 62 presents the median cost-effectiveness estimates for the range of transit amenity improvement project scenarios:

Table 62. Median Cost-Effectiveness Estimates (dollars per ton) – Transit Amenity Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Transit Amenity Improvements	$5,476,783	$1,507,431	$16,441	$185,347	$271,445

Intersection Improvements

This section reviews the analysis of projects involving improvements to intersections, namely reconstructed or repurposed lanes (i.e., adding left-turn lanes). These projects focus on the use of engineering approaches to improve the flow of traffic through intersections and along corridors. The analyses of scenarios were conducted using outputs from the FHWA CMAQ Emissions Calculator Toolkit and project-level inputs from CMAQ projects and various State departments of transportation.[39] Emission rate data were determined using the CMAQ Toolkit.

Distinct to other project types, each of the intersection improvement scenarios involved a reduction in delay, generally improving by one level of service, from E to D or from F to E.[40] All together, one hundred scenarios were included in the analysis.

This analysis included the following steps:

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[39] CMAQ project data from the PAS was queried and analyzed. A sample of recent intersection improvement projects was collected from State DOTs through internet research. These data were used to calibrate the analytical scenarios tested.

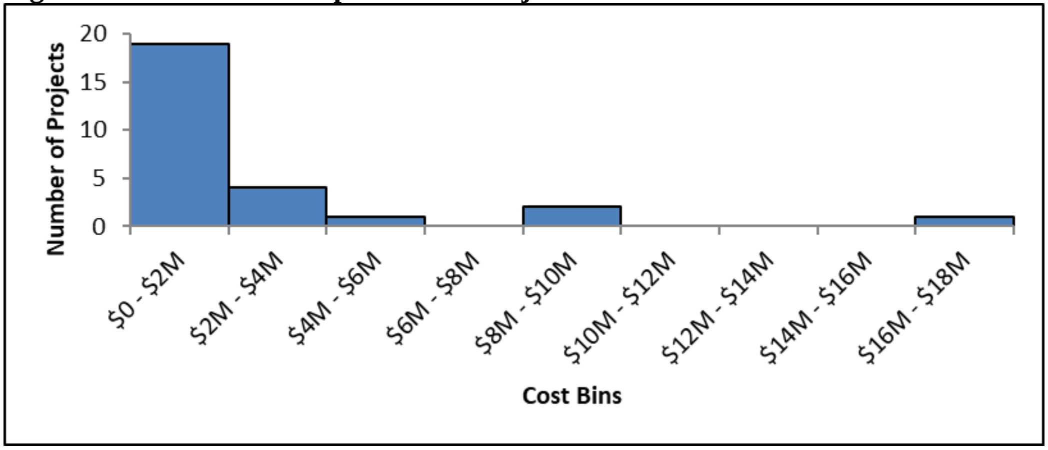
[40] "Highway Capacity Manual: Level of Service Reference Table, Exhibit 21-2" (AASHTO, 2010).

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

Cost Analysis

The PAS contains 27 intersection reconstruction projects identified for analysis from 2016.[41] The identified projects included adding acceleration and deceleration lanes, turning lanes, curb and ramp facilities, diverging interchanges, and/or realignments. The median project cost was approximately $2.2 million. The distribution of projects costs are shown in Figure 12 below.

Figure 17: Intersection Improvement Project Cost Distribution



A majority of the funded intersection improvement projects were under $2 million and focused primarily on adding turn lanes or signals. The distribution skews right, as small number of projects consisted of large reconstruction and corridor-level improvements that included intelligent transportation technology.

Scenario Building

One hundred analytical scenarios were developed using four primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above),
- The FHWA CMAQ Emissions Calculator Toolkit, and
- Internet research of publicized projects.

Using the CMAQ Toolkit, a range of input values were needed to determine the scenarios. The range, and the proportion of each value used across the one hundred scenarios, is described in Table 63 below.

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[41] 2016 was chosen as it was the most recent year with full available data.

Table 63: Intersection Improvement Scenarios

Parameter	Value
Area Type	33% Rural; 67% Urban
Business District	50% Yes; 50% No
Peak Hours per Day	4 hours
Existing Intersection Design	50% Signalized; 50% Unsignalized; 1-3 lanes; No existing turn lanes
Average Annual Daily Travel	Distributed Range: 5,000 to 40,000
Peak Hour Volume	Distributed Range: 500 to 3,500
Truck Percentage	6%
Existing Delay	35 to 50 seconds per vehicle
Cycle Length	90 Seconds
Improved Intersection Design	Left turn lanes and phases added; Right turn phases added
Project Lifetime	20 years
Project Cost	Distributed Range: $400,000 to $2.8 Million

Methodology

As an illustrative example, consider a scenario involving improvements to an urban, single lane, signalized intersection.

In this scenario, the following assumptions were used:

- Average annual daily traffic is approximately 19,800 on the first roadway and 20,700 on the second roadway;
- The peak hours volume is approximately 1,540 vehicles and 1,580 vehicles on the two roadways respectively;
- The existing delay is 35 – 40 seconds per vehicles for the two roadways;
- A left turn lane was added to both roadways and both right and left phases were added;
- The project lifetime is twenty years; and
- The project cost is $920,000.

Step One: Improving the average travel speed by adding turn lanes and phases would lead to the following reductions in emissions of NOx and $PM_{2.5}$:

Table 64. Sample Calculation of Emissions Benefit from an Intersection Improvement

Pollutant	Emissions Reduced (kilograms per day)	Lifetime Emission Impact (Tons)
NOx	0.282	1.482
$PM_{2.5}$	0.021	0.111

Step Two: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 65. Cost-Effectiveness Estimates from an Intersection Improvement

Pollutant	**Lifetime Emission Impact (tons)**	**Project Cost**	**Cost-effectiveness (dollars per ton)**
NOx	1.482	$920,000	$620,876
$PM_{2.5}$	0.111		$8,287,586

Cost-Effectiveness

The median cost-effectiveness estimates for the range of intersection improvement scenarios are presented in Table 12 below:

Table 66. Median Cost-Effectiveness Estimates (dollars per ton) – Intersection Improvement Projects

Project Type	$PM_{2.5}$	PM_{10}	**CO**	**NOx**	**VOCs**
Intersection Improvement	$13,255,774	$12,130,195	$447,858	$993,075	$3,685,105

Roundabouts

These projects focus on the use of engineering approaches to improve the flow of traffic through intersections and along corridors through the construction of roundabouts... The analyses of scenarios were conducted using outputs from the FHWA CMAQ Emissions Calculator Toolkit and project-level inputs from CMAQ projects and various State departments of transportation.[42] Emission rate data were determined using the Toolkit.

Similar to the intersection improvement project type, each of the roundabout scenarios involved a reduction in delay. In all, thirty scenarios were included in the analysis.

