A REVIEW OF ON-ROAD VEHICLE MITIGATION MEASURES

Contract AQ-04-01: Developing Effective and Quantifiable Air Quality Mitigation Measures

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By

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Abstract

Background: On-road vehicular mitigation measures are programs or strategies designed to decrease the amount of vehicular emissions for a particular region or area, and are necessary for the development of State Implementation Plans. These control measures can reduce vehicular emissions directly or indirectly. There has been growing interest in assessing the effectiveness of control measure programs that are proposed or have been implemented in practice.

Methods: This study reviewed a range of literature to provide insight into available control measures with their large- and small-scale applications for both gasoline and diesel fueled vehicles. Large-scale measures were classified into four categories: fleet retirement/replacement, retrofitting, inspection and maintenance, and fuel additives/alternative fuel vehicles. Small-scale measures included transportation system management, travel demand management, and special focus on project-level diesel particulate matters (DPM).

Results: The vehicle mitigation measures could be essential strategies to reduce vehicular emissions and mitigate negative health effects. At both large and small scales, the cost-effectiveness of different measures may vary widely. Improving Inspection/Maintenance (I/M) programs seemed to be the most cost-effective measure among large-scale measures. Many project-level measures appeared costly and their cost-effectiveness were hard to quantify due to involving expensive marketing tactics with cooperation from the public, employers, and trucking industry.

About The U.C. Davis-Caltrans Air Quality Project

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Mission: The Air Quality Project (AQP) seeks to advance understanding of transportation related air quality problems, develop advanced modeling and analysis capability within the transportation and air quality planning community, and foster collaboration among agencies to improve mobility and achieve air quality goals.

History: Since the 1990s, the U.S. Federal Highway Administration and Caltrans have funded the AQP to provide transportation-related air quality support. Caltrans and AQP researchers identify and resolve issues that could slow clean air progress and transportation improvements.

Accessibility: AQP written materials and software tools are distributed through our website, peer-reviewed publications, conference presentations, training classes, formal reports and technical memoranda, and periodic newsletters.

Research: AQP investigations focus on project-level, regional-scale, and national-level assessments. Tools and publication topics cover pollutant-specific problems such as those involving particulate matter, carbon monoxide, carbon dioxide, ozone and air toxics; activity data collection and assessment for on- and off-road vehicles and equipment; mitigation options such as transportation control measures; policy analyses addressing transportation conformity and state implementation plan development; litigation support; and goods movement assessments.

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Introduction

The Clean Air Act of 1990 required the Environmental Protection Agency (EPA) to establish the National Ambient Air Quality Standards (NAAQS), which set national standards for pollutants which were considered harmful or hazardous to human health and the environment [1]. The pollutants and their standards are shown in Table 1.

Table 1: NAAQS current standards [1].

Pollutant	Primary Standards	Averaging Times	Secondary Standards
Carbon Monoxide	9 ppm (10 mg/m^3)	8-hour[1]	None
	35 ppm (40 mg/m^3)	1-hour[1]	None
Lead	1.5 µg/m^3	Quarterly Average	Same as Primary
Nitrogen Dioxide	0.053 ppm (100 µg/m^3)	Annual (Arithmetic Mean)	Same as Primary
Particulate Matter (PM_{10})	50 µg/m^3	Annual[2] (Arithmetic Mean)	Same as Primary
	150 ug/m^3	24-hour[1]	-
Particulate Matter ($PM_{2.5}$)	15.0 µg/m^3	Annual[3] (Arithmetic Mean)	Same as Primary
	65 ug/m^3	24-hour[4]	
Ozone	0.08 ppm	8-hour[5]	Same as Primary
Sulfur Oxides	0.03 ppm	Annual (Arithmetic Mean)	-
	0.14 ppm	24-hour[1]	-
	-	3-hour[1]	0.5 ppm (1300 ug/m^3)

[1] Not to be exceeded more than once per year.
[2] To attain this standard, the 3-year average of the weighted annual mean PM_{10} concentration at each monitor within an area must not exceed 50ug/m^3.
[3] To attain this standard, the 3-year average of the weighted annual mean $PM_{2.5}$ concentrations from single or multiple community-oriented monitors must not exceed 15ug/m^3.
[4] To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 65ug/m^3.
[5] To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.08 ppm.

According to the Clean Air Act section 176(c)(1)(B), if a transportation project is federally supported, it should not cause any violations, increase the severity of current violations, or effect the timely attainment of standards in any area. Areas that do not meet the NAAQS standards (non-attainment areas), or areas that have previously violated NAAQS standards (maintenance areas), are required to develop State Implementation Plans (SIPs) [2, 3]. SIPs document how the NAAQS standards will be met or maintained, and should take into account the cost of the program, the amount of emissions reduced, and also document how the SIP will affect current regulatory programs [2, 3]. Additionally, SIPs for non-attainment areas must include regional emissions budgets for the nonattainment pollutants and their precursors. Because $PM_{2.5}$ non-attainment areas risk losing federal funding, NAAQS attainment is an important issue currently facing the state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) [3].

Hot-spot analysis is required for carbon monoxide (CO) and particulate matter (PM) nonattainment areas, and can assess potential (new or worsened) NAAQS violations [2]; however, implementation strategies to prevent violations are not provided in the regulations. In addition, there is growing interest in evaluating mobile source air toxics at the hotspot level. Some MPOs and DOTs have voiced concern about the effectiveness of control measure programs, as well as the lack of information about proven measures already implemented [4]. Vehicular control measures are programs or strategies designed to decrease the amount of vehicular emissions for a particular region or area, and are necessary for the development of SIPs. Control measures can reduce vehicular emissions for an area or region directly (by changing the amount emissions coming directly from the vehicle), or indirectly (by reducing congestion/or number of vehicles on the road). Direct control measures can include vehicle retrofits, stricter engine emission standards, engine modifications, and fuel reformulations to achieve emission reductions, while indirect control measures include strategies such as implementing rideshare programs, building toll roads to reduce traffic, and encouraging use of public transportation/biking/walking. Although control measures will reduce emissions, their effectiveness depends on their applicability (what emissions/situations are they most suited for) as well as their cost-effectiveness (dollars per ton of pollutant reduced). Some control measures are more effective at a smaller-scale, or project level, while others are more appropriate for large-scale or regional levels. Small-scale mitigation measures are emissions reducing strategies that are more applicable at a project-level, such as reducing congestion (and therefore emissions) on a busy stretch of highway. To reduce congestion, a carpool, or HOV lane could be installed, or converting the highway into a toll-road could also encourage people to take a different route, and therefore reduce congestion. It would not be feasible (both in cost and applicability) to require stricter emission standards for a highway or intersection to reduce emissions; therefore, it would be a large-scale control measure, and not applicable on a project-level.

The following literature review is designed to provide insight into available control measures for both gasoline and diesel fueled vehicles, and to also distinguish between their small- and large-scale applications (small-scale in this context means at the project or microscale, and large-scale applications refers to regional- or state- or national-scale controls). The review focuses on control strategies applicable to the range off mobile source emissions, such as CO, PM, and ozone precursor pollutants such as volatile organic compounds (VOCs)[*] and oxides of nitrogen (NO_X). However, the assessment places special emphasis on diesel

[*] Many documents in this review used different terms for the organic vehicular emissions, including hydrocarbons (HC or HC_X), volatile organic carbons (VOCs), and reactive organic gases (ROGs). For the exact compounds specified by each term, please refer to the referenced document from which the term was originally used.

particulate matter (DPM), since various studies have emphasized DPM as the single most important air toxic in urban areas [5, 6].

