A METHODOLOGY FOR COMPARING THE COST EFFECTIVENESS OF CMAQ PROJECTS

PREPARED FOR THE EMISSIONS CONTROL TECHNOLOGY ASSOCIATION

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I. INTRODUCTION

The U.S. Department of Transportation (DOT) recently issued Interim Program Guidance for the Congestion Mitigation and Air Quality (CMAQ) Program. An important element of this guidance is an assessment of the cost effectiveness of CMAQ-eligible projects, such as rideshare programs, telework programs, bike path programs, and diesel retrofits.[1] Unfortunately, the assessment suffers from several notable shortcomings which prevent an "apples-to-apples" comparison among alternative strategies, undermining the guidance's ability to promote informed decision making and facilitate the efficient use of public monies.

The purpose of this document is to present a methodology to harmonize these cost-effectiveness estimates and thereby facilitate direct comparisons across potential CMAQ strategies. Fortunately, the estimates presented in the DOT interim guidance can be adjusted in a logical and straightforward manner to correct for deficiencies and express cost effectiveness for all potential strategies in a common metric. The basic procedure is to: (1) account for emission reductions across multiple pollutants to the greatest extent possible and (2) assign weights to those reductions according to the per unit damage costs that each pollutant inflicts on society.

This approach is neither original nor unorthodox, and previous studies have adopted the same general methodology. For instance, in its cost-effectiveness analysis of CMAQ projects, the Transportation Research Board (TRB) weighted reductions in volatile organic compounds (VOC) and nitrogen oxides (NO_X) according to an assessment of the relative damage each pollutant inflicts on affected population.[2] This analysis merely recommends extending this methodology to a third key pollutant, particulate matter (PM), to provide a more comprehensive picture of the true benefits of CMAQ projects.[3] Indeed, the TRB implicitly acknowledges the logic of this extension by providing data on PM reductions for a majority of projects. Its only shortfall is that it assigns a weight of zero to these reductions when computing cost-effectiveness estimates.[4]

To remedy this shortfall, the approach presented here extends the TRB data to include PM reductions and then employs damage cost estimates published in academically accepted studies to construct weights for VOC, NO_X, and PM emission reductions. This approach results in more complete cost-effectiveness estimates that are expressed in a common metric and that are directly comparable across CMAQ-eligible strategies.

II. DATA SOURCES

The current analysis employs emissions reductions and cost data from two sources: (1) the TRB study of CMAQ projects and (2) an EPA analysis of diesel retrofits.[5] Descriptions of each data source and the steps taken to prepare it for analysis are provided below.

[1] See Appendix A for cost-effectiveness estimates as presented in the DOT interim guidance (2006).
[2] See TRB (2002), pg. 124. For similar approaches, see Wang (2004) and Wescott (2005).
[3] All references to PM in this paper refer to PM_{10}, unless otherwise noted.
[4] This weight of zero for PM is simply a placeholder and does not represent a judgment by the TRB that PM reductions are not worthwhile. Indeed, the study explicitly cites the especially pernicious and costly nature of PM emissions relative to other pollutants (TRB, pg. 49). The TRB study also notes that there were no national standards for $PM_{2.5}$ at the time of publication. (TRB, pg. 209).
[5] See TRB (2002), Appendix E. EPA (2006), pg. 13. Actually, the EPA analysis presents estimates for seven combinations of vehicle type and retrofit technology. The remaining estimates were taken from the tables provided in the DOT guidance, which are from a similar EPA analysis of off-road vehicles that has not been released.

2.1 TRB Study Data

Using data published in the TRB study of CMAQ cost-effectiveness, a database was created of CMAQ projects, their costs, and their estimated emission reductions. This resulted in an initial sample of 141 projects. Next, the TRB cost-effective estimates were replicated using a 1:4:0 weighting system for VOC, NO_X, and PM emission reductions and the original cost estimates. If the replicated cost-effectiveness estimate differed from the published cost-effectiveness estimate by more than 5%, the observation was discarded.[6] This data verification process resulted in a final sample of 118 example projects throughout the United States, with each observation including estimates for emissions reductions by pollutant, emission discount factors, and annualized project costs. These projects were then classified into the same 19 control strategies analyzed in the CMAQ guidance (e.g., regional rideshare programs, traffic signalization programs, telework programs).[7]

2.2 EPA Study Data

The EPA analysis provided cost-effectiveness data for diesel retrofits across 17 combinations of vehicle (e.g., school buses, class 8b trucks, bulldozers) and retrofit technology (e.g., diesel oxidation catalyst (DOC) and catalyzed diesel particulate filter (CDPF)). Cost-effectiveness estimates were calculated as the discounted lifetime costs divided by discounted lifetime reductions of PM emissions. Estimates were presented as ranges, with the value within the range representing estimated emissions reductions based on vehicle attrition rates, vehicle model year, and expected remaining lifespan of the vehicle receiving the retrofit. Using this data, point estimates for cost-effectiveness were evaluated as the midpoint of the range for each vehicle/technology combination. To facilitate comparisons among alternative weighting systems, these 17 combinations were then grouped into four larger categories based on vehicle use (on-road, off-road) and technology (DOC, CDPF).

III. Methodology

The methodology employed to harmonize the cost-effectiveness estimates of various CMAQ-eligible projects is rooted in two basic concepts. First, each project should be credited with the net emissions reductions it generates. Second, emission reductions should be weighted by the relative per unit damage costs that each pollutant inflicts on society and converted into a common metric to facilitate comparisons. The following sections discuss the implementation, implications, and limitations of these two concepts.

[6] This typically occurred for projects in which the published cost-effectiveness estimate was significantly different than the result of manually dividing costs by emission reductions, as reported by the TRB. In some instances, the source of the discrepancy — such as transposed columns in the published data tables — was identified and resolved. In other cases, the source of the discrepancy could not be determined and the project was discarded from the analysis. Ultimately, 23 project observations were eliminated from the sample.

[7] There are actually 20 control strategies presented in Figure A of the DOT guidance – 19 strategies from the TRB analysis and 1 strategy (advanced truck stop electrification) from an EPA analysis. However, the strategy of advanced truck stop electrification was not considered in this analysis because comparable emissions data for each pollutant was not readily available.

3.1 Emissions Reductions Accounting

A key inconsistency between the various sets of cost-effectiveness estimates presented in the DOT guidance is the configuration of pollutants being credited to each control strategy. Estimates for conventional CMAQ strategies, as presented in Figure A of the DOT guidance, only credit strategies for VOC and NO_X reductions, while ignoring PM reductions. In contrast, estimates for diesel retrofits, as presented in Figure B and Figure C of the DOT guidance, only credit on-road and off-road applications for PM reductions, while ignoring VOC and NO_X reductions. Undoubtedly, both conventional CMAQ strategies and diesel retrofit applications reduce non-trivial quantities of VOC, NO_X, and/or PM. Best practice dictates that every effort should be made to extend the accounting of emission reductions across all three criteria pollutants, given the practical limitations of data availability, data integrity, and reasonable estimation techniques.