This analysis included the following steps:

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

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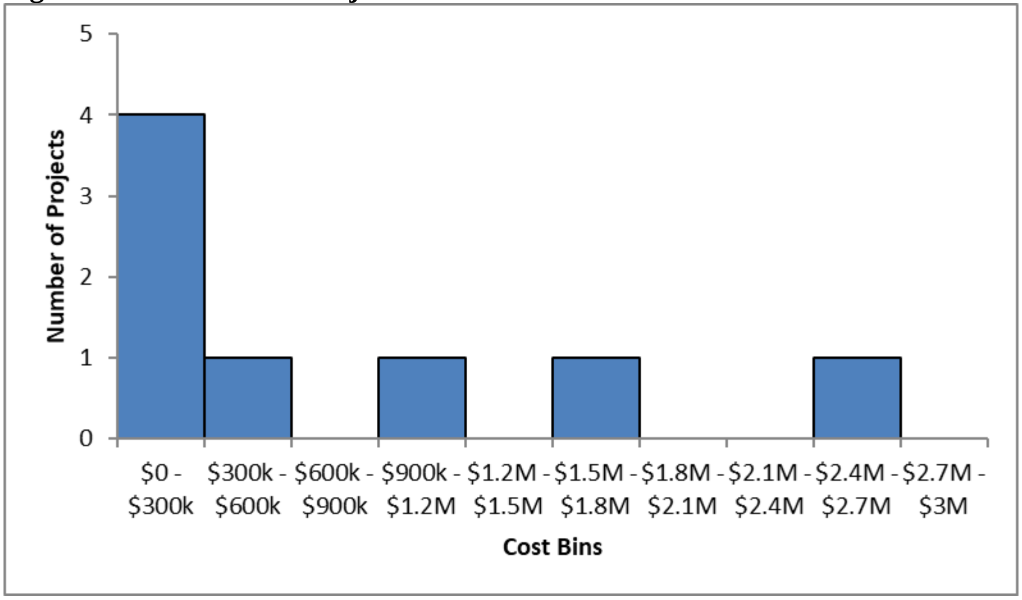
[42] CMAQ project data from the PAS was queried and analyzed. A sample of recent traffic signal synchronization projects was collected from State DOTs through internet research. These data were used to calibrate the analytical scenarios tested.

Cost Analysis

The PAS contains eight roundabout-related projects identified for analysis from 2016.[43] The identified projects included adding acceleration and deceleration lanes, turning lanes, curb and ramp facilities, diverging interchanges, and/or realignments. The median project cost was approximately $867,000. The distribution of project costs is shown in Figure 18 below.

Figure 18: Roundabout Project Cost Distribution



A majority of the funded roundabout projects were under $300,000 and focused primarily on modifying existing, signalized intersections. A small number of projects consisted of larger reconstruction of the existing intersections. Overall, there were only a few very expensive ($2M+) projects, i.e. the distribution is not very skewed. Many projects that included roundabouts also included other activities, which is why a limited number of roundabout only projects (eight total) were available to sample.

Scenario Building

Thirty analytical scenarios were developed using four primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above),
- The FHWA CMAQ Emissions Calculator Toolkit, and
- Internet research of publicized projects.

Using the CMAQ Toolkit, a range of input values were needed to determine the scenarios. The range, and the proportion of each value used across the thirty scenarios, is described in the table below.

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[43] 2016 was chosen as it was the most recent year with full available data.

Table 67: Roundabout Scenarios

Parameter	Value
Area Type	33% Rural; 67% Urban
Business District	50% Yes; 50% No
Peak Hours per Day	4 hours
Existing Intersection Design	50% Signalized; 50% Unsignalized; 3-4 approaches
Existing Traffic Flow	Distributed Range: 15%-20% left turns, 25%-85% right turns
Average Annual Daily Travel	Distributed Range: 5,000 to 32,000 vehicles
Peak Hour Volume	Distributed Range: 400 to 1,700
Truck Percentage	6%
Existing Delay	55-65 seconds per Vehicle
Improved Intersection Design	Distributed Range: 1-2 circulating roundabout lanes; 3-4 approaches
Project Lifetime	20 years
Project Cost	Distributed Range: $250,000 to $2.6 million

Methodology

As an illustrative example, consider a scenario involving an urban, three-approach, signalized intersection, converted to being a roundabout.

In this scenario, the following assumptions were used:

- Average annual daily traffic volume ranges from 18,000 to 22,000 vehicles across the three approaches to the intersection;
- The average delay ranges from 55 to 65 seconds per vehicles across the three approaches to the intersection;
- The left turn percentage ranges from 15% to 20% and the average right turn percentage ranges from 80% to 85% across the three approaches to the intersection;
- Two of the approaches have two lanes and one of the approaches has one lane, the roundabout has two circulating lanes;
- The project lifetime is twenty years; and
- The project cost is $1.25 million.

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

Table 68. Sample Calculation of Emissions Benefit from a Roundabout Installation

Pollutant	Emissions Reduced (kilograms per day)	Lifetime Emission Impact (Tons)
NOx	0.715	3.940
$PM_{2.5}$	0.262	1.445

Step Two: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 69. Cost-Effectiveness Estimates for a Roundabout Installation

Pollutant	Lifetime Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	3.940	$1,250,000	$317,258
$PM_{2.5}$	1.445		$864,776

Cost-Effectiveness

The median cost-effectiveness estimates for the range of roundabout scenarios are presented in Table 70 below:

Table 70. Median Cost-Effectiveness Estimates (dollars per ton) – Roundabout Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Roundabouts	$1,091,411	$5,098,858	$188,255	$417,433	$1,549,013

Traffic Signal Synchronization

This analysis involves the improvement of traffic flow attributed to projects involving traffic signal improvements and synchronization, namely adding traffic signals or synchronizing corridors across several signals. These projects focus on the use of engineering approaches to improve the flow of traffic through intersections and along corridors. The scenario analyses were conducted using outputs from the CMAQ Toolkit and project-level inputs from CMAQ projects and various State departments of transportation.[44] Emission rate data were determined using the Toolkit.

Similar to the intersection improvement project type, each of the traffic signal synchronization scenarios involved a reduction in delay. In all, fifty scenarios were included in the analysis.

This analysis included the following steps:

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

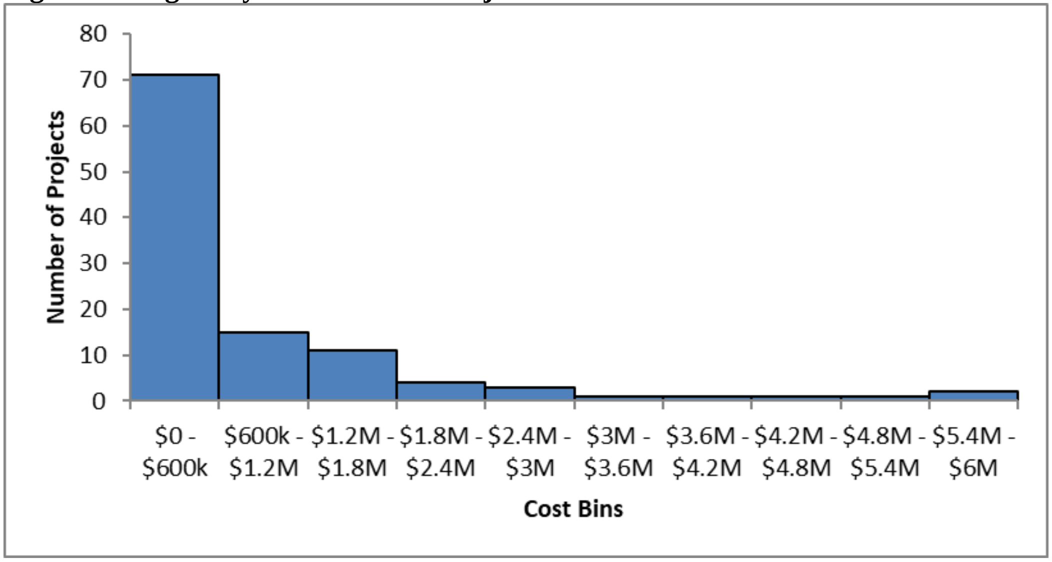
---

[44] CMAQ project data from the PAS was queried and analyzed. A sample of recent traffic signal synchronization projects was collected from State DOTs through internet research. These data were used to calibrate the analytical scenarios tested.