Large-Scale Control Measures

Two main ways to reduce vehicular emissions without reducing vehicle numbers would be to reduce tail pipe emissions, and reduce traffic congestion. There are many large-scale ways to reduce vehicular emissions, including: (1) introducing newer and cleaner vehicles into older fleets by implementing early retirement/replacement programs, (2) retrofitting existing vehicles, (3) implementing/enforcing more inspection and maintenance (I/M) programs, and (4) introducing emission reducing fuels, or fuel additives, including the use of alternative fuel vehicles. For large-scale emission control strategies to be successful, they should concentrate on controlling the emissions of groups of vehicles currently on the road, as well as future vehicles introduced into the fleet. The following is a comparison of the cost effectiveness and emission reducing capabilities of the emissions control strategies listed above.

Fleet Retirement/Replacement Programs

Heavy-duty diesel vehicle (HDDV) PM emissions have declined over time due to more stringent new-vehicle emission standards. The EPA established exhaust smoke standards for HDDVs beginning in 1970; however, it was not until 1988 that exhaust PM standards were implemented [7]. Tables 2 and 3 show PM and NO_X standards over time.

Table 2: California and federal HDDV exhaust PM standards over time [8-12].

PM exhaust emission standards for HDDVs model year	California and Federal Emissions Standards (g/bhp-hr)
1988-1990	0.60
1991-1993	0.25
1994-2006	0.10
2007 and beyond	0.01

Table 3: California and federal HDDV exhaust NO_X standards over time [8-12].

NO_X exhaust emission standards for HDDVs model year	California and Federal Emissions Standards (g/bhp-hr)
1988-1990	6.0
1991-1997	5.0
1998-2001	4.0
2002-2006	2.0
2007 and beyond	0.2

Figures 1 and 2 show estimated decreases in PM and NO_X in diesel vehicles due to new engine emissions standards.

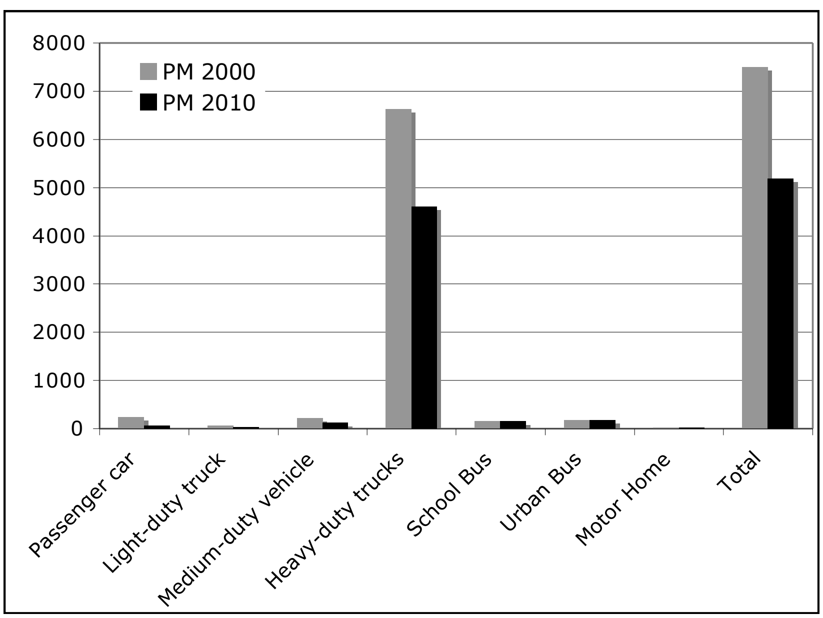

Figure 1: Diesel vehicle PM emissions (in Tons/Year) in California for 2000 and 2010 (Light-duty trucks: up to 5,750 lbs. GVWR, medium-duty vehicle: 5,751-8,500 lbs. GVWR, and heavy-duty trucks: over 8,501 lbs. GVWR) [8].

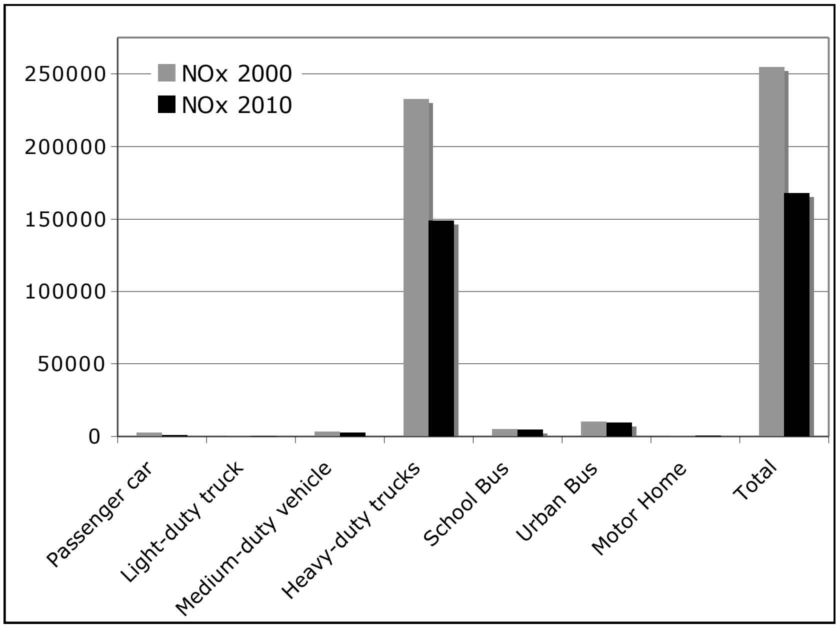

Figure 2: Diesel vehicle NO_X emissions (in Tons/Year) in California for 2000 and 2010 [8].

In another study, Schimek (2001) found that a 1998 transit bus (an urban example of a high-emitting diesel vehicle) emits 50% less PM, and 5% less NO_X than a bus built 8 years earlier. An increase in emissions due to vehicle age and higher standards (both PM and NO_X) is shown Table 4 for diesel buses. The following calculations assume that engines are rebuilt in the eighth year after accumulating about 290,000 miles and follow this same mileage accumulation curve. Transit buses were used because they have been the focus of previous emissions regulations, and are regularly found in large numbers in cities [13].

Table 4: Lifetime emissions of diesel buses[13].

Model year	**Lifetime emissions (Mg^a)**	
	PM	**NO_X**
1990	0.514	8.847
1998	0.242	8.352
Difference	0.272	0.495

[a]$Mg = 10^6$ g

Although new emission standards are meant to reduce overall emissions, the benefits can be offset by the lack of new vehicles being introduced into the fleet. As engines are built to be more durable, they will last longer, and the positive impact of introducing cleaner vehicles into the fleet will decrease over time. In addition, emission standards applied to only new vehicles, along with the durability of diesel engines, can discourage rapid fleet turnover [14, 15]. In order to gain the benefits of newer and cleaner vehicles (particularly diesel vehicles), vehicle scrappage and/or retirement programs can be implemented to remove older high emitting vehicles from fleet. These programs are usually operated by a private organization that pay the owners of older vehicles to voluntarily turn their high-emitters over for scrapping, or removal from the road [16]. Vehicles are usually eligible for scrapping based on their model year or age; however, as the number of older vehicles in the fleet decreases, so will the benefits of vehicle scrappage/retirement programs.

Retrofitting

For many years, it has been widely understood that a small fraction of motor vehicles produces the majority of emissions for any single pollutant. A common approximation ahs been to estimate that 10% of vehicles produce 50% of the emissions for any single pollutant [1], although in recent years data indicate that, as the vehicle fleet rolls over to cleaner operating vehicles, an even smaller fraction of vehicles may be responsible for the bulk of the emissions [17]. An effective long-term way to reduce tail pipe emissions is to target gross polluters by either replacing, or retrofitting them. These programs target all gross polluting vehicles (both heavy- and light-duty); however, PM emitted from heavy-duty diesel vehicles (HDDV) has been identified as one of the most important pollutants form a public health perspective and is therefore a greater concern [13]. Estimated PM and NO_X emissions for California are shown in Figures 3 and 4 for both gasoline and diesel vehicles.