Fortunately, although the TRB study failed to credit projects with PM reductions through the application of a zero value weight, it did provide PM reduction estimates for 61 of the 118 projects examined. For missing values, PM reductions were imputed using the average NO_X to PM ratio of projects within the same category that reported reductions of both pollutants.[8] This approach resulted in a complete set of VOC, NO_X, and PM emission reduction estimates across all projects. Total emissions reductions were then calculated for each project using the weighting formula described in the following section.

Unfortunately, the EPA study of diesel retrofit applications did not consider VOC and NO_X reductions in its analysis and, therefore, even partial estimates of emission reductions from these two pollutants were not available. It was determined that the method used to impute emission reductions for conventional CMAQ strategies cannot be reliably extended to diesel retrofits.[9] Thus, diesel retrofits were only credited with the PM emissions reductions they generate.

The practice of crediting conventional CMAQ strategies with reductions in all three pollutants while only crediting diesel retrofit applications with reductions in PM is less than ideal. While only a handful of retrofit technologies reduce NO_X emissions, all technologies reduce significant quantities of VOC emissions, with some reducing VOC emissions by as much as 90%. Nevertheless, this approach was deemed to be the best solution given the relative importance of PM reductions and the practical limitations of data availability. Ultimately, the failure to extend emissions reductions accounting to VOC and NO_X will make retrofits appear to be less cost-effective than they are in reality.

3.2 Damage-Cost Based Weighting

With emissions reductions accounted for to the extent possible, the next step is to consider the relative importance of reducing each pollutant. The weight of scientific evidence demonstrates that not all pollutants are equal with respect to the unit costs they inflict on society and the corresponding benefits of emission reductions. For instance, the benefits of reducing a ton of

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[8] Research suggests that there is a strong positive correlation between NO_X and PM emissions (see North *et. al* (2006) and Janhall *et. al* (2004)).

[9] Although diesel retrofits have been shown to substantially reduce pollutants other than PM, the extent of these reductions can vary significantly depending on the technology and application. Moreover, most retrofit technologies do not reduce significant quantities of NO_X and, therefore, there is little data to support the choice of a reliable NO_X to PM ratio to impute values.

NO_X are greater than the benefits of reducing a ton of VOC.[10] Likewise, as stated in the DOT's guidance, the benefits of reducing a ton of PM are significantly greater than the benefits of reducing a ton of NO_X.[11] In fact, researchers are increasingly appreciating the harmful effects of PM_{10} and the especially pernicious nature of the finer $PM_{2.5}$. Given that not all pollutants are equal with respect to the unit costs they inflict on society, it is appropriate to weight emissions reductions when comparing the cost effectiveness of strategies that address multiple pollutants.

Following the approach advocated by Wang (2004) and employed by the TRB (2002), the current analysis uses weights for VOC, NO_X, and PM emission reductions that correspond to the relative damage cost per unit of pollutant.[12] In simple terms, if a ton of pollutant X inflicts five times the damages on society as pollutant Y, then a CMAQ project that reduces one ton of pollutant X and one ton of pollutant Y should be equivalent to a similarly expensive project that reduces no pollutant X and six tons of pollutant Y. Thus, to account for the relative harmfulness of various pollutants and evaluate alternative projects on a practical basis, a weight of 5.0 should be assigned to pollutant X and a weight of 1.0 should be assigned to pollutant Y.

A review of the academic literature and environmental policy research reveals a small set of studies that attempt to quantify the per unit damage costs of multiple pollutants. Of these studies, an analysis by Donald McCubbin and Mark Delucchi published in the *Journal of Transport Economics and Policy* appears to provide the most applicable, credible, and often cited estimates.[13] These researchers estimate the costs of health endpoints such as hospitalization, chronic illness, asthma attacks, and lost work days attributable to various air pollutants in the U.S. as a whole, in urban areas, and in the Los Angeles basin. Recognizing the inherent uncertainty in estimating the links between emissions, exposure, health effects, and economic values, the authors estimate damage costs for each pollutant under two sets of extreme assumptions to generate "low" and "high" estimates. For U.S. urban areas, they estimate the following range of damage costs per metric ton of VOC, NO_X, and PM_{10}:[14]

Table 1: Damage Cost Estimates
(1991$ per Metric Ton)

	VOC	NOx	PM10
Low	$130	$1,590	$13,740
High	$1,450	$23,340	$187,470

Source: McCubbin & Delucchi (1999), Table 5. Estimates converted from cost per kilogram to cost per metric ton.

These estimates support two important conclusions. First, the study estimates that the per unit damage costs attributable to PM are far greater than the per unit damage costs of VOC and NO_X.

[10] For example, see Heany et. al (1999) and European Commission (2005).

[11] See DOT Interim Guidance (2006), pg. 37.

[12] Studies that examine cost effectiveness within a multiple-pollutant framework often use some system of weights. Although one could choose weights based on a variety of criteria, it seems logical that damage costs per unit of pollutant are likely to serve as the most appropriate proxy for society's valuation of pollutant reductions.

[13] McCubbin and Delucchi (1999).

[14] It should be noted that the damage cost estimates presented here are different than those presented in Wescott (2005). This occurs for several reasons. First, the current study uses PM_{10} damage costs instead of the higher $PM_{2.5}$ damage costs. This was done to be consistent with the data presented in the TRB and EPA analyses. In addition, Wescott (2005) presented damage costs in terms of short tons, while the current analysis presents damage costs in terms of the more universally utilized metric tons.

Second, the approach of using extreme assumptions to generate low and high bounds results in a considerable range of estimates for each pollutant. However, as noted in the TRB study, the relative importance of the various pollutants is of far greater interest. Although the absolute per unit damage cost estimates are extremely variable across the low and high bounds, the relative per unit damage costs are fairly stable. In both scenarios, estimates of the per unit damage costs attributable to PM are almost one full order of magnitude greater than those attributable to NO_X and more than two orders of magnitude greater than those attributable to VOC. Indexed to a unit of VOC, these ratios are presented in Table 2:[15]

Table 2: Damage Cost Ratios
(Indexed to VOC Damage Costs)

	VOC	NOx	PM10
Low	1.0	12.2	105.7
High	1.0	16.1	129.3
Average Ratio	1.0	14.2	117.5

Source: McCubbin & Delucchi (1999), Table 5. Authors' conversion from absolute to relative damage costs.