Cost Analysis

The PAS contains 100 traffic signal-related projects identified for analysis from 2016.[45] The identified projects included adding signals or installing a series of synchronized signals over the length of a corridor. The median project cost was approximately $825,000. The distribution of projects costs are shown in Figure 19 below.

Figure 19: Signal Synchronization Project Cost Distribution



A majority of the funded signal synchronization projects were under $600,000 and focused primarily on modifying existing signals or adding one to two improved signals. A small number of projects consisted of larger reconstruction and corridor-level improvements that included broader intelligent transportation technology and a large number of signals, skewing the distribution to the right.

Scenario Building

Fifty analytical scenarios were developed using four primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above),
- The FHWA CMAQ Emissions Calculator Toolkit, and
- Internet research of publicized projects.

Using the CMAQ Toolkit, a range of input values were needed to determine the scenarios. The range, and the proportion of each value used across the fifty scenarios, is described in the table below.

---

[45] 2016 was chosen as it was the most recent year with full available data.

Table 71: Signal Synchronization Scenarios

Parameter	Value
Area Type	33% Rural; 67% Urban
Corridor Length	Distributed Range:2 to 5
Peak Hours per Day	4 hours
Existing Corridor Speed Limit	Distributed Range: 35 to 55 mph
Number of Signals	Distributed Range: 2 to 8
Number of Lanes	Distributed Range 1 to 3
Average Annual Daily Travel	Distributed Range: 20,000 to 75,000 (both directions)
Peak Hour Volume	Distributed Range: 1,200 to 6,600 (both directions)
Truck Percentage	6%
Cycle Length	90 Seconds
Project Lifetime	20 years
Project Cost	Distributed Range: $500,000 to $2.9 million

Methodology

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

In this scenario, the following assumptions were used:

- Average annual daily traffic volume is 50,000 vehicles (in both directions);
- The average peak hour volume is 4,500 vehicles;
- The average travel time is 3 minutes and the speed limit is 35 mph;
- The project lifetime is twenty years; and
- The project cost is $1.25 million.

Step One: Improving the average travel speed by synchronizing the three signals would lead to the following reductions in emissions of NOx and $PM_{2.5}$

Table 72. Sample Calculation of Emissions Benefit from a Signalization Improvement

Pollutant	Emissions Reduced (kilograms per day)	Lifetime Emission Impact (Tons)
NOx	0.111	0.611
$PM_{2.5}$	-0.015	-0.082

Step Two: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 73. Cost-Effectiveness Estimates for a Signalization Improvement

Pollutant	Lifetime Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	0.611	$1,250,000	$2,046,847
$PM_{2.5}$	-0.082		-$15,164,914

Cost-Effectiveness

The median cost-effectiveness estimates for the range of traffic signal synchronization scenarios are presented in Table 74 below:

Table 74. Median Cost-Effectiveness Estimates (dollars per ton) – Traffic Signal Synchronization Projects

Project Type	$PM_{2.5}$	PM_{10}	**CO**	**NOx**	**VOCs**
Traffic Signal Synchronization	$1,136,071	$330,188	$40,868	$327,263	$933,170

Incident Management

Incident management projects focus on providing equipment or personnel for the purpose of advising or re-routing drivers during incidents of non-recurring congestion. These activities can reduce emissions primarily through reducing the idle time associated with congestion. Emission impacts were identified as the product of per-mile emission rates and VMT totals across mitigated LDV trips, and project lifetimes.

This analysis included the following steps:

- Generate light-duty emission rates for $PM_{2.5}$, PM_{10}, NO_x, VOC and CO in MOVES2014b for the range of relevant travel speeds;
- Identify LDV travel activity estimates (per incident and annual idle hours) reduced through projects;
- Identify project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains 59 incident management projects from 2014 through 2016.[46] The median project cost was approximately $1.1 million. However, there were two outliers. While 57 of the incident management projects were under $3.9 million, the final two projects were $11.7 million and $16.6 million respectively. When removing these, two outliers, the median project cost was $648,000. The distribution of projects costs are shown in Figure 20 below.

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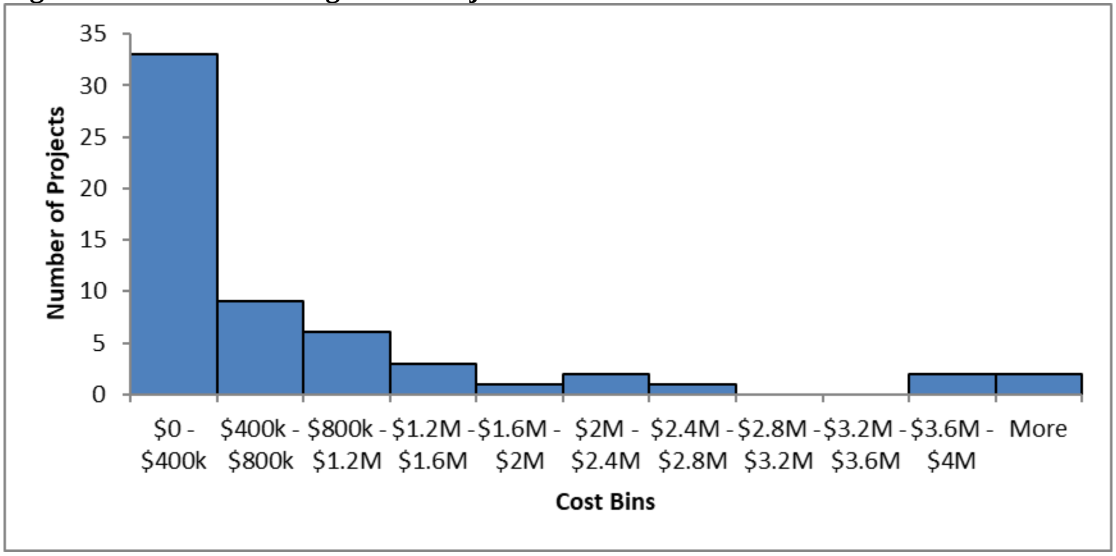
[46] 2016 was chosen as it was the most recent year with full available data.

Figure 20: Incident Management Project Cost Distribution



Project costs are skewed to the right with the majority of the projects costing less than $800,000 each. This cost range was taken into consideration when constructing cost-effectiveness scenarios.