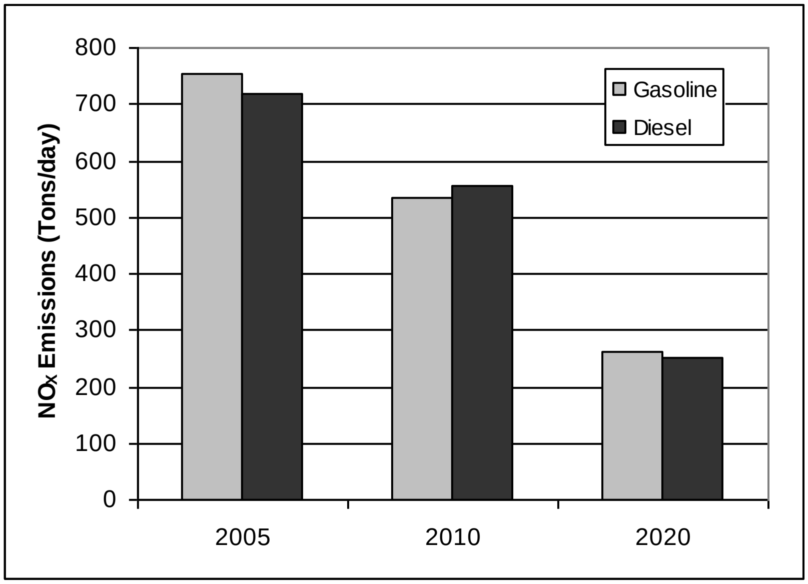

Figure 3: Past and future NO_X emissions for California [18].

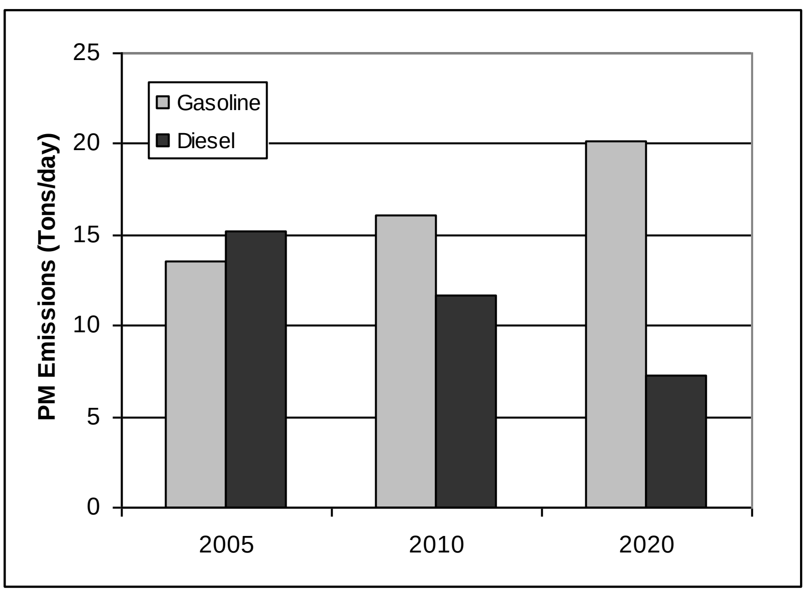

Figure 4: Past and future PM emissions for California [18].

Although NO_X and PM are predicted to decrease over time, this will only occur if assumed vehicle turnover rates occur. Newer diesel engines will produce less PM and NO_X; however, diesel vehicles are long-lived and it will take many years for older vehicles to be replaced by cleaner-operating vehicles. In addition, because DPM is an important contributor to air toxics risk, there is a greater need to either replace older HDDV, or retrofit them with newer, cleaner technologies.

For the control of PM and NO_X, re-designing engines to produce higher pressure and a shorter burning period (more precise regulation of the fuel/air mixture) can result in a decrease in emissions [13]. Also, changes in the fuel injection system, intake air system, and combustion chamber can all result in lower emissions of PM and NO_X [13]. Included in the 1990 Clean Air Act Amendments was a retrofit/rebuild program, which required the addition of PM emissions reductions kits when, for example, a bus engine was rebuilt [1, 2, 19]. A “full retrofit kit” and a “25% retrofit kit” had to be EPA certified for a specific engine type, and would reduce bus PM emissions to 0.10 g/bhp-h. Depending on the retrofit kit and bus model type, the kits could potentially result in an overall PM reduction rate ranging from 30% to more than 50% (full kit); a “25% retrofit kit” can also be used to reduce current emissions by 25%, at a lower cost to the installer. [13]. The lifetime PM emissions are shown in Table 5 for each kit type.

Table 5: PM emissions reductions from retrofit/rebuild [13]

Engine Type (kit type)	**Lifetime PM emissions (Mg[a])**		
	No kit	**With kit**	**Δ**
1987 or older diesel (full)	0.340	0.050	0.290
1987 or older diesel (25%)	0.679	0.408	0.272
1988-1989 diesel (25%)	0.408	0.289	0.119

[a]Mg = 10^6 g = 1.102 Tons

Diesel retrofit technologies can target many different types of emissions, one being particulate matter (PM). Ways to control PM from a diesel engine include diesel particulate filters (DPFs) and diesel oxidation catalysts (DOCs). DPFs can drastically reduce PM emissions, usually by 80 to 95%, as well as reducing hydrocarbon and carbon monoxide emissions [15]. DPFs trap particulate matter on a filter, and then, depending on the type of DPF, burn the matter off, releasing small amounts of water and carbon dioxide. This "filter regeneration" can occur in many different ways, sometimes as a result of a catalyst. Using a catalyzed filter causes the PM to ignite at the typical temperature of exhaust, and has been used successfully worldwide as a retrofit technology [15]. Although this type of filter has been used with positive results, it is not compatible with many older engine types, and also because of its requirement of an ultra-low sulfur fuel (<=30ppm sulfur), for optimum filter performance [15]. Because of these restrictions, an actively regenerating filter is sometimes used. This filter does not require any special fuel regulations, and is also compatible with older diesel engines. Although use of this filter has less restrictions then the catalyzed filter, it is still considered an experimental retrofit, and has not been used in mass production for larger fleet sizes [15]. These active regeneration filters use a burner (fuel or electric) to heat the exhaust, which burns off the PM from the filter. This method causes increased fuel consumption because of the extra energy needed by the burner to heat the exhaust. DOCs are an alternative form of PM control that oxidizes the soluble organic fraction of the PM released overall reducing PM emissions by 20-50% [15]. DOCs are established technology that is easy to retrofit and maintain; although they are a more popular and cheaper way to retrofit, they are also not as effective as a DPF [15]. A table of emission reductions due to DPFs and DOCs is shown in Table 6.

Table 6: Estimated reduction in $PM_{2.5}$ and hydrocarbon emissions due to a 2010 retrofit program, averaged over all diesel vehicles retrofit [15].

	Catalyzed DPF Newer Vehicles[a]	Active Regeneration DPF[a]		Oxidation Catalyst (DOC)[a]	
		Newer Vehicles[b]	Older Vehicles[c]	Newer Vehicles[b]	Older Vehicles[c]
PM	21	21	68	5.7	19
HC	160	160	250	140	220

[a] Values given in kg per vehicle per year over an average distance each vehicle type is assumed to drive per year.
[b] Model-year 1994 and newer.
[c] Model-year 1993 and older.

Large amounts of PM can be reduced as a result of diesel retrofits, and therefore, decreases in negative health effects will occur. Table 7 is an estimate of averted deaths per year due to DPFs and DOCs.

Table 7: Median estimate of statistical deaths averted per year per 1,000 vehicles retrofit in 2010 [15].