Taking the average for each pollutant, a ton of NO_X is estimated to be more than 14 times more harmful than a ton of VOC and a ton of PM_{10} is estimated to be more than 8 times more harmful than a ton of NO_X and more than 117 times more harmful than a ton of VOC. Based on these relative damage cost estimates, the following formula was used to weight emissions reductions for each project:

$$\textit{Total Reductions} = 1.0(\textit{VOC Reductions}) + 14.2(NO_x \textit{ Reductions}) + 117.5(\textit{PM Reductions})$$

Because damage cost ratios are indexed to a metric ton of VOC, total emissions reductions are now denominated in tons of VOC-equivalent. With total emissions reductions calculated and given a project's annualized cost, the cost effectiveness of a given CMAQ project is then computed as:[16]

$$\textit{Cost Effectiveness} = \frac{\textit{Project Costs}}{\textit{Total Emissions Reductions}}$$

[15] As with the absolute damage costs, the relative damage costs used in this analysis differ from those used in Wescott (2005). The previous study adopted the ultra-conservative assumption that all emissions reductions from CMAQ-eligible projects were NO_X as opposed to some mixture of NO_X and VOC. Since the current analysis accounts for the emissions reductions of each pollutant, this assumption is no longer necessary and individual weights are assigned to both VOC and NO_X emission reductions. In addition, the point estimates used as weights in this analysis were calculated as the average of the damage cost ratios for each pollutant, whereas the point estimates used in Wescott (2005) were calculated as the ratio of the average damage costs. While either method is correct, based on an assessment of the particular properties of the damage cost estimates used here, the average of the ratios was used in the current analysis – resulting in a slightly smaller set of weights for NO_X and PM_{10} than if calculated under the alternative method. Nevertheless, performing the analysis with the ultra-conservative weighting assumptions used in Wescott (2005) results in a relative ranking of control strategies that is similar to the relative rankings generated by the sensitivity analysis presented below.

[16] In practice, both the costs and the emissions should be discounted back to a net present value. However, explicit discounting calculations were unnecessary in this exercise. The diesel retrofit data used in this exercise already included discounted costs and emissions reductions. The TRB data for conventional CMAQ strategies included discounted costs and supporting data — specifically, a "benefits discount factor" — which allows one to calculate discounted emissions reductions indirectly.

IV. Results & Sensitivity Analysis

4.1 Primary Results

With cost-effectiveness estimates for conventional CMAQ strategies and diesel retrofits calculated, the two sets of results were then merged and ranked according to cost effectiveness.[17] Denominated in 2006$, the results are shown in Table 3:[18]

Table 3: Cost-Effectiveness of CMAQ Strategies
Weights = {VOC : NOx : PM} = {1.0 : 14.2 : 117.5}
(2006$ per Ton of VOC-Equivalent)

Rank	Category	Median	Min	Max
1	Off-Road Vehicle Diesel Retrofits (CDPF)	$191	$137	$246
2	Inspection & Maintenance	$228	$204	$1,286
3	Off-Road Vehicle Diesel Retrofits (DOC)	$248	$164	$297
4	On-Road Vehicle Diesel Retrofits (DOC)	$268	$226	$418
5	On-Road Vehicle Diesel Retrofits (CDPF)	$275	$246	$431
6	Charges & Fees	$509	$74	$4,556
7	Regional Rideshare	$531	$98	$1,034
8	Vanpool Programs	$855	$429	$7,372
9	Misc. TDM	$1,025	$199	$2,971
10	Freeway Management	$1,372	$239	$16,918
11	Employer Trip Reduction	$2,329	$582	$17,212
12	New Transit Capital Systems/Vehicles	$2,539	$400	$47,356
13	Park-and-Ride Lots	$2,966	$599	$5,377
14	Alternative-Fuel Vehicles	$3,550	$911	$6,190
15	Conventional Fuel Bus Replacements	$3,777	$2,541	$6,481
16	Conventional Service Upgrades	$3,782	$842	$17,784
17	Alternative-Fuel Buses	$4,081	$566	$57,818
18	Modal Subsidies & Vouchers	$5,029	$71	$192,047
19	Shuttles, Feeder, Paratransit	$5,627	$1,101	$59,526
20	Traffic Signalization	$6,313	$2,005	$13,513
21	Bike/Pedestrian	$10,490	$410	$35,338
22	Telework	$13,705	$1,144	$74,977
23	HOV Lanes	$21,823	$1,386	$42,260

Note: Estimates for conventional CMAQ projects were evaluated at median values across a range of projects within the same category. Estimates for diesel retrofits were evaluted at the median values across a range of midpoint estimates of retrofit applications within the same category. Advanced truck stop electrification was not considered in the analysis.
DOC = Diesel Oxidation Catalyst
CDPF = Catalyzed Diesel Particulate Filter