Scenario Building

25 analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized projects.

For the purposes of the analysis, it was assumed that the incident management practices are applied to a range of 15 to 35 incidents per year, and that the useful life of the practices was ten years. Additionally, it was assumed that the idle hours reduced per incident ranged from 3,000 to 7,000 hours, across the entire roadway or corridor.[47] Finally, it was assumed that the cost ranged from $20,000 to $860,000. The cost data was based on publicized data as well as PAS data.

Table 8 below shows the full range of the scenario parameters.

Table 75: Incident Management Scenarios

Parameter	Value Range
Number of Incidents Mitigated per Year	Distributed Range: 15 to 35
Delay Hours Reduced per Incident	Distributed Range: 3,000 to 7,000
Project Lifetime	20 Years
Project Cost	Distributed Range: $20,000 to $860,000

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[47] Assumptions on hours reduced per incident derived from the SHRP2 Traffic Incident Management Responder Training Program Final Report: https://www.fhwa.dot.gov/publications/research/randt/evaluations/18038/18038.pdf

Methodology

As an illustrative example, consider a scenario involving a new incident management system to reduce LDV idle time.

In this scenario, the following assumptions were used:

- The average travel speed for public transit trips and LDV trips is 35 miles per hour;
- The average light-duty idle time emission rates are 9.333 grams per mile for NOx and 0.682 grams per mile for $PM_{2.5}$;
- The average number of incidents mitigated per year is twenty;
- The average delay hours reduced per incident is 6,000, resulting in total delays hours reduced per year of 120,000;
- The project lifetime is ten years; and
- The project cost is $300,000.

Step One: Identify annual emissions impacts by multiplying per-trip emissions by the number of affected trips:

Table 76. Sample Calculation of Annual Emission Benefit from an Incident Management Project

Pollutant	Emissions Reduced (grams)	Annual Idle Hours Reduced	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
NOx	9.333	2,250,000	1,119,911	1.234
$PM_{2.5}$	0.682		81,886	0.090

Step Two: Identify project-level emission impacts by multiplying each of the estimated annual emissions benefits by the project lifetime:

Table 77. Sample Calculation of Total Emission Impacts from an Incident Management Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Total Emission Impact (tons)
NOx	1.234	10	12.345
$PM_{2.5}$	0.090		0.903

Step Three: Calculate cost-effectiveness estimates by dividing the project cost by the estimated project-level emission impacts:

Table 78. Sample Calculation of Cost-Effectiveness Estimates for an Incident Management Project

Pollutant	Total Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)
NOx	12.345	$300,000	$24,302
$PM_{2.5}$	0.903		$332,360

Cost-Effectiveness

The median cost-effectiveness estimates for the range of incident management project scenarios are presented in Table 79 below:

Table 79. Median Cost-Effectiveness Estimates (dollars per ton) – Incident Management Projects.

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Incident Management	$433,650.54	$398,231.0068	$32,994.79	$31,707.72	175,407.00

Heavy-Duty Vehicle Replacements

These projects reduce emissions through the replacement of older, high-emission diesel vehicles with new, lower-emission vehicles. A basic example of a relevant vehicle replacement would be replacing an older (model year 2004) diesel truck with a new (model year 2019) truck. Not only would the MY2019 vehicle operate free of the effects of long-term engine wear and tear (unlike the MY2004 engine), but the MY2019 engine would also be designed under more rigorous emission standards for key pollutants such as PM and NOx.

This section replaces heavy-duty engine replacements, due to a lack of real world engine replacement projects funded by the CMAQ program. Within the CMAQ Public Access System from 2014 to 2016, there were only three engine replacement projects reported and 184 vehicle replacement projects. Engine replacements and vehicle replacements have the same emissions impact through the use of new engines and vehicle's with new engines. Note that the costs of a vehicle replacement are higher than an engine replacement, so the cost-effectiveness is lower than that of an engine replacement.

This analysis included the following steps:

- Generate per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES for relevant travel speeds for travel affected by the project;
- Identify estimates of travel activity (annual VMT) affected by the project (such as estimates of the reduction in emissions for each user through buying a vehicle replacement);
- Identify estimates of project lifetimes; and
- Identify estimates of project costs.

Cost Analysis

The PAS contains 184 vehicle replacement projects from 2014 to 2016 that were identified for analysis. The median cost was approximately $7.4 million However, this median cost represents replacing multiple vehicles, which underscores a data limitation: the PAS reports the project costs but does not specify the number of vehicles replaced. As a result, the cost distribution from the PAS is not reproduced here. The scenarios, example calculations, and the cost-effectiveness values report the cost-effectiveness of replacing a single vehicle as drawn from other sources.

Scenario Building

300 analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study (which considered engine replacements),
- The cost analysis of CMAQ projects (described above), on a per vehicle basis,
- A review of vehicle replacement project documentation and supporting literature.

Note this analysis considers the cost-effectiveness of an individual vehicle replacement, rather than the cost-effectiveness of a given CMAQ project. This analysis focuses on transit and school buses: 89% of the known project types in the PAS were related to school or transit bus replacement. School buses were assumed to all use diesel fuel, while transit buses may either use CNG or diesel. The analysis uses a national activity estimate, in this case VMT, from MOVES2014b for these vehicles. Prices for school buses, CNG transit buses, and diesel transit buses are all based on the literature review. Three replacement cycles are assumed for the vehicles; a low of ten years, a middle of fifteen years, and a high of twenty years.

Table 80: Vehicle Replacement Project Scenarios

Parameter	Value Range
Replacement Cycle (years)	10, 15, 20
Vehicle year	1999-2018
VMT (annual, 2019)	8,154, 36,985
Vehicle types	School bus, Diesel transit bus, CNG transit bus
Costs	$190,000, $200,000, $300,000

Methodology

As an illustrative example, consider a project involving a new vehicle replacement project (single vehicle).

In this scenario, the following assumptions were applied (on a per-vehicle basis):

- The original vehicle is a diesel transit bus MY1999
- The representative VMT (annual in 2019) is 19,352 miles
- The new vehicle is a CNG transit bus MY2019
- The new vehicle VMT (annual in 2019) is 36,985 miles
- The replacement cycle (project lifetime) is 20 years
- The cost of the new bus is $300,000

Step One: The emissions from the 2019 model are subtracted from the 1999 model to represent the emissions reduction from the project. Annual emission impacts are identified by multiplying the per-mile emission rate mitigation by the representative VMT.