Retrofit Type	Vehicle	Deaths averted per 1,000 vehicles retrofit	Interquartile Range of Predicted Values (Error)
Catalyzed DPF	Buses	3	1 – 7.5
	Trucks	2.2	1.5 - 10
	Trailers	1.2	-
Oxidation Catalyst	Buses	1.4	0.8 – 5.2
	Trucks	1.2	1.4 – 8.8
	Trailers	1.0	-
Active Regeneration DPF	Buses	4	0.4 – 3.2
	Trucks	3.5	1.2 – 7.6
	Trailers	3	-

Each DPF and DOC will result in health benefits; however, the benefits are greater with an active regeneration device because it can be used on older, dirtier vehicles. Although the greatest health effects are achieved through retrofitting older vehicles, the health benefits due to retrofitting will decrease over time as the fleet becomes newer and cleaner.

For light-duty vehicles (LDVs), the most effective retrofit strategy in the United States was to phase out carbureted leaded-fuel vehicles for ones where electric fuel injectors ran on unleaded gasoline [20]. By using electric fuel injectors, the engine can run more oxygen rich and fuel lean, decreasing the overall emissions [13]. In addition, using rare-earth oxides (REOs) in catalytic converters (REO catalysts) is a cost effective way to reduce emissions by an average of 99% for CO, 80% for HC, and 92% for NO_X [20].

Inspection and Maintenance (I/M)

States or areas that are located within an ozone transport region, and are classified as a non-attainment area, are required by the CAA to implement I/M programs. In addition, larger metro statistical areas (MSA) may be required, depending on their size, to implement I/M programs as well, regardless of their attainment status [21]. A “basic” I/M program uses relatively simple equipment to measure tail pipe emissions while a vehicle idles; however, in areas that contain more challenging air quality issues, the CAA Amendments of 1990 require an “enhanced” I/M program be implemented [22]. An “enhanced” I/M program usually uses a dynamometer, which is a more complex piece of equipment [22]. Enhanced smog checks are estimated to reduce fleet emissions in California on an average of 17% for HCs, 9% for NO_X, and 28% for CO [23], with another possible estimate is a 14-28% reduction of HCs in Southern California’s South Coast Air Basin [22].

An I/M program works by requiring inspection (either basic or enhanced) on a periodic basis; in California, I/M (or “Smog Checks”) are required once every two years and upon change of ownership in the larger metropolitan areas. Tests can be completed at a centralized, decentralized, or hybrid station. A centralized station is commonly referred to as a Test-Only station, which only tests for emissions, and does not do any on-site vehicular repairs. Although this type of station has a low cost to operate, and performs a high volume of inspections, there are fewer testing sites, and sometimes a longer travel time to reach them [17]. In addition, if the vehicle is repaired off-site, and returns to a centralized location only to fail the test again (referred to as the "ping-pong" effect), it may potentially discourage motorists from seeking additional vehicle repair [17]. The second type of inspection station solves this "ping-pong" effect by providing on-site vehicles repairs, and is a decentralized or Test-and-Repair station. Test-and-Repair stations are low volume, but larger in number, resulting in smaller lines when compared to a Test-Only station [17]. Although the Test-and-Repair stations are more convenient to motorists, they are also more difficult to monitor, and lead to more instances of fraud [17]. Test-and-repair stations have a potential conflict of interest: they may intentionally fail vehicles in order to receive more money in on-site repairs; or, they may intentionally pass vehicles that require repair, to maintain good customer relationships [17]. Also, the lack of quality control of monitoring and repair equipment can result in fewer emissions reduced. Average emission reductions for both types of testing stations are shown in Figure 5.

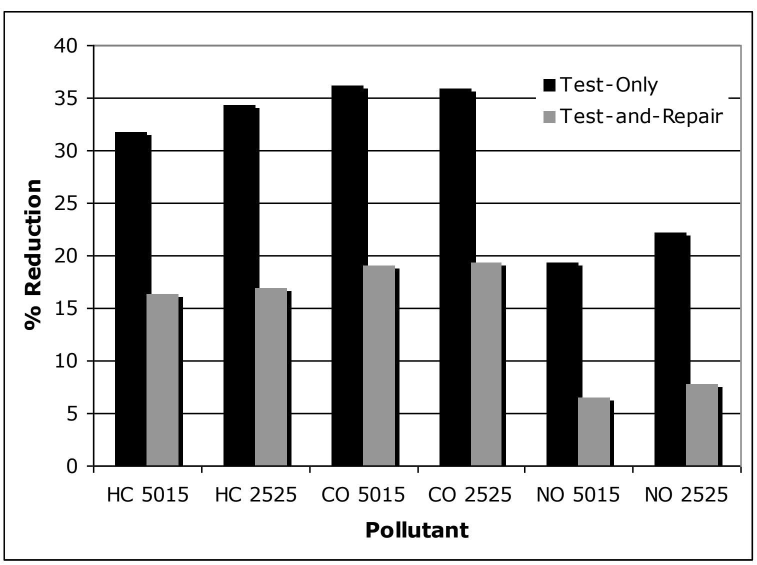

Figure 5: Average emission reductions before and after Smog Check [24].

From Figure 5, it is shown that average emission reductions can be as large as 35% for some pollutants, and have the potential to dramatically decrease emissions of HCs, CO, and NO_X for a non-attainment area. However, from Figure 5 it is also shown that the amount of emission reductions can depend heavily upon the type of station conducting the inspection. Since SIP emission reductions depend on at least 40% of vehicles with the highest probability of failure visiting a Test-Only facility [24], if fewer vehicles are directed there, an overestimation of emissions reductions can occur. If Test-and-Repair stations consistently perform poorly, they give gross emitters a greater probability of escaping repair through I/M programs. As a solution to this problem, hybrid stations can be used, which incorporate a number of high volume Test-Only stations with fewer low-volume Test-and-Repair stations [17]. Under this program, a larger fraction of vehicles which are estimated to have high emissions are sent to Test-Only stations, which ensures those vehicles will be tested at stations with high quality control [17]. Although the program can significantly reduce NO_X, CO, and HC emissions, a significant portion of high emitting vehicles must be directed to Test-Only stations to achieve significant results [24].

In addition to tail-pipe inspections, gas cap inspections are also conducted at I/M facilities. The gas cap is an important component which prevents fumes from inside the tank from releasing into the atmosphere; however, it is one that should be repeatedly replaced over the vehicles' lifetime [17]. If a faulty gas cap is not replaced, an estimated 20 g of HC per day of evaporative emissions will be released [17]. Reductions in gas cap failures before and after smog check is shown in Figure 6. For this test, there was no difference between the Test-Only and Test-and-Repair stations.

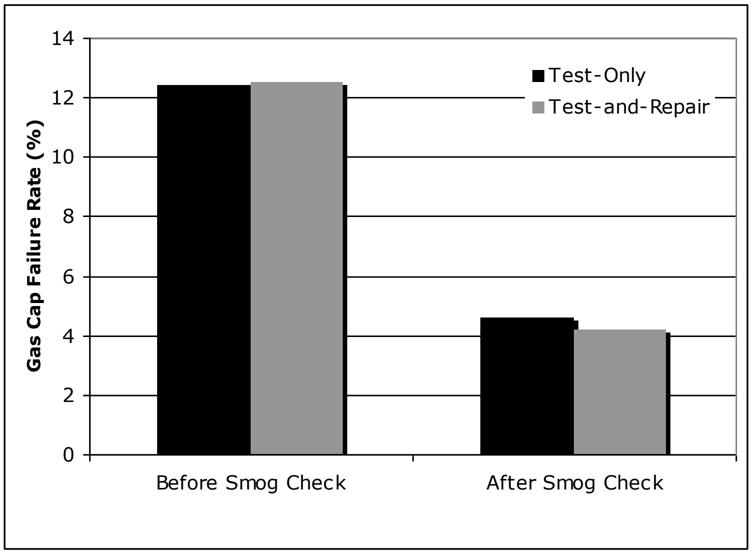

Figure 6: Gas cap failure rate for before and after Smog Check by testing station [24].