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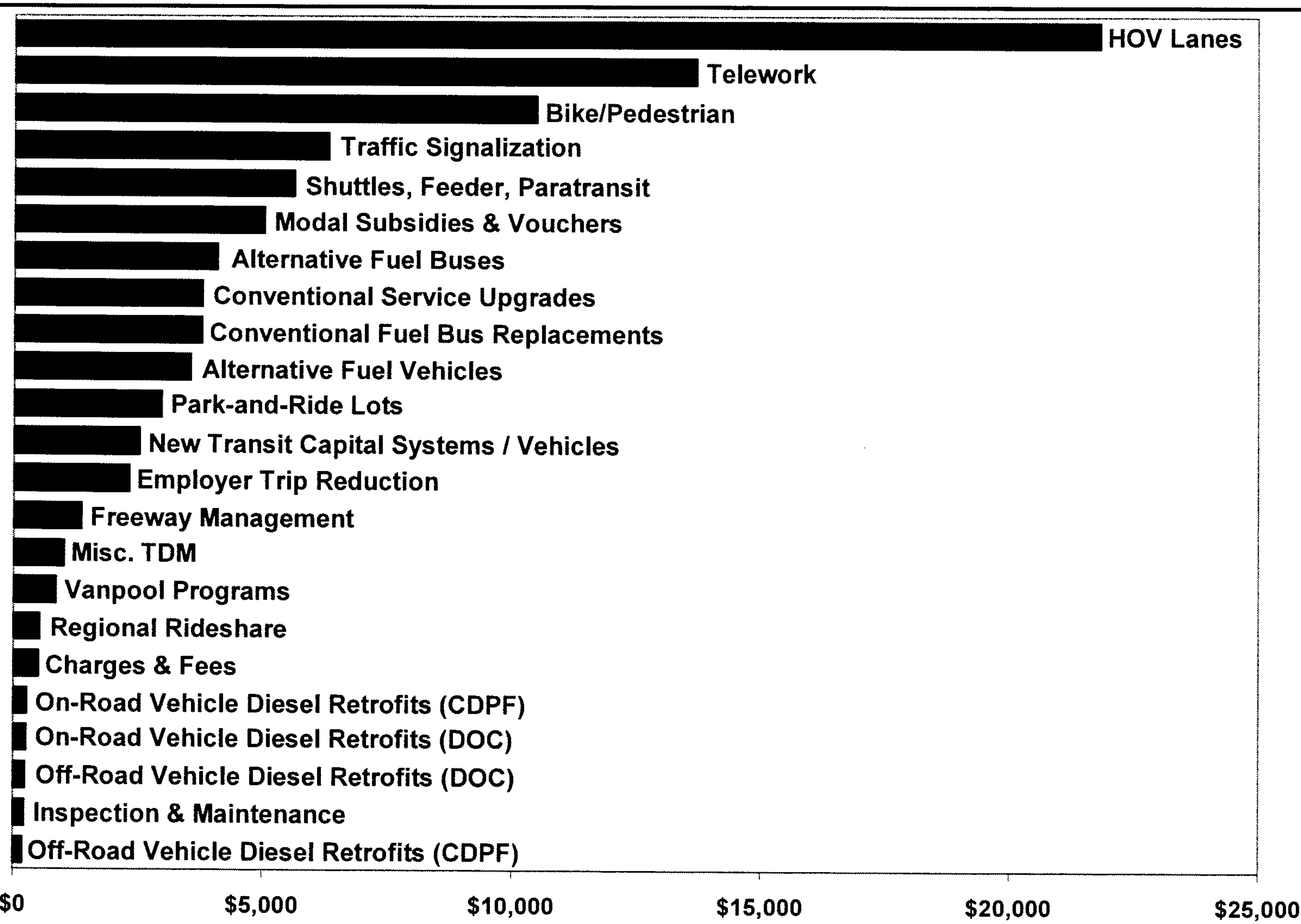
[17] The results presented here aggregate the 17 retrofit vehicle/technology combinations into 4 larger groups. This was done to more easily illustrate how diesel retrofits compare to other strategies on a cost-effective basis and facilitate comparisons among alternative weighting systems. Appendix B includes expanded tables with separate estimates for the 17 different retrofit applications. These tables are more representative of a straightforward merge between Tables A, B, and C of the DOT guidance when cost effectiveness is computed under a unifying framework.

[18] The TRB data was originally denominated in 2000 dollars and adjusted to 2006 dollars using a GDP deflator series published by the Federal Reserve. The EPA study does not explicitly state dollar denominations for retrofit data and, in the absence of notation stating otherwise, it was assumed that data published in early 2006 would be valued in 2005 dollars. Thus, employing the same GDP deflator series, diesel retrofit data was adjusted from 2005 dollars to 2006 dollars.

Figure 1: Cost Effectiveness of CMAQ Strategies
Weights = {VOC : NOX : PM} = {1 : 14.2 : 117.5}
(2006$ per Ton of VOC-Equivalent)



As expected, weighting emissions based on their relative damage costs results in much smaller absolute cost-effectiveness estimates. However, the value in a cost-effectiveness analysis is primarily found in the relative rankings of strategies, not in the absolute estimates themselves. Several conclusions about these relative rankings can be drawn from the data in Table 3:

- Although there was some movement within the relative rankings of conventional CMAQ strategies, the results are fairly consistent with those found in the TRB study. Specifically, strategies that the TRB concluded were relatively more cost effective (e.g., inspection and maintenance program, regional rideshares, charges and fees, etc.) remain more cost effective relative to other conventional CMAQ strategies. Likewise, strategies that the TRB concluded were relatively less cost effective (e.g., HOV lanes, telework programs, bike paths, etc.) remain less cost effective relative to other conventional CMAQ strategies.

- The relative rankings of a limited number of strategies (e.g., freeway management programs) are significantly different than those reported by the TRB. These movements were the result of both excluding observations which could not be replicated using the data and methodology presented in the TRB study and the weighting formula chosen. In most cases, the excluded observations tended to be extreme outliers and their elimination from the analysis resulted in a significant downward revision in the estimate and a narrowing of the range.

- Diesel retrofits, regardless of application, are extremely competitive relative to other CMAQ projects. This result is even more convincing considering that diesel retrofits were not credited with potential VOC or NO_X reductions, making retrofits appear to be less cost effective than they are in reality.

- In fact, only inspection and maintenance programs are more cost effective than certain diesel retrofit categories. Moreover, the second and third most cost-effective conventional CMAQ strategies (charges/fees and regional rideshare programs) are almost twice as expensive per ton of VOC-equivalent reduced as the least cost-effective retrofit category.

4.2 Sensitivity Analysis

Under the current methodology, a primary determinant of the cost-effectiveness estimates is the configuration of weights chosen for the pollutants. Thus, best practice dictates that a sensitivity analysis should be conducted to determine the extent to which the choice of weights influences the rank ordering of alternatives and, consequently, the conclusions of the analysis. To conduct this analysis, two alternative sets of weights were constructed and applied to the data.

4.2.1 TRB Weights with an Extension to PM

In its primary analysis, the TRB assumed that a ton of NO_X is approximately four times more harmful than a ton of VOC. Yet, as previously mentioned, the TRB analysis did not extend its analysis to PM emissions and, consequently, implicitly assigned a weight of zero to PM reductions. The current analysis takes the TRB assumption that NO_X reductions should be valued at four times the rate of VOC reductions as given. It then adds an additional assumption that PM reductions should be valued at four times the rate of NO_X reductions, a very conservative assumption based on credible estimates of NO_X and PM damage costs. This results in the alternative weighting formula:

$$Total\ Reductions = 1.0(VOC\ Reductions) + 4.0\ (NO_x\ \ Reductions) + 16.0(PM\ Reductions)$$

Cost-effectiveness estimates were then calculated based on the same procedure outlined above. The results of this first sensitivity analysis are presented in Table 4:

Table 4: Cost-Effectiveness of CMAQ Strategies
Weights = {VOC : NOx : PM} = {1.0 : 4.0 : 16.0}
(2006$ per Ton of VOC-Equivalent)