Table 81: Sample Calculation of Annual Emission Benefits of a Vehicle Replacement (single vehicle)

Pollutant	Emission Rates (grams/mile)	Annual VMT	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
CO	5.15	19,352	99,713	0.11
$PM_{2.5}$	0.36	19,352	7,024	0.01
PM_{10}	0.39	19,352	7,634	0.01
NOx	15.29	19,352	295,884	0.33
VOCs	1.42	19,352	27,456	0.03

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

Table 82: Sample Calculation of Total Emission Benefits of a Vehicle Replacement (single vehicle)

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Lifetime Emission Benefit (tons)
CO	0.11	20	2.2
$PM_{2.5}$	0.01	20	0.2
PM_{10}	0.01	20	0.2
NOx	0.33	20	6.6
VOCs	0.03	20	0.6

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

Table 83: Sample Calculation of Cost-Effectiveness Estimates of a Vehicle Replacement Project (single vehicle)

Pollutant	Lifetime Emission Benefit (tons)	Vehicle Cost	Cost-effectiveness (dollars per ton)
CO	2.2	$300,000	$136,468
$PM_{2.5}$	0.2	$300,000	$1,937,270
PM_{10}	0.2	$300,000	$1,782,560
NOx	6.6	$300,000	$45,990
VOCs	0.6	$300,000	$4,187

Cost-Effectiveness

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

Table 84: Median Cost-Effectiveness Estimates (dollars per ton) – Vehicle Replacement Emission Mitigation Cost-Effectiveness (on a per-vehicle basis)

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Vehicle Replacement	$33,942,507	$31,309,499	$317,323	$309,889	$3,909,224

Diesel Engine Retrofit Technologies

These projects reduce emissions by retrofitting the engines on older diesel vehicles with emissions reduction technologies. A basic example of a relevant diesel engine retrofit would be installing a diesel particulate filter on a MY2002 Combination Long-Haul truck. Diesel particulate filters (DPF) and other emissions technologies reduce some, but not all emissions by capturing them before they can fully exit the exhaust system of the vehicle.

This analysis included the following steps:

- Generate per-mile emission rates for $PM_{2.5}$, PM_{10}, NOx, VOC and CO in MOVES 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. service life for retrofit devices);
- Identify estimates of technological effectiveness for retrofit devices; and
- Identify estimates of unit costs for retrofit devices

Cost Analysis

The PAS contains 27 diesel retrofit projects identified for analysis from 2014 to 2016. The median cost was approximately $1.4 million. The distribution of project costs shown in below is concentrated in the range between $100,000 and $3,000,000.

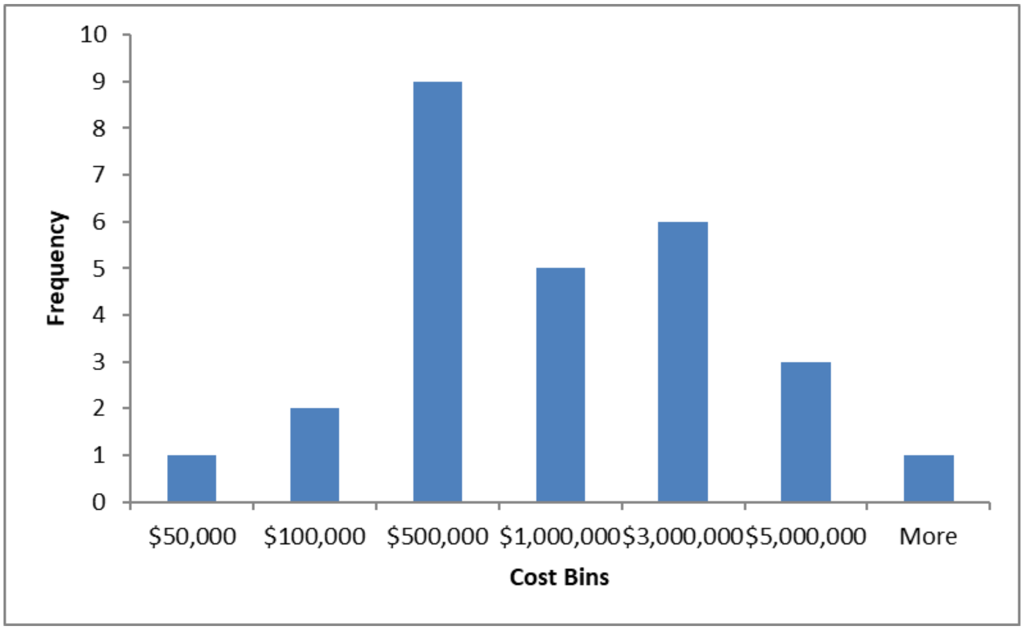
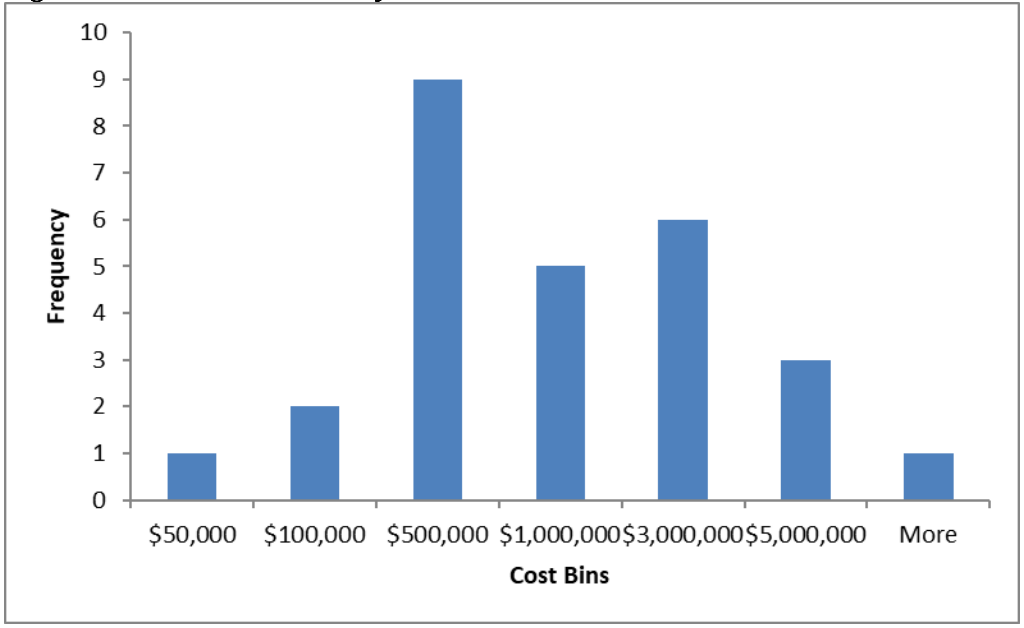


Figure 21: Diesel Retrofit Project Cost Distribution



The majority of the projects cost under $1,000,000. In addition, information on diesel projects was validated through a review of engine retrofit project documentation and supporting literature. This cost range was taken into consideration when constructing cost-effectiveness scenarios.

Scenario Building

252 analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study (diesel retrofits),
- The cost analysis of CMAQ projects (described above)
- A review of diesel retrofit project documentation and supporting literature.

This analysis builds its scenario around a variety of buses and trucks. The analysis uses a national activity estimate, in this case VMT, from MOVES2014b for these vehicles. The types of retrofit and their mitigation factors are pulled from the CMAQ Toolkit. The range of years for retrofitted vehicles is 1999 to 2006. Note that model year 2007 and later heavy-duty engines are required to include emissions reductions technologies as standard[48] and are omitted from this analysis. Vehicles from 2004 to 2006 already have Diesel Oxidization Catalysts (DOCs) and Exhaust Gas Recirculation (EGR) technologies, and thus do not receive those retrofits in any of the analysis' scenarios.