Although vehicles in some areas are required by the CAA to visit I/M facilities yearly, many vehicles, including gross polluters, avoid inspection to prevent potential costly repairs. As a solution to this problem, remote sensing of gross polluters (similar to red light sensors) has been suggested near schools and off/on ramps to freeways as a way to catch vehicles illegally avoiding I/M programs [25]. In addition, these sensors can be a useful way to track fleet emissions, as well as estimate the effectiveness of I/M repairs over time [25]. Although remote sensors may be used to catch delinquent vehicles, there are several problems when using this equipment conjointly with I/M programs. If apparent gross polluters are identified under this system, and letters are sent to the owners of these, it is estimated that only 35%-40% of people are likely to respond [26]. In addition, since only one second of the vehicle's emission profile is recorded by the remote sensor, the emissions captured may not accurately represent the total emissions of the vehicle [25]. False reporting (or false positives for gross polluting) could potentially decrease public support, and decrease the effectiveness of the program [26]. Without an effective way to enforce I/M compliance, gross polluters that refuse inspection will hinder the ability of the program to reduce emissions.

Fuel Additives and Alternative Fuel Vehicles

Changing the fuel of a vehicle is an effective way to reduce emissions in both light- and heavy-duty vehicles. One way to change the composition of the fuel is by adding a cetane number enhancer. Adding this enhancer will cause the fuel to ignite earlier, requiring less fuel for the same power output, as well as reduction in NO_X emissions [27]. Because these reformulated fuels for heavy-duty vehicles require no engine modifications, they are also a cost-beneficial way to reduce emissions [27]. In addition to decreasing NO_X, PM reductions are also a priority when reducing heavy-duty vehicular emissions. By requiring the sulfur content in diesel fuels to decrease, sulfur particulate formation will be reduced, and will also reduce damage to emissions control systems that are sensitive to higher sulfur contents fuels [13]. Throughout 2006, the EPA will require a reduction in sulfur content in diesel fuels to be no more than 15 ppm for use in highway vehicles, for terminal level, and for retail stations fleets [12]. The EPA estimates that the decrease in sulfur particulate will prevent 8,300 premature deaths, over 9,500 hospitalizations and 1.5 million missed work days [12]. Each new truck or bus will be approximately 90% cleaner, with projected emissions reductions (by 2030) shown in Table 8.

Table 8: Projected emissions reductions by 2030 from diesel fuel sulfur control [12].

Emission Reduced	Tons
NO_X	2.6 million
Non-Methane HC	115,000
PM	109,000

Another way to reduce emissions from diesel vehicles is to replace a portion of the diesel fuel with biodiesel. Biodiesel is diesel fuel that is made from natural, renewable resources, such as vegetable oils [28]. A study by Graboski *et al.* (1996) compared emissions from 5 different fuels, including a 20, 35, 65, and 100% biodiesel (blended with diesel fuel) mixture, and a reference fuel (no biodiesel); the engine efficiency for the biodiesel blends, biodiesel and the reference fuel did not change [28]. For the mixture containing only 35% biodiesel, the NO_X emissions increased by 1%, with little change of the other emissions; however, for the 100% biodiesel, the NO_X increased by 11%, the PM decreased by 66%, the CO was reduced by 47%, and the HCs were reduced by 44%. This study concludes that biodiesel may decrease some emissions, such as PM, CO, and HCs, but it does not reduce NO_X [28].

For light-duty vehicles (LDVs), the EPA has regulated gasoline fuels and additives to decrease emissions, and in the past has banned lead and highly volatile gasoline across the country [29]. The EPA began requiring (beginning in 1995) that severe ozone nonattainment areas use reformulated gasoline (RFG) in the summer to reduce ozone precursors [29]; the use of RFG blends show a much lower total mass of toxins emitted than average industry level gasoline [30]. RFG blends combine compounds such as aromatics, olefin, and oxygenates such as ethyl tert-butyl ether (ETBE) or methyl tert-butyl ether (MTBE) with gasoline to maintain an octane level decreased by the phasing out of lead compounds [30]. However, because of the groundwater contamination cause by MTBE, some states have banned its use in RFG [29]. Although using RFG reduces VOCs such as formaldehyde and benzene, they do little to decrease (and in some cases increase) NO_X emissions; however, reducing the sulfur content can effectively decrease vehicular NO_X [30]. As a result, the allowable sulfur content in gasoline has been reduced by the EPA, to an average of 30 ppm, and a cap of 80 ppm sulfur requirement that must be implemented by the end of 2006 [29].

The replacement of current vehicles with vehicles that run on clean fuels (fuels that produce fewer emissions than current gasoline/diesel fuels) is another option for reducing vehicular emissions. This option is less widely used because it requires engine modification, or total vehicle replacement which can be costly. Replacing current vehicles with ones that run on electricity, ethanol, methanol, natural gas (methane), or propane are all options that will produce less emissions then vehicles currently running on gasoline or diesel fuel [31]. A summary of the advantages and disadvantages associated with these vehicles is available from the EPA, and is also shown in Table 9.

Table 9: Advantages and disadvantages of clean fuels [31].

Fuel	Advantages	Disadvantages
Electricity	Potential for zero vehicular emissions Power plant emissions easier to control Can recharge at night when power demand is low	Current technology is limited Higher vehicle cost; lower vehicle range, performance Less convenient refueling
Ethanol	Excellent automotive fuel Very low emissions of ozone-forming HCs and toxics Made from renewable sources Can be domestically produced	High fuel cost Somewhat lower vehicle range
Methanol	Excellent automotive fuel Very low emissions of ozone-forming HCs and toxics Can be made from a variety of feedstock, including renewables	Fuel could initially be imported Somewhat lower vehicle range
Natural Gas	Very low emissions of ozone-forming HCs, toxics, and CO Can be made from a variety of feedstock, including renewables Excellent fuel, especially for fleet vehicles	Higher vehicle cost Lower vehicle range Less convenient refueling
Propane	Cheaper than gasoline today Most widely available clean fuel today Somewhat lower emissions of ozone-forming HCs and toxics Excellent fuel, especially for fleet vehicles	Cost will rise with demand Limited supply No energy security or trade balance benefits

As shown in Table 9, many of the alternative clean fuels have their advantages; however, the cost to produce the fuels as well as the limited available technology make them more suited for fleet vehicles, and not for most passenger vehicles.

Cost Effectiveness

Estimated costs for possible large-scale mitigation measures are shown in Table 10. It is shown that each CM can have a large range of high and low cost-effective options. Although introducing more stringent NAAQS for new vehicles every few years could be a cost-effective way to reduce emissions, the price per ton of emissions reduced would increase over the years due to complexity of reducing the emissions of the cleaner vehicle. Also, if approximately 10% of vehicles produce 50% or more of the pollution, this solution does little to reduce the emissions of cars already present on the road [1]. Some aspects of retrofitting or retiring vehicles can be cost-effective; however, replacing entire fleets can cost as much as $4 million/ton for the reduction of ROGs [32, 33]. Additionally, replacing current fleets with alternative fuel vehicles can be cost-effective; however, without readily available fueling stations, these technologies are not feasible for large-scale passenger use [31]. By retrofitting older HDV and LDV, and using fuel additives in existing engines, there are more cost effective possibilities for reducing vehicular emissions. However, the CM with the most cost-effective measures is improving current I/M programs. Although this is not a complete list of control measures and their cost-effectiveness, I/M programs have frequently been listed as core air pollution controls for urban areas [22].

Table 10: Cost effectiveness of large-scale mitigation measures.