Rank	Category	Median	Min	Max
1	Inspection & Maintenance	$1,110	$1,069	$5,161
2	Off-Road Vehicle Diesel Retrofits (CDPF)	$1,406	$1,007	$1,804
3	Off-Road Vehicle Diesel Retrofits (DOC)	$1,819	$1,206	$2,181
4	On-Road Vehicle Diesel Retrofits (DOC)	$1,965	$1,663	$3,072
5	On-Road Vehicle Diesel Retrofits (CDPF)	$2,023	$1,808	$3,162
6	Charges & Fees	$2,843	$406	$25,062
7	Regional Rideshare	$3,083	$555	$6,127
8	Freeway Management	$4,300	$1,275	$96,885
9	Vanpool Programs	$4,870	$2,429	$41,822
10	Misc. TDM	$5,808	$1,111	$16,500
11	Employer Trip Reduction	$12,397	$3,099	$93,272
12	Alternative-Fuel Vehicles	$15,254	$3,555	$26,952
13	Conventional Service Upgrades	$15,538	$3,418	$70,657
14	Conventional Fuel Bus Replacements	$15,674	$10,606	$30,700
15	New Transit Capital Systems/Vehicles	$16,578	$2,712	$254,170
16	Park-and-Ride Lots	$17,583	$3,550	$31,065
17	Traffic Signalization	$21,935	$10,766	$70,811
18	Alternative-Fuel Buses	$21,937	$3,260	$308,921
19	Modal Subsidies & Vouchers	$27,574	$402	$518,526
20	Shuttles, Feeder, Paratransit	$31,617	$6,066	$338,611
21	Bike/Pedestrian	$54,157	$2,225	$188,801
22	Telework	$75,815	$6,393	$421,233
23	HOV Lanes	$105,109	$7,721	$202,498

Note: Estimates for conventional CMAQ projects were evaluated at median values across a range of projects within the same category. Estimates for diesel retrofits were evaluted at the median values across a range of midpoint estimates of retrofit applications within the same category. Advanced truck stop electrification was not considered in the analysis.
DOC = Diesel Oxidation Catalyst
CDPF = Catalyzed Diesel Particulate Filter

A comparison between Tables 3 and 4 shows that the alternative weights do not change the basic conclusions of the primary results. Specifically, although inspection and maintenance programs are now ranked as the most cost-effective alternative, diesel retrofits remain extremely cost effective relative to other CMAQ strategies. And, again, the relative rankings between conventional CMAQ strategies were fairly well preserved.

4.2.2 Carl Moyer Program Weights

The California Air Resource Board (CARB) also applies a system of weights to calculate total emissions reductions when calculating the cost-effectiveness of projects conducted under its Carl Moyer program, one of the most highly respected air pollution abatement programs in the nation. As described in its January 2006 report, based on a thorough assessment of the relative importance of various air pollutants, CARB applies the following weighting formula when calculating total emission reductions:

$$Total\ Reductions = 1.0\,(VOC\ Reductions) + 1.0\,(NO_x\ Reductions) + 20.0\,(PM\ Reductions)$$

In short, the CARB formula implicitly assumes that NO_X and VOC are equally harmful pollutants, while PM is 20 times more harmful than both.[19] Applying this alternative weighting formula to the data results in the cost-effectiveness rankings shown in Table 5.

A comparison among Tables 3, 4, and 5 shows that the Carl Moyer weights have very little impact on the relative rankings of strategies and, consequently, do not alter the basic conclusions reached in the primary analysis.

Table 5: Cost-Effectiveness of CMAQ Strategies
Weights = {VOC : NOx : PM} = {1.0 : 1.0 : 20.0}
(2006$ per Ton of VOC-Equivalent)

Rank	Category	Median	Min	Max
1	Off-Road Vehicle Diesel Retrofits (CDPF)	$1,124	$805	$1,444
2	Inspection & Maintenance	$1,275	$1,234	$5,738
3	Off-Road Vehicle Diesel Retrofits (DOC)	$1,455	$965	$1,745
4	On-Road Vehicle Diesel Retrofits (DOC)	$1,572	$1,330	$2,457
5	On-Road Vehicle Diesel Retrofits (CDPF)	$1,619	$1,446	$2,529
6	Charges & Fees	$3,249	$471	$28,921
7	Regional Rideshare	$3,260	$601	$6,316
8	Freeway Management	$4,631	$1,491	$115,062
9	Vanpool Programs	$5,481	$2,746	$47,090
10	Misc. TDM	$6,467	$1,234	$18,924
11	Employer Trip Reduction	$14,575	$3,644	$110,090
12	New Transit Capital Systems/Vehicles	$15,520	$2,395	$300,018
13	Park-and-Ride Lots	$19,179	$3,913	$34,136
14	Traffic Signalization	$23,912	$12,608	$82,503
15	Alternative-Fuel Buses	$25,694	$3,876	$361,375
16	Conventional Service Upgrades	$26,460	$5,851	$118,531
17	Alternative-Fuel Vehicles	$26,616	$5,690	$47,543
18	Modal Subsidies & Vouchers	$31,919	$459	$1,037,052
19	Shuttles, Feeder, Paratransit	$35,854	$6,830	$366,829
20	Conventional Fuel Bus Replacements	$37,853	$25,003	$52,533
21	Bike/Pedestrian	$66,376	$2,597	$223,044
22	Telework	$84,978	$7,176	$482,663
23	HOV Lanes	$117,465	$8,833	$226,097

Note: Estimates for conventional CMAQ projects were evaluated at median values across a range of projects within the same category. Estimates for diesel retrofits were evaluted at the median values across a range of midpoint estimates of retrofit applications within the same category. Advanced truck stop electrification was not considered in the analysis.
DOC = Diesel Oxidation Catalyst
CDPF = Catalyzed Diesel Particulate Filter

In fact, with some notable exceptions (e.g., freeway management programs and traffic signalization) the relative rankings in Table 5 are virtually identical to those in Table 3. Again, diesel retrofits as a whole are found to be extremely competitive on a cost-effectiveness basis relative to the vast majority of CMAQ alternatives.

[19] In fact, an analysis by CARB determined that the health benefits of reducing a ton of PM_{10} are 30 times greater than the health benefits of reducing a ton of NO_X. However, based on discussions with stakeholder groups, CARB chose to use a weight of 20 for PM_{10}. (CARB, 2006)

V. CONCLUSIONS & RECOMMENDATIONS FOR FURTHER RESEARCH

A methodology that presents cost-effectiveness estimates for CMAQ projects on an unequal basis undermines the ability of the DOT guidance to inform public policy decision makers and assist them in appropriately evaluating alternative projects. This analysis shows that the simple extension of the methodology already implicit in the TRB results, as presented in the DOT guidance, would remedy this problem. The linchpin for this extension is careful scientific and economic analysis that provides well accepted estimates of the health and other damage caused by different pollutants. A study by McCubbin and Delucchi in the *Journal of Transport Economics and Policy* is such a credible and accepted analysis. Using the weights from this study allows all classes of CMAQ projects to be evaluated on an equal basis.