Prices for retrofitted devices reflect literature and EPA sources. Three different cost sources were consulted to build scenarios: an EPA report on the cost-effectiveness of diesel retrofit technology[49], a report by the International Council on Clean Transportation[50], and a fact sheet developed by the Manufacturers of Emission Control Association.[51] The relevant service life for the retrofits depends on vehicle use. However, an analysis of the VMT values and literature yields estimates of five years for the Selective Catalytic Reduction (SCR) technology and eight years for all other technologies.

Table 85: Diesel Retrofit Project Scenarios

Parameter	Value Range
Replacement Cycle (years)	8, except for SCR + DCF (5)
Vehicle year	1999-2006
VMT (annual, 2019)	5,103-84,649
Vehicle types	Intercity Bus, Transit Bus, School Bus, Single Unit Long-Haul Truck, Combination Long-Haul Truck
Costs	DOC + DPF: $6,000 DOC: $750-$1500 DOC + CCV: $4,000 DPF: $5,000-$7,000 EGR + DPF: $18,000 SCR + DPF: $15,000

Methodology

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[48] U.S. EPA's heavy-duty engine standards require use of emission control technologies for model years 2007 and later (40 CFR 86.007-11: Emission standards and supplemental requirements for 2007 and later model year diesel heavy-duty engines and vehicles).

[49] U.S. EPA (2007). An Analysis of the Cost-Effectiveness of Reducing Particulate Matter Emissions from Heavy-Duty Diesel Engines Through Retrofits. https://nepis.epa.gov/Exe/ZyPDF.cgi/900N0800.PDF?Dockey=900N0800.PDF

[50] International Council on Clean Transportation (2017). Diesel Retrofit Technologies and Experience for On-road and Off-road Vehicles. https://theicct.org/sites/default/files/publications/Diesel-Retrofits_ICCT_Consultant-Report_13062017_vF.pdf

[51] Manufacturers of Emission Control Association (MECA). (2011). Diesel Retrofit Frequently Asked Questions http://www.meca.org/galleries/files/DieselRetrofitFAQ_0106.pdf

As an illustrative example, consider a project involving a retrofit project.

In this scenario, the following assumptions were used:

- The original vehicle is a Combination Short-Haul Truck MY2000
- The representative VMT (annual in 2019) is 11,492 miles
- The retrofit being applied is a DOC+DPF
- The service life is 8 years
- The cost of the retrofit is $6,000

Step One: The emissions from the retrofitted vehicle are subtracted from the 2000 pre-retrofit vehicle to represent the mitigated emissions. Annual emission impacts are identified by multiplying the per-mile emission rate mitigation by the representative VMT.

Table 86: Sample Calculation of Annual Emission Benefits of a Diesel Retrofit Project

Pollutant	Emission Rates (grams/mile)	Annual VMT	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
CO	3.17	11,492	36,430	0.0402
$PM_{2.5}$	0.54	11,492	6,258	0.0069
PM_{10}	0.59	11,492	6,802	0.0075

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

Table 87: Sample Calculation of Total Emission Benefits of a Diesel Retrofit Project

Pollutant	Annual Emission Benefit (tons)	Project Lifetime (years)	Lifetime Emission Benefit (tons)
CO	0.0402	8	0.322
$PM_{2.5}$	0.0069	8	0.055
PM_{10}	0.0075	8	0.060

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

Table 88: Sample Calculation of Cost-Effectiveness Estimates of a Diesel Retrofit Project

Pollutant	Lifetime Emission Benefit (tons)	Project Cost	Cost-effectiveness (dollars per ton)
CO	0.32	$6,000	$18,680
$PM_{2.5}$	0.05	$6,000	$108,723
PM_{10}	0.06	$6,000	$100,026

Cost-Effectiveness

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

Table 89: Median Cost-Effectiveness Estimates (dollars per ton) – Diesel Retrofits

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
Diesel Retrofits	$165,130	$151,919	$14,671	$22,133	$53,831

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 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%).

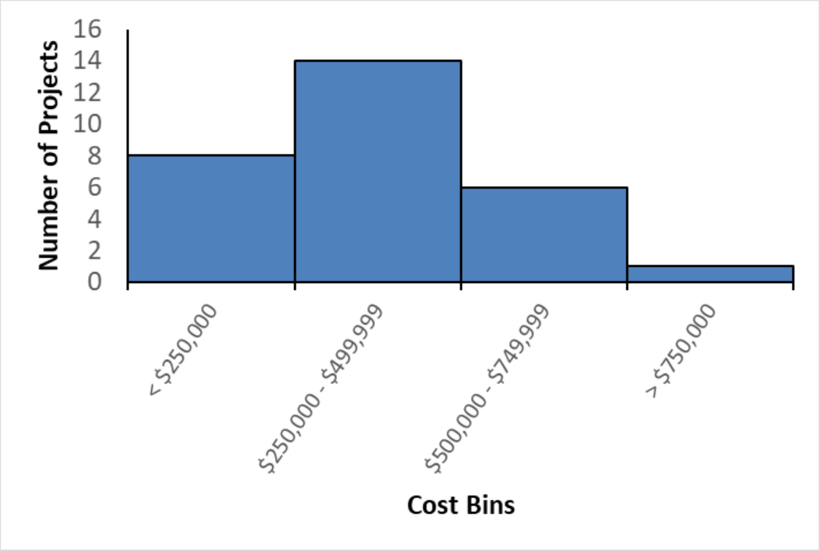
This analysis included the following steps:

- 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.

Cost Analysis

The CMAQ Public Access Database contains 30 ETCS technologies from 1999 to 2016.[52] The projects relating to ETCS technologies ranged from education and incentive programs, operating assistance, retrofitting, and installation of block heaters. As described in the previous section, we are only interested in engine block heater programs. The median project cost was approximately $448,000. The distribution of projects costs are shown in Figure 22 below.

Figure 22: Extreme-Temperature Cold-Start (ETCS) Cost Distribution



As shown above, project costs are slightly skewed to the left with the majority of the projects costing between $250,000 and $749,999. Four of the PAS entries have listed the quantity of engine block heaters being installed. Calculating per unit cost gives the range $250-$550. This per unit average found in the PAS does not deviate too far from the market average of $200 to $300.[53] This cost range was taken into consideration when constructing cost-effectiveness scenarios.

Scenario Building

The analysis relies on MOVES 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.

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[52] 2016 was chosen as it was the most recent year with full available data.

[53] https://community.cartalk.com/t/engine-block-heaters/88063/4

Lower- and upper-bound values for usage rates (60 and 120 annual cold starts), project lifetime (ten years), and project costs ($250, $500 and $750 per block heater) were used in 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.

Thirty-two analytical scenarios were developed using three primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above), and
- Internet research of publicized block heater projects.

Methodology

As an illustrative example, consider the use of a block heater for a passenger vehicle, making 120 starts in -40°F weather. In this scenario, we assume the following details:

- The effective fleet-average emissions for passenger vehicles during starts in zero-degree weather are: 1.262 grams of NOx and 0.9081 grams of $PM_{2.5}$;
- The ETCS technology reduces 40 percent of cold-start emissions;;
- The service life of the technology is 10 years; and;
- The cost of the project is $250 per unit.