Control Measures				Potential Emission reductions (%)		Cost effectiveness Range ($/Ton)		Average Cost Effectiveness ($/Ton)	Source
Category and Affected Vehicle Type: Gasoline (G) or Diesel (D)		Type	Pollutant	Low	High	Low	High		
New-vehicle standards	**G and D**	Require on-board diagnostics on new diesel and gasoline trucks and buses	NO_X	-	1.1	-	$28,251	$28,251	[32, 33]
			ROG	-	4.2	-	$162,228	$162,228	
New-vehicle standards	**G and D**	Stricter Engine Standards (1991-1998)	NO_X	-	-	-	$419	$419	[13]
New-vehicle standards	**G and D**	Stricter Engine Standards (1991-1996)	PM	-	-	-	$3,207	$3,207	[13]
Retrofitting	**D**	Retrofit emission controls on heavy duty diesel vehicles	NO_X	1.7	24.0	$4,700	$17,000	$10,850	[32, 33]
			ROG	3.1	7.7	$0	$90,500	$45,250	
Retrofitting	**D**	Retrofit heavy-duty diesel vehicles with dual fuel (LNG and diesel) engines	NO_X	-	30.2	-	$31,700	$31,700	[32, 33]
Retrofitting	**G**	Retrofit with 3-way catalysts on gasoline-burning heavy duty trucks that currently have 2-way catalysts or no catalysts	NO_X	2.2	89.9	$200	$2,300	$1,250	[32, 33]
			ROG	2.7	55.9	TBD	TBD	TBD	
Retrofitting	**G**	Install new engines with 3-way catalysts on gasoline-burning heavy duty trucks that currently have 2-way catalysts or no catalysts	NO_X	3.6	70.9	$3,000	$13,000	$8,000	[32, 33]
			ROG	0.3	52.8	TBD	TBD	TBD	
Retrofitting	**D**	Repower heavy-duty diesel vehicles with newer, lower emitting engines	NO_X		17.8	$9,100	$10,500	$9,800	[32, 33]
			ROG	-	79.1	$36,300	$87,100	$61,700	
Retrofitting	**G and D**	Reduce emission from heavy-duty vehicles serving transportation facilities	NO_X	0.0	0.3	-	$13,000	$13,000	[32, 33]
			ROG	NA	NA	-	$420,000	$420,000	
Retrofitting	**D**	Heavy-duty engine ECM recalibration	NO_X	-	7.2	-	$149	$149	[32, 33]
			ROG	-	23.8	-	$1,135	$1,135	

Table 10: Cost effectiveness of large-scale mitigation measures (continued).

Retrofitting	**G**	Implement a program to replace catalysts in light duty vehicles and trucks, including SUVs	NO_X	5.4	9.6	\$3,800	\$6,800	\$5,300	[32, 33]
			ROG	5.3	8.9	\$3,900	\$6,500	\$5,200	
Retrofitting	**D**	25% Reduction retrofit kit	PM	-	-	\$8,800	\$20,150	\$14,475	[13]
Retrofitting	**D**	Full reduction retrofit kit	PM	-	-	-	\$32,800	\$32,800	[13]
Fuel Additives	**D**	Use emulsified diesel fuel in all diesel-burning heavy duty vehicles	NO_X	2.1	8.3	-	\$38,989	\$38,989	[32, 33]
Fuel Additives	**G**	CA Phase 3 Reformulated Gasoline	VOC + NO_X	-	-	\$2,000	\$2,000	\$2,000	[34]
Fuel Additives	**G**	Federal Phase 2 Reformulated Gasoline	VOC + NO_X	-	-	\$3,600	\$83,500	\$43,550	[34]
Fuel Additives	**G**	CA Phase 2 Reformulated Gasoline	VOC + NO_X	-	-	\$3,600	\$45,000	\$24,300	[34]
I/M	**G and D**	Provide free replacement gas caps to light- and medium-duty vehicle owners	ROG	-	1.8	\$31,000	\$142,000	\$86,500	[32, 33]
I/M	**G and D**	Improve smog check	NO_X	4.8	7.3	\$10,700	\$12,700	\$11,700	[32, 33]
			ROG	3.4	7.2	\$11,400	\$13,700	\$12,550	
I/M	**G and D**	Increased smoking vehicle enforcement	NO_X	-	0.1	-	\$696,300	\$696,300	[32, 33]
			ROG	-	2.5	-	\$15,800	\$15,800	
I/M	**G and D**	Use remote sensors and license plate photos to identify smoking vehicles	ROG	-	0.0	-	\$324,633	\$324,633	[32, 33]
I/M	**G and D**	Allow district to opt into test-only program	NO_X	-	1.1	-	\$6,523	\$6,523	[32, 33]
			ROG	-	1.4	-	\$4,882	\$4,882	
I/M	**D**	Include NO_X screening in the heavy-duty vehicle inspection program	NO_X	-	1.6	-	\$7,900	\$7,900	[32, 33]
			ROG	-	10.4	-	\$24,700	\$24,700	
I/M	**G**	End the motorcycle smog check exemption	NO_X	-	3.8	-	\$167,880	\$167,880	[32, 33]
			ROG	-	6.7	-	\$30,166	\$30,166	

Table 10: Cost effectiveness of large-scale mitigation measures (continued).

I/M	**D**	Augment truck and bus inspections with community-based inspections	NO_X	0.1	2.4	-	$4,000	$4,000	[32, 33]
			ROG	0.6	8.6	-	$10,000	$10,000	
I/M	**D**	Establish a heavy-duty smog check program	NO_X	-	2.6	-	$7,900	$7,900	[32, 33]
			ROG	-	6.7	-	$24,800	$24,800	
I/M	**G and D**	Halt the rolling 30-year exemption in the Smog Check program	NO_X	-	0.5	-	$25,100	$25,100	[32, 33]
			ROG	-	2.3	-	$9,500	$9,500	
I/M	**G and D**	Transfer Smog Check operations to a government agency	NO_X	-	1.1	-	$6,004	$6,004	[32, 33]
			ROG	-	1.4	-	$4,493	$4,493	
I/M	**G and D**	Inspection and Maintenance	NO_X + VOC	-	-	$1,800	$5,800	$3,800	[34]
I/M	**G and D**	Remote Sensing	NO_X + VOC	-	-	-	$4,100	$4,100	[34]
I/M	**G and D**	Inspection and Maintenance	NO_X + HC	-	-	-	$5,300	$5,300	[35]
I/M	**G and D**	Inspection and Maintenance	NO_X + HC	-	-	$4,400	$9,000	$6,700	[17]
Fleet retirement/ replacement programs	**G and D**	Implement a light duty vehicle retirement program for gross polluters	NO_X	0.7	1.3	$59,000	$118,000	$88,500	[32, 33]
			ROG	1.2	1.8	$39,300	$59,000	$49,150	
Fleet retirement/ replacement programs	**D**	Accelerate the turnover of older, higher emitting engines to cleaner, late model engines for heavy duty diesel vehicles	NO_X	2.6	27.4	$7,000	$34,000	$20,500	[32, 33]
			ROG	4.0	40.0	$50,000	$500,000	$275,000	
Fleet retirement/ replacement programs	**G and D**	Establish Clean Fleet Requirements for public fleets	NO_X	0.1	0.2	$13,000	$30,000	$21,500	[32, 33]
			ROG	0.1	0.2	$25,000	$59,000	$42,000	
Fleet retirement/ replacement programs	**D**	Purchase new low-emission heavy-duty vehicles instead of diesel vehicles	NO_X	-	1.6	-	$95,800	$95,800	[32, 33]
			ROG	-	1.3	-	$3,900,000	$3,900,000	
Fleet retirement/ replacement programs	**G and D**	New Capital Transit Systems/Vehicles	NO_X + VOC	-	-	$8,500	$471,000	$239,750	[34]
Fleet retirement/ replacement programs	**G and D**	Conventional Transit Service Upgrades	NO_X + VOC	-	-	$3,800	$120,000	$61,900	[34]

Table 10: Cost effectiveness of large-scale mitigation measures (concluded).