A sensitivity analysis shows that the basic policy conclusions are relatively unaffected by the choice of weights. Employing both a set of weights prescribed by CARB's Carl Moyer program and a set of weights that value PM reductions relative to those of other pollutants far below what the balance of scientific evidence suggests, the relative rankings of potential strategies were not significantly different. Moreover, diesel retrofits were shown to be more cost effective than the vast majority of conventional CMAQ strategies, despite the fact that data limitations required a methodology and set of assumptions that were more generous to conventional CMAQ strategies than to retrofits.

As more research on the damage costs of various pollutants is published in credible and refereed scientific, medical, public policy, and economics journals, the DOT should continue to update the emission weights used to derive cost-effectiveness estimates of CMAQ projects. For example, as more studies become available, it would be logical to rely on an average of damage cost assessments across a sample of studies. This will insure that public policy decision makers are receiving the most recent and accurate cost-effectiveness estimates when choosing among alternative pollution abatement projects.

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APPENDIX A

Cost-Effectiveness Estimates as Presented in DOT Interim Guidance, Appendix 4

FIGURE A: NOx/HC Cost-Effectiveness of Various Project Types		
Vehicle	**Median Cost** *(2005$/Ton NOx/HC Reduced)*	**Cost Range** *(2005$/Ton NOx/HC Reduced)*
Inspection & Maintenance	$2,155	$2,041 - $6,577
Regional Rideshare	$8,392	$1,361 - $18,144
Charges and Fees	$11,680	$907 - $56,020
Vanpool Programs	$11,907	$5,897 - $100,926
Misc. TDM	$14,175	$2,608 - $37,649
Conventional Fuel Bus Replacements	$18,257	$12,474 - $45,247
Alternative-Fuel Vehicles	$20,185	$4,536 - $35,834
Traffic Signalization	$22,793	$6,804 - $145,152
Employer Trip Reduction	$25,742	$6,464 - $199,017
Conventional Service Upgrades	$27,896	$4,309 - $136,193
Park-and-Ride Lots	$48,762	$9,752 - $80,174
Modal Subsidies & Vouchers	$52,844	$907 - $534,114
New Transit Capital Systems/Vehicles	$75,298	$9,639 - $533,887
Bike/Pedestrian	$95,369	$4,763 - $390,890
Shuttles, Feeder, Paratransit	$99,225	$13,948 - $223,398
Freeway Management	$116,122	$2,608 - $616,783
Alternative-Fuel Buses	$143,338	$7,598 - $644,772
HOV Lanes	$199,811	$6,464 - $381,931
Telework	$285,541	$15,082 - $9,329,418

Advanced Truck Stop Electrification	$1,696	$1,414 - $1,976

FIGURE B: PM Cost-Effectiveness in Diesel Retrofit Applications		
Vehicle	**Median Cost** *(2007$/Ton PM Reduced)*	**Cost Range** *(2007$/Ton PM Reduced)*
School Bus Diesel Retrofit (DOC)	-	$12,000 - $49,100
School Bus Diesel Retrofit (CDPF)	-	$12,400 - $50,500
Class 6 & 7 Truck Diesel Retrofit (DOC)	-	$27,600 - $67,900
Class 6 & 7 Truck Diesel Retrofit (CDPF)	-	$28,400 - $69,900
Class 8b Truck Diesel Retrofits (DOC)	-	$11,100 - $40,600
Class 8b Truck Diesel Retrofits (CDPF)	-	$12,100 - $44,100

FIGURE C: PM Cost-Effectiveness in Nonroad Retrofit Applications		
Equipment	**Median Cost** *(2007$/Ton PM Reduced)*	**Cost Range** *(2007$/Ton PM Reduced)*
Off-Highway Trucks Diesel Retrofits	-	$17,200 - $43,500
Off-Highway Trucks Diesel Retrofits	-	$14,300 - $36,300
Loaders/Backhoes/Tractors Diesel	-	$13,800 - $25,100
Loaders/Backhoes/Tractors Diesel	-	$11,500 - $20,900
Excavators Diesel Retrofits (DOC)	-	$17,800 - $49,600
Excavators Diesel Retrofits (CDPF)	-	$14,800 - $41,300
Skid Steer Loaders Diesel Retrofits (DOC)	-	$11,600 - $25,900
Skid Steer Loaders Diesel Retrofits	-	$9,700 - $21,600
Generator Sets Diesel Retrofits (DOC)	-	$15,500 - $36,900
Generator Sets Diesel Retrofits (CDPF)	-	$12,900 - $30,800
250 hp Bulldozer Diesel Retrofits (DOC)	-	$18,100 - $49,700

APPENDIX B

The failure to present cost-effectiveness estimates on an equal basis prevents an "apples-to-apples" comparison among competing CMAQ projects and may inadvertently encourage decision makers to reach faulty policy conclusions. To illustrate this point, the table below represents a straightforward merger of the tables presented in the DOT guidance — that is, it ignores differences in valuations. Strategies were ranked based on range midpoints, the only common measure across all strategies that can be derived from the tables in the DOT guidance.