Step One: Using a block heater during 120 -40 degree starts would lead to the following annual reductions in emissions of NOx and $PM_{2.5}$:

Table 90: Sample Calculation of Annual Emission Impacts of Block Heaters

Pollutant	Emission Reduction from Block Heater	Baseline Idle Emission Rate (grams/start)	Annual Cold Starts	Annual Reduction in Emissions from Block Heater (grams)
NOx	40%	1.23616611	120	59.336
$PM_{2.5}$	40%	0.90816188	120	43.592

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

Table 91: Sample Calculation of Total Emission Impacts of Block Heaters

Pollutant	Annual Reduction in Emissions from Block Heater (grams)	Project Lifetime (years)	Lifetime Reduction in Emissions from Block Heater (tons)
NOx	59.336	10	0.00065
$PM_{2.5}$	43.592		0.00048

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

Table 92: Sample Calculation of Cost-Effectiveness Estimates for Block Heaters

Pollutant	Block Heater Cost	Lifetime Reduction in Emissions from Block Heater (tons)	Cost-effectiveness (dollars per ton)
NOx	250	0.00065	$1,700,984.52
$PM_{2.5}$	250	0.00048	$4,714,771.41

Cost-Effectiveness

The median cost-effectiveness estimates for the range of extreme-temperature cold-start (ETCS) technologies projects scenarios are presented in the table below:

Table 93: Median Cost-Effectiveness Estimates (dollars per ton) – ETCS Projects

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
ETCS	$4,714,771.41	$4,170,907.57	$35,410.39	$1,700,984.52	$227,960.51

Dust Mitigation

Dust mitigation projects make use of chemical stabilization for dust suppression on unpaved surfaces, or pave previously unpaved surfaces to reduce fugitive dust emissions. Though paving can reduce emissions for other pollutants, since both types are directed at dust emissions, this analysis only reports effects on $PM_{2.5}$ and PM_{10}. The analyses of scenarios were conducted using outputs from the FHWA CMAQ Emissions Calculator Toolkit and project-level inputs from CMAQ projects and various State Departments of Transportation.[54] Emission rate data were determined using the CMAQ Toolkit. The tool was made available to the analysis team for this use only. Note that street sweeping was not considered in the dust mitigation analysis.

This analysis included the following steps:

- Generate per-day emission rates for $PM_{2.5}$ and PM_{10} in the Toolkit for the range of relevant travel volumes and speeds, including time at idle;
- Identify estimates of vehicle travel activity;
- Identify estimates of project lifetimes; and

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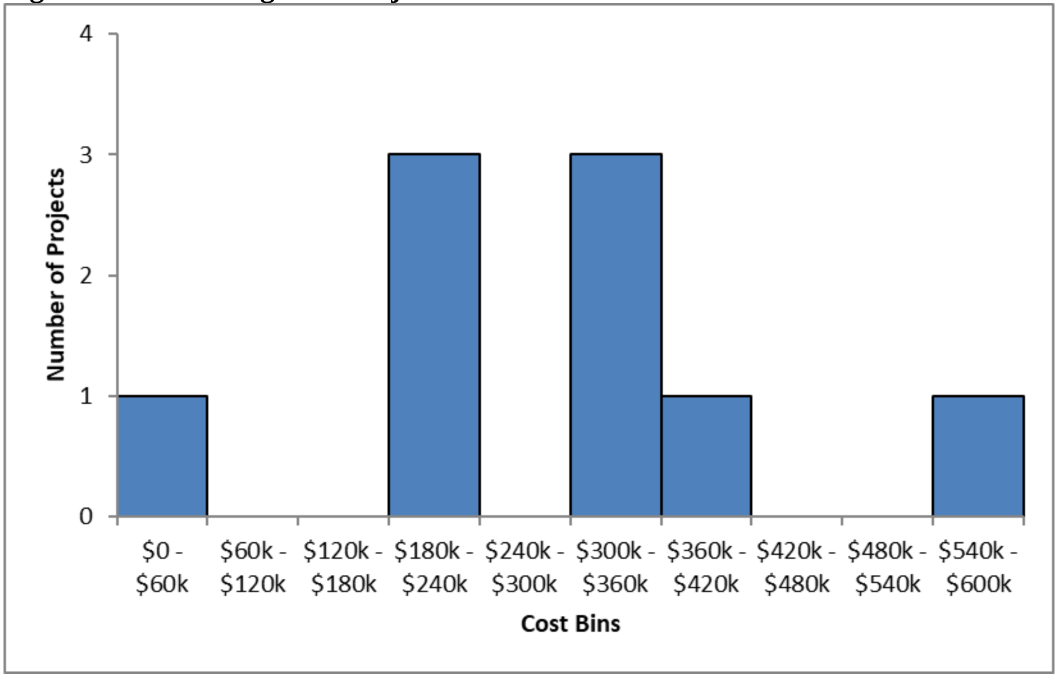
[54] CMAQ project data from the PAS was queried and analyzed. A sample of recent dust mitigation projects was collected from State DOTs through internet research. These data were used to calibrate the analytical scenarios tested.

- Identify estimates of project costs.

Cost Analysis

The PAS contains nine dust mitigation projects identified for analysis involving chemical stabilization or dust suppression from 2014 to 2016.[55] The median project cost was approximately $293,000. The distribution of projects costs are shown in Figure 23 below.

Figure 23: Dust Mitigation Project Cost Distribution



The limited number of chemical stabilization dust mitigation projects funded by the CMAQ program from 2014 to 2016 is fairly normally distributed. The average cost of $293,000 approximates the midpoint of the distribution reasonably well.

Scenario Building

Ten analytical scenarios were developed using the following primary sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above),
- The FHWA CMAQ Emissions Calculator Toolkit, and
- Average traffic counts on unpaved roads collected by California Air Resources Board and the Wyoming LTAP Center.[56]

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[55] 2016 was chosen as it was the most recent year with full available data.

[56] Wyoming University Transportation Center (2019). Assessing the Cost-Effectiveness of Wyoming's CMAQ Unpaved Road Dust Suppression Program, Year 2. https://www.ugpti.org/resources/reports/downloads/mpc19-386b.pdf
U.S. EPA (2002). Estimating Statewide Vehicle Activity and Roadway Mileage for Unpaved Roads in California. https://ww3.arb.ca.gov/research/apr/reports/99-715.pdf

An average annual VMT on unpaved roads of 98,000 was determined based on the Wyoming LTAP study, which showed a mean average daily traffic count (ADT) of 269, or 98,000 annually.

Using the CMAQ Toolkit, a range of input values were needed to determine the scenarios. The range, and the proportion of each value used across the one hundred scenarios, is described in the table below.

Table 94: Dust Mitigation Scenarios

Parameter	Value
Annual VMT	Average of 98,000
Vehicle Speed	Distributed Range: 20 mph to 39 mph (based on roadway type)
Unpaved Surface Silt Content	Gravel (6.4% Silt Content) or Dirt (11% Silt Content)
Unpaved Surface Moisture Content	Typical (1.1% Moisture Content)
Dust Control Type	Chemical Stabilization
Control Strategy Efficiency	Chemical Treatment (0.8 Efficiency Factor)
Project Lifetime	5 years
Project Cost	Distributed Range: $100,000 to $550,000

Methodology

As an illustrative example, consider a scenario involving chemical suppression of a rural, five mile, gravel roadway.