Fleet retirement/ replacement programs	**G and D**	Conventional-Fuel Bus Replacement	NO_X + VOC	-	-	$11,000	$39,900	$25,450	[34]
Fleet retirement/ replacement programs	**G and D**	Old-vehicle Scrappage	NO_X + VOC	-	-	$2,500	$6,400	$4,450	[34]
Alternative Fuel Vehicles	**G and D**	Alternative-Fuel Buses	NO_X + VOC	-	-	$6,700	$569,000	$287,850	[34]
Alternative Fuel Vehicles	**G and D**	Compressed Natural Gas Vehicles	NO_X + VOC	-	-	$0	$3,600	$1,800	[34]
Alternative Fuel Vehicles	**G and D**	Methanol Vehicles	NO_X + VOC	-	-	$5,300	$43,600	$24,450	[34]
Alternative Fuel Vehicles	**G and D**	Hybrid Electric Vehicles	NO_X + VOC	-	-	$1,100	$18,900	$10,000	[34]
Alternative Fuel Vehicles	**G and D**	Electric Vehicles	NO_X + VOC	-	-	$6,600	$72,400	$39,500	[34]
Alternative Fuel Vehicles	**G and D**	Liquefied Petroleum Gas Vehicles	NO_X + VOC	-	-	$13,000	$80,000	$46,500	[34]
Alternative Fuel Vehicles	**G and D**	Ethanol Vehicles	NO_X + VOC	-	-	$12,600	$152,200	$82,400	[34]
Alternative Fuel Vehicles	**G and D**	Alternative-Fuel Vehicles	NO_X + VOC	-	-	$4,000	$31,600	$17,800	[34]

Project-Level Control Measures

Project-level control measures are those that are applicable on a small-scale level, and can be used to improve air quality over a limited range, such as a section of roadway, or area of a city. These CMs are driven largely by PM hot-spots, and by conformity assessments for CO; however, diesel particulate matter (DPM) and HCs are also of growing concern. CMs that reduce vehicular emissions on the project level work in two main ways: by changing the behavior of drivers, Transportation Demand Management (TDM), or by changing the way traffic flows, Transportation System Management (TSM). Examples of TSM and TDM are shown in Table 11.

Table 11: Possible project-level control measures [3, 16, 34, 36, 37].

Project-Level Control Measure	Categories	Examples
TSM	Roadway Limitations	Install High Occupancy Vehicle (HOV) lanes Increase roadway capacity (increase lanes) Limit access to clean vehicles (ZEV, pZEV, SULEV, ULEV) Limited use/access to downtown areas (during peak congestion times) Charge to enter congested area Set up a toll road system
	Traffic Operations	Traffic signal timing Ramp metering Turning restrictions Conversion of two-way to one-way streets
	Accident Avoidance	Enhance roadside assistance Visual electronic traffic alerts
	Commercial vehicle control	Loading zone controls Truck routing/scheduling
TDM	Park-and-Rides	Additional park-and-ride facilities
	Employer Programs/Ridesharing	Employer trip reduction programs Telecommute (Satellite work centers) Permitting flexible work schedules Vanpools Ridesharing
	Public education	Additional public outreach
	Bicycle/pedestrian-oriented programs	Bicycle paths Secure bicycle storage Pedestrian malls Road limitations to support non-motorized vehicles and pedestrians
	Transit/paratransit improvements	Shuttles Bus service Rail service Additional park-and-ride facilities
	Pricing	Gasoline/vehicle taxation Transit fare/toll adjustments
	Trip reduction ordinances (TROs)	Requiring a reduction of VMT, trips, or other methods of reducing travel
	Parking management	Parking restrictions /rate changes
Other Controls	Truck controls	Reductions in truck or vehicle idling Re-direct trucks around central business areas Designated loading zones

Transportation System Management (TSM)

Single occupancy vehicles (SOVs) as a percentage of commuters have increased over the years [38]. It has been hypothesized that these increases have resulted because of increased vehicle availability, an increase in vehicle ownership (because of increased wages, or decrease in vehicle ownership cost), or because ridesharing has lost its convenience/cost effectiveness for the commuter [38]. One way to reduce the amount of SOVs on the roadway is to introduce incentives for HOVs. HOV lanes are lanes designated for use by vehicles with more than one occupant, and include vanpools, carpools, and transit vehicles. The EPA lists HOV implementation as one of the most popular CM, and can add additional capacity to a roadway, decreasing congestion and therefore vehicular emissions [16]. HOV lanes can operate full-time, during peak hours for commuter traffic, and can also involve reversal of travel direction depending on the more congested trip direction [16]. In addition, adding parking facilities at the entrance to HOV lanes may also decrease vehicular emissions by making a more efficient transfer point between the vehicle and the HOV lane [16]. It has also been suggested that offering the use of HOV lanes to SOVs for a small fee would reduce traffic congestion and also reduce the cost of implementation. Although the additions of HOV lanes are a popular choice when reducing vehicular emissions, they may not have as great of emission reducing potential. Some studies suggest that HOV lanes have an average emissions reduction of about 1%, which is small compared to its potential cost [16]. In addition, the EPA estimates that the average time for a HOV lane to be planned, designed, and constructed can be between 3 to 8 years [16].

Traffic operations are used to increase traffic system efficiency, and are achieved by improving traffic flow along corridors and intersections. Decreases in idling time as well as improving traffic speeds can reduce emissions such as CO and HC, and in some cases can even decrease fuel consumption [29]. An increase in efficient traffic signalization can improve traffic flow through both intersections and entrances and exits to freeways. For local streets and intersections, timing traffic signals to correspond with peak traffic flows can minimize delays; also, removing traffic signals that are no longer necessary can also improve traffic flows during peak times [16]. Although improving signal timing can initially prevent idling and congestion, additional cars may be attracted to these corridors that are experiencing less traffic, causing a displacement of vehicles, and little emissions reductions [16]. Also, extensive fieldwork and intensive observation of congested areas must be performed before signaling improvements or signal removal is made. Another way to improve traffic flow is to improve the systems efficiency by introducing new signage or lane markings. Preventing left-turns at busy intersections or changing roads from two-way to one-way can achieve improved flow of the roadway during peak traffic hours [16]. These methods require little construction, and are easily implemented in short amounts of time causing improved circulation for localized areas [16, 29].

Accident avoidance measures include using visual electronic traffic alerts and rapid response teams when there are roadway delays. Visual electronic traffic alerts can warn approaching motorists of accidents, abrupt changes in speeds, or time delays due to construction or accidents. These signs can also suggest alternative routes; however, this is sometimes seen as a displacement of emissions instead of increasing the flow of traffic [26]. Rapid response teams are used for faster removal of stalled vehicle or debris that is causing congestion in the roadway. In some cases, such as with the TranStar Management Center in Houston, response time by authorities to reach incidents has decreased by one-third [34]. This decrease in response time will speed up the process of removing wreckage/debris from the roadway, and therefore decrease opportunities for additional accidents as well as minimize delays and congestion.

Transportation Demand Management (TDM)

The 1990 CAAA requires the implementation of employer programs or ozone nonattainment areas that are sever and extreme, and can consist of mandatory and voluntary measures [2]. Employer-based programs can be very cost effective, and are primarily implemented in urban areas (population ≥ 250,000) by employers that have 100 employees or more working on-site [16]. There are three main types of employer-based programs identified by the EPA, the first one being general travel allowance programs [16]. The administrative costs for these programs are low, and involve giving bonuses to employees for use of any transportation mode [16]. The only cost incurred by the employer is the actual cost of the bonus, and this type of program can lead to additional benefits such as reductions in cost of employee parking and parking maintenance [16]. The other two types of employer-based programs are specific allowance and flexible use allowance programs. These programs budget money for specific transit programs, such as vanpools, or flexible use of funds for many different transit providers; however, they can be very costly and complicated due to their great accounting and monitoring needs [16]. In addition to the EPA listed programs, employers can establish or mandate other trip-reduction programs, such as ridesharing, bicycling/walking, and guaranteed ride home programs which assist commuters if they miss their bus/train [34]. Although the commuter market is the best target for these types of ridesharing programs, without financial incentives, high employee turnover as well as a lack of employer funding with decrease the effectiveness of these programs. Tax incentives, subsidy programs, and enabling legislation (such as mandating employer involvement) are all needed to successfully create long-term employer-based CMs. In addition to trip-reducing programs, employers can also allow employees the options of telecommuting, flextime, and compressed work weeks. These programs allow employees to either work from home, set their own arrival/departure times, or work more than eight hours per day for a shorter amount of days per week [16]. All these measures allow a reduction in commuter traffic, and can reduce emissions during peak commuter times. Since these measures are voluntary, they do not require government funds, and are easy to implement at a low cost if they are carefully coordinated by employers and employees [16]. In 1997, the Commuter Connections program was established in the Washington D.C. region, and aimed to reduce SOV travel [34]. Using the assistance of government funding, this organization promoted transportation demand strategies to employers, and over a course of two years reduced daily trips by 7300, and VMT reductions of 90,000 [34].