Table B1: Cost Effectiveness of Potential CMAQ Projects

Results from a Straight Merge of Tables A,B, and C in the CMAQ Guidance

Rank	Strategy	Midpoint	Units
1	Inspection & Maintenance	$4,309	2005$ per Ton VOC-Equivalent Reduced
2	Regional Rideshare	$9,753	2005$ per Ton VOC-Equivalent Reduced
3	Skid Steer Loaders Diesel Retrofits (CDPF)	$15,650	2007$ per Ton of PM Reduced
4	Loaders/Backhoes/Tractors Diesel Retrofits (CDPF)	$16,200	2007$ per Ton of PM Reduced
5	Skid Steer Loaders Diesel Retrofits (DOC)	$18,750	2007$ per Ton of PM Reduced
6	Loaders/Backhoes/Tractors Diesel Retrofits (DOC)	$19,450	2007$ per Ton of PM Reduced
7	Misc. TDM	$20,129	2005$ per Ton VOC-Equivalent Reduced
8	Alternative-Fuel Vehicles	$20,185	2005$ per Ton VOC-Equivalent Reduced
9	Generator Sets Diesel Retrofits (CDPF)	$21,850	2007$ per Ton of PM Reduced
10	Off-Highway Trucks Diesel Retrofits (CDPF)	$25,300	2007$ per Ton of PM Reduced
11	Class 8b Truck Diesel Retrofits (DOC)	$25,850	2007$ per Ton of PM Reduced
12	Generator Sets Diesel Retrofits (DOC)	$26,200	2007$ per Ton of PM Reduced
13	Excavators Diesel Retrofits (CDPF)	$28,050	2007$ per Ton of PM Reduced
14	Class 8b Truck Diesel Retrofits (CDPF)	$28,100	2007$ per Ton of PM Reduced
15	Charges and Fees	$28,464	2005$ per Ton VOC-Equivalent Reduced
16	Conventional Fuel Bus Replacements	$28,861	2005$ per Ton VOC-Equivalent Reduced
17	Off-Highway Trucks Diesel Retrofits (DOC)	$30,350	2007$ per Ton of PM Reduced
18	School Bus Diesel Retrofit (DOC)	$30,550	2007$ per Ton of PM Reduced
19	School Bus Diesel Retrofit (CDPF)	$31,450	2007$ per Ton of PM Reduced
20	Excavators Diesel Retrofits (DOC)	$33,700	2007$ per Ton of PM Reduced
21	250 hp Bulldozer Diesel Retrofits (DOC)	$33,900	2007$ per Ton of PM Reduced
22	Park-and-Ride Lots	$44,963	2005$ per Ton VOC-Equivalent Reduced
23	Class 6 & 7 Truck Diesel Retrofit (DOC)	$47,750	2007$ per Ton of PM Reduced
24	Class 6 & 7 Truck Diesel Retrofit (CDPF)	$49,150	2007$ per Ton of PM Reduced
25	Vanpool Programs	$53,412	2005$ per Ton VOC-Equivalent Reduced
26	Conventional Service Upgrades	$70,251	2005$ per Ton VOC-Equivalent Reduced
27	Traffic Signalization	$75,978	2005$ per Ton VOC-Equivalent Reduced
28	Employer Trip Reduction	$102,741	2005$ per Ton VOC-Equivalent Reduced
29	Shuttles, Feeder, Paratransit	$118,673	2005$ per Ton VOC-Equivalent Reduced
30	HOV Lanes	$194,198	2005$ per Ton VOC-Equivalent Reduced
31	Bike/Pedestrian	$197,827	2005$ per Ton VOC-Equivalent Reduced
32	Modal Subsidies & Vouchers	$267,511	2005$ per Ton VOC-Equivalent Reduced
33	New Transit Capital Systems/Vehicles	$271,763	2005$ per Ton VOC-Equivalent Reduced
34	Freeway Management	$309,696	2005$ per Ton VOC-Equivalent Reduced
35	Alternative-Fuel Buses	$326,185	2005$ per Ton VOC-Equivalent Reduced
36	Telework	$4,672,250	2005$ per Ton VOC-Equivalent Reduced

Note: Although advanced truck stop electrication was not considered in the current analysis and, therefore, was not included in the current table in order to faciliate comparisons. However, it is worth noting that it would rank as the most cost-effective strategy in the table above.

The following tables represent expanded versions of the tables presented in the main document, but with diesel retrofit applications evaluated individually. These tables represent a more direct comparison with the "implied rankings" of the DOT guidance and demonstrate how the presentation of cost-effectiveness estimates can lead to significantly different policy conclusions.

Table B2: Cost Effectiveness of Potential CMAQ Strategies **Weights = {VOC : NOx : PM} = {1.0 : 14.2 : 117.5}** ***(2006$ per Ton of VOC-Equivalent)***				
Rank	**Category**	**Estimate**	**Min**	**Max**
1	Skid Steer Loaders Diesel Retrofits (CDPF)	$137	$85	$189
2	Loaders/Backhoes/Tractors Diesel Retrofits (CDPF)	$142	$101	$183
3	Skid Steer Loaders Diesel Retrofits (DOC)	$164	$102	$227
4	Loaders/Backhoes/Tractors Diesel Retrofits (DOC)	$170	$121	$220
5	Generator Sets Diesel Retrofits (CDPF)	$191	$113	$270
6	Inspection & Maintenance	$228	$204	$1,286
7	Off-Highway Trucks Diesel Retrofits (CDPF)	$222	$125	$318
8	Class 8b Truck Diesel Retrofits (DOC)	$226	$97	$356
9	Generator Sets Diesel Retrofits (DOC)	$230	$136	$323
10	Excavators Diesel Retrofits (CDPF)	$246	$130	$362
11	Class 8b Truck Diesel Retrofits (CDPF)	$246	$106	$386
12	Off-Highway Trucks Diesel Retrofits (DOC)	$266	$151	$381
13	School Bus Diesel Retrofits (DOC)	$268	$105	$430
14	School Bus Diesel Retrofits (CDPF)	$275	$109	$442
15	Excavators Diesel Retrofits (DOC)	$295	$156	$434
16	250 hp Bulldozer Diesel Retrofits (DOC)	$297	$159	$435
17	Class 6 & 7 Truck Diesel Retrofits (DOC)	$418	$242	$595
18	Class 6 & 7 Truck Diesel Retrofits (CDPF)	$431	$249	$612
19	Charges & Fees	$509	$74	$4,556
20	Regional Rideshare	$531	$98	$1,034
21	Vanpool Programs	$855	$429	$7,372
22	Misc. TDM	$1,025	$199	$2,971
23	Freeway Management	$1,372	$239	$16,918
24	Employer Trip Reduction	$2,329	$582	$17,212
25	New Transit Capital Systems/Vehicles	$2,539	$400	$47,356
26	Park-and-Ride Lots	$2,966	$599	$5,377
27	Alternative-Fuel Vehicles	$3,550	$911	$6,190
28	Conventional Fuel Bus Replacements	$3,777	$2,541	$6,481
29	Conventional Service Upgrades	$3,782	$842	$17,784
30	Alternative-Fuel Buses	$4,081	$566	$57,818
31	Modal Subsidies & Vouchers	$5,029	$71	$192,047
32	Shuttles, Feeder, Paratransit	$5,627	$1,101	$59,526
33	Traffic Signalization	$6,313	$2,005	$13,513
34	Bike/Pedestrian	$10,490	$410	$35,338
35	Telework	$13,705	$1,144	$74,977
36	HOV Lanes	$21,823	$1,386	$42,260

Note: Estimates for conventional CMAQ projects were evaluated at median values across a range of projects within the same category. Estimates for diesel retrofits were evaluted at the median values across a range of midpoint estimates of retrofit applications within the same category. Advanced truck stop electrification was not considered in the analysis.