In this scenario, the following assumptions were used:

- Average annual vehicle miles traveled on the rural roadway of 98,000;
- The moisture and silt content are typical of a gravel roadway and the efficiency of the chemical treatment is also standard;
- The project lifetime is five years; and
- The project cost is $250,000.

Step One: Applying chemical stabilization to a gravel roadway would lead to the following reductions in emissions of $PM_{2.5}$ and PM_{10}:

Table 95. Sample Calculation of Emission Rate Impacts from a Dust Mitigation Project

Pollutant	Emissions Reduced (kilograms per day)	Lifetime Emission Impact (Tons)
$PM_{2.5}$	7.95	16.02
PM_{10}	79.84	160.6

Step Two: Divide the project cost by the estimated project-level emission impacts to calculate cost-effectiveness estimates.

Table 96. Cost-Effectiveness Estimates, Dust Mitigation (dollars per ton)

Pollutant	Lifetime Emission Impact (tons)	Project Cost	Cost-effectiveness (dollars per ton)

$PM_{2.5}$	16.02	$250,000	$15,623
PM_{10}	160.6		$1,556

Cost-Effectiveness

The median cost-effectiveness estimates for the range of dust mitigation scenarios are presented in the table below:

Table 97. Median Cost-Effectiveness Estimates (dollars per ton) – Dust Mitigation Projects

Project Type	**$PM_{2.5}$**	**PM_{10}**	**CO**	**NOx**	**VOCs**
Dust Mitigation	$14,487	$1,445	-	-	-

Natural Gas Re-Fueling Infrastructure

These projects involve the provision of natural gas fueling infrastructure (NGFI) projects. 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. 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.

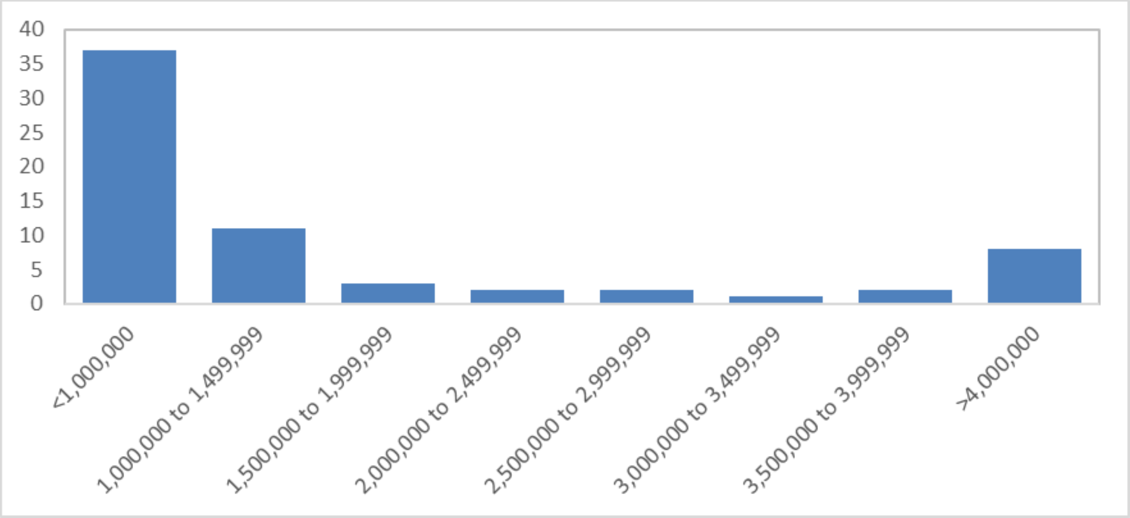
This analysis included the following steps:

- Generate estimates of per-mile emission rate reductions for travel via natural-gas vehicle relative to diesel-fueled vehicle;
- Identify estimates of the number of vehicles using facilities provided within the project and their associated annual VMT;
- Identify Project lifetime estimates; and
- Identify project cost estimates.

Cost Analysis

The PAS contains 66 NFGI projects from 2015 and 2016 identified for analysis. The median project cost was $2,071,942. The distribution of project costs is shown in Figure 24 below.

Figure 24: Natural Gas Fueling Infrastructure Project Cost Distribution



Project costs are skewed to the left, with majority of the projects costing between $1,000,000 and $4,000,000. This falls within the bounds identified in a literature review: costs for installing a CNG fueling station can range up to $1.8 million depending on the size and application, and constructing a liquefied natural gas (LNG) fueling site can cost between $1-4 million. This cost range was taken into consideration when constructing cost-effectiveness scenarios.

Scenario Building

Nine analytical scenarios were developed using the following sources:

- The original scenario structure developed for the 2015 CMAQ cost-effectiveness research study,
- The cost analysis of CMAQ projects (described above)
- Internet research of publicized transit projects.

This analysis assumes that the average travel speed of CNG buses as 35 mph. Additionally, the useful life of the project is assumed to be twenty years.

Across the nine scenarios, three inputs varied: the number of transit buses switching from diesel to natural gas, miles traveled by NG buses per year and project cost.

Methodology

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

In this scenario, the following assumptions were applied:

- Due to the presence of the facility, 20 transit buses switch from diesel to natural gas;;
- Switching from diesel to natural gas reduces bus emissions by 0.0407 grams per mile for PM_{10}, and by 0.036 grams per mile for $PM_{2.5}$;
- The natural gas buses travel 40,000 miles per year (no change from prior travel using diesel);
- The project lifetime is 20 years; and

- The project cost is $1.5 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 98: Sample Calculation of Annual Emission Benefit of a Natural Gas Fueling Station Project

Pollutant	Emission Impact per Bus (grams/mile)	Annual VMT per Bus	Annual Number of Affected Trucks	Annual Emission Benefit (grams)	Annual Emission Benefit (tons)
$PM_{2.5}$	0.036	40,000	20	28,802.5	0.03175
PM_{10}	0.0407	40,000	20	32,559	0.03589

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

Table 99: 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)
$PM_{2.5}$	0.03175	20	0.63499
PM_{10}	0.03589	20	0.7178

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

Table 100: Sample Calculation of Cost-Effectiveness Estimate for a Natural Gas Fueling Project

Pollutant	Lifetime Emission Benefit (tons)	Project Cost	Cost-effectiveness (dollars per ton)
$PM_{2.5}$	0.63499	1.5 M	2,362,257.45
PM_{10}	0.7178	1.5 M	2,089,709.60

Cost-Effectiveness

The median cost-effectiveness estimates for the range of CNG projects scenarios are presented in Table 4 below:

Table 4. Median Cost-Effectiveness Estimates (Dollars per Ton) – CNG Projects.

Project Type	$PM_{2.5}$	PM_{10}	CO	NOx	VOCs
CNG	1,866,475.02	1,651,128.57	9,413.00	19,701.68	128,388.44

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