DOC = Diesel Oxidation Catalyst

CDPF = Catalyzed Diesel Particulate Filter

Table B3: Cost Effectiveness of Potential CMAQ Strategies Weights = {VOC : NOx : PM} = {1.0 : 4.0 : 16.0} *(2006$ per Ton of VOC-Equivalent)*				
Rank	**Category**	**Estimate**	**Min**	**Max**
1	Inspection & Maintenance	$1,110	$1,069	$5,161
2	Skid Steer Loaders Diesel Retrofits (CDPF)	$1,007	$624	$1,390
3	Loaders/Backhoes/Tractors Diesel Retrofits (CDPF)	$1,042	$740	$1,344
4	Skid Steer Loaders Diesel Retrofits (DOC)	$1,206	$746	$1,666
5	Loaders/Backhoes/Tractors Diesel Retrofits (DOC)	$1,251	$888	$1,615
6	Generator Sets Diesel Retrofits (CDPF)	$1,406	$830	$1,981
7	Off-Highway Trucks Diesel Retrofits (CDPF)	$1,628	$920	$2,335
8	Class 8b Truck Diesel Retrofits (DOC)	$1,663	$714	$2,612
9	Generator Sets Diesel Retrofits (DOC)	$1,685	$997	$2,374
10	Excavators Diesel Retrofits (CDPF)	$1,804	$952	$2,657
11	Class 8b Truck Diesel Retrofits (CDPF)	$1,808	$778	$2,837
12	Off-Highway Trucks Diesel Retrofits (DOC)	$1,952	$1,106	$2,798
13	School Bus Diesel Retrofits (DOC)	$1,965	$772	$3,159
14	School Bus Diesel Retrofits (CDPF)	$2,023	$798	$3,249
15	Excavators Diesel Retrofits (DOC)	$2,168	$1,145	$3,191
16	250 hp Bulldozer Diesel Retrofits (DOC)	$2,181	$1,164	$3,197
17	Charges & Fees	$2,843	$406	$25,062
18	Regional Rideshare	$3,083	$555	$6,127
19	Class 6 & 7 Truck Diesel Retrofits (DOC)	$3,072	$1,776	$4,368
20	Class 6 & 7 Truck Diesel Retrofits (CDPF)	$3,162	$1,827	$4,497
21	Freeway Management	$4,300	$1,275	$96,885
22	Vanpool Programs	$4,870	$2,429	$41,822
23	Misc. TDM	$5,808	$1,111	$16,500
24	Employer Trip Reduction	$12,397	$3,099	$93,272
25	Alternative-Fuel Vehicles	$15,254	$3,555	$26,952
26	Conventional Service Upgrades	$15,538	$3,418	$70,657
27	Conventional Fuel Bus Replacements	$15,674	$10,606	$30,700
28	New Transit Capital Systems/Vehicles	$16,578	$2,712	$254,170
29	Park-and-Ride Lots	$17,583	$3,550	$31,065
30	Traffic Signalization	$21,935	$10,766	$70,811
31	Alternative-Fuel Buses	$21,937	$3,260	$308,921
32	Modal Subsidies & Vouchers	$27,574	$402	$518,526
33	Shuttles, Feeder, Paratransit	$31,617	$6,066	$338,611
34	Bike/Pedestrian	$54,157	$2,225	$188,801
35	Telework	$75,815	$6,393	$421,233
36	HOV Lanes	$105,109	$7,721	$202,498

Note: Estimates for conventional CMAQ projects were evaluated at median values across a range of projects within the same category. Estimates for diesel retrofits were evaluted at the median values across a range of midpoint estimates of retrofit applications within the same category. Advanced truck stop electrification was not considered in the analysis.

DOC = Diesel Oxidation Catalyst

CDPF = Catalyzed Diesel Particulate Filter

Table B4: Cost Effectiveness of Potential CMAQ Strategies Weights = {VOC : NOx : PM} = {1.0 : 1.0 : 20.0} *(2006$ per Ton of VOC-Equivalent)*				
Rank	**Category**	**Estimate**	**Min**	**Max**
1	Skid Steer Loaders Diesel Retrofits (CDPF)	$805	$499	$1,112
2	Loaders/Backhoes/Tractors Diesel Retrofits (CDPF)	$834	$592	$1,076
3	Skid Steer Loaders Diesel Retrofits (DOC)	$965	$597	$1,333
4	Loaders/Backhoes/Tractors Diesel Retrofits (DOC)	$1,001	$710	$1,292
5	Generator Sets Diesel Retrofits (CDPF)	$1,124	$664	$1,585
6	Inspection & Maintenance	$1,275	$1,234	$5,738
7	Off-Highway Trucks Diesel Retrofits (CDPF)	$1,302	$736	$1,868
8	Class 8b Truck Diesel Retrofits (DOC)	$1,330	$571	$2,089
9	Generator Sets Diesel Retrofits (DOC)	$1,348	$798	$1,899
10	Excavators Diesel Retrofits (CDPF)	$1,444	$762	$2,125
11	Class 8b Truck Diesel Retrofits (CDPF)	$1,446	$623	$2,270
12	Off-Highway Trucks Diesel Retrofits (DOC)	$1,562	$885	$2,239
13	School Bus Diesel Retrofits (DOC)	$1,572	$618	$2,527
14	School Bus Diesel Retrofits (CDPF)	$1,619	$638	$2,599
15	Excavators Diesel Retrofits (DOC)	$1,734	$916	$2,553
16	250 hp Bulldozer Diesel Retrofits (DOC)	$1,745	$931	$2,558
17	Class 6 & 7 Truck Diesel Retrofits (DOC)	$2,457	$1,420	$3,494
18	Class 6 & 7 Truck Diesel Retrofits (CDPF)	$2,529	$1,462	$3,597
19	Charges & Fees	$3,249	$471	$28,921
20	Regional Rideshare	$3,260	$601	$6,316
21	Freeway Management	$4,631	$1,491	$115,062
22	Vanpool Programs	$5,481	$2,746	$47,090
23	Misc. TDM	$6,467	$1,234	$18,924
24	Employer Trip Reduction	$14,575	$3,644	$110,090
25	New Transit Capital Systems/Vehicles	$15,520	$2,395	$300,018
26	Park-and-Ride Lots	$19,179	$3,913	$34,136
27	Traffic Signalization	$23,912	$12,608	$82,503
28	Alternative-Fuel Buses	$25,694	$3,876	$361,375
29	Conventional Service Upgrades	$26,460	$5,851	$118,531
30	Alternative-Fuel Vehicles	$26,616	$5,690	$47,543
31	Modal Subsidies & Vouchers	$31,919	$459	$1,037,052
32	Shuttles, Feeder, Paratransit	$35,854	$6,830	$366,829
33	Conventional Fuel Bus Replacements	$37,853	$25,003	$52,533
34	Bike/Pedestrian	$66,376	$2,597	$223,044
35	Telework	$84,978	$7,176	$482,663
36	HOV Lanes	$117,465	$8,833	$226,097

Note: Estimates for conventional CMAQ projects were evaluated at median values across a range of projects within the same category. Estimates for diesel retrofits were evaluted at the median values across a range of midpoint estimates of retrofit applications within the same category. Advanced truck stop electrification was not considered in the analysis.

DOC = Diesel Oxidation Catalyst

CDPF = Catalyzed Diesel Particulate Filter