Public education and outreach programs are designed to inform the public about a region’s emission problem (most commonly ozone), and encourage voluntary emission reducing programs. Programs that promote proper vehicle maintenance or the reducing/combining of vehicle trips can be successful in reducing emissions, and can also result in an increase in transit ridership as well as a reduction in roadway congestion [34]. “Ozone action Days” or “Spare the Air” days can be popular programs that promote reducing trips on days/times when ozone formation is more likely to occur [26]. Offering reduced or free public transit rides on these days can help increase awareness of public transportation, resulting in an overall increase in year-round ridership [34].

Bicycle and pedestrian programs can involve the construction or improvement of pedestrian walkways as well as bicycle paths. Employer-based programs can also improve these programs by offering bicycles for employee use, shower and locker facilities, free bicycle maintenance and supplies (such as helmets, bicycle lights, etc.), free or cost-reduced bicycles, bonus days off for bicycle use, and occasional tardiness allowances [16]. The EPA suggests that walking and bicycling can be substituted for trips less than one-half miles and 5 miles, respectively; although the VMT reduced is small, emissions reductions may be greater due to the elimination of some cold-start and hot-soak emissions [16]. In addition, zoning that promotes dense developments incorporating both housing and commercial areas could potentially increase the use of bicycle and pedestrian walkways [29].

Public transit includes buses, rail transportation (both heavy and light), and paratransit (passenger transportation that does not involve set routes or schedules). The EPA identified three main ways public transit could be improved, and includes system/service expansion projects, system/service operational improvements, and inducements to transit users [16]. The goal of expansion projects is to increase ridership of public transit, and can be accomplished by increasing the number of routes and/or increasing the frequencies of the service [16]. However, similar goals can also be met, sometimes at a lower cost, by making operational improvements; these improvements focus on scheduling changes and geographical coverage to increase transit use [16]. In addition, inducements to potential transit users can focus on marketing strategies, customer, or fare structures can cause a beneficial increase in public/paratransit use [16]. Although these strategies are designed to decrease vehicular congestion by encouraging commuter use, the costs of the projects must be seriously evaluated, and aggressive marketing strategies must be used to make this CM cost effective [16]. The Transportation Research Board (TRB) evaluated many CMs, one being a free shuttle serving riders commuting out of Chicago. Service began in 1996, and, with steady ridership increases over time, the program expanded its shuttle service from vans to busses. An evaluation in the early 2000s showed that 55% of commuters using the service reported that they used to ride alone [34]. It is estimated that this

SOV decrease has reduced VOCs by a total 2.7 tons, and eliminated 1.8 million VMT [34]. Although improving public transit may initially be costly, it is a long-term solution for reducing VMT and the resulting vehicular emissions.

Park-and-Ride facilities are designed to accommodate passengers transferring to public transit, carpools, vanpools, or any other ridesharing program [36]. Transportation agencies can either formally or informally designate these lots, and their use reduces emissions by reducing the number of trips make from home to work [16]. Most of these lots are built near highway interchanges or key areas along heavily traveled roadways, which are not close to the business district or center of town [16]. The costs of acquiring land and maintenance requirements are high, but not as costly as HOV facilities [16].

Trip-reduction ordinances (TROs) consist of voluntary or mandatory reduction in VMT, trips, or the use of alternative forms of transport, such as public transit or ridesharing [16]. These programs are most successful when used by employees and agencies, and are most applicable to larger businesses. TROs can be used to enforce employer-based trip reduction programs, with violation penalties ranging from fines to criminal prosecution (although this severe punishment is rarely used) [16]. Because TROs can become a burden on small or new businesses, this TDM is most commonly applied to businesses with more than 50 employees [16].

Parking controls and parking management are designed to reduce vehicle trips or VMT by offering parking incentives to those that rideshare. By increasing parking costs or decreasing parking availability for SOVs, drivers are encouraged to participate in vanpools, carpools, or other ridesharing programs to obtain preferential parking [16, 29]. Some examples of parking controls are: preferential parking for HOVs, an increase in parking costs, limitations on public and private parking spaces, and parking structures that discourage long-term parking through fees [16]. The emissions reductions from these programs are hard to quantify but are most successful when used jointly with employer-based rideshare programs, and when adequate pedestrian, bicycle, and other transit facilities are located nearby [16].

Special Focus: Project Level Diesel CMs

For smaller sections of roadway that are near to pollution sensitive populations (such as schools), project level control measures should be used to reduce vehicular emissions in these sensitive areas. Diesel exhaust contains over 40 substances listed as toxic air contaminants by the Air Resources Board (ARB), and the small particles that comprise DPM are severe lung irritants [39]. The strict regulation of diesel emissions is important to maintain low cancer risks and prevent other potential lung related conditions for those exposed to exhaust near roadways. Although retrofitting and other large-scale CMs are successful at reducing diesel emissions, they are not feasible for project-level needs. Truck controls such as idling limits, scheduling changes, or re-routing HDDVs around emissions sensitive areas are all options to reduce diesel exposure. By restricting truck use in central business areas or in emission sensitive areas (such as schools), emissions can be reduced where there are potentially more pedestrians. Limiting delivery schedules, designating loading zones, and mandating delivery consolidation for multiple businesses can also decrease local street congestion, or congestion during peak hours in a central business district [16]. To implement this CM, many things must be taken into consideration, such as current truck routes, financial impacts on the economy due to truck relocation, and also the direct costs occurred by the businesses for the truck controls [16, 37]. Additionally, idling controls can be used to lower CO emissions from diesel- or gasoline-powered vehicles in nonattainment areas [16, 37]. By controlling the construction of businesses with drive-through facilities, and restricting the idling times of commercial delivery trucks, additional emissions can be reduced [16]. Truck idling uses the diesel engine to produce a small load, such as running an air conditioner, while producing excess emissions [29]. Using auxiliary engines to provide a small load (instead of the diesel engine supplying the load) is an idling reduction technology that could reduce fuel consumption by approximately 15% [29]. Also, regulations mandating a maximum idling time (~15 minutes) can also be used to cut down on excess emissions of vehicles making deliveries, as well as buses that are loading/unloading for extended periods of time [29, 37]. For idling/trucking restrictions to successfully reduce emissions, the cooperation of the trucking industry, local businesses, and effective legal restrictions is required [16].

Cost Effectiveness

Estimated costs for potential regional CMs are shown in Table 12.

Table 12: Cost effectiveness of large-scale mitigation measures.

Control Measures				Potential emission reductions (%)		Cost effectiveness Range ($/Ton)		Average Cost Effectiveness ($/Ton)	Source
Category and Affected Vehicle Type: Gasoline (G) or Diesel (D)		Type	Pollutant	Low	High	Low	High		
TDM	G and D	Develop a station car/low emission vehicle share program	NO_X	-	0.1	-	$1,784,153	$1,784,153	[32, 33]
TDM	G and D	Develop a station car/low emission vehicle share program	ROG	-	0.1	-	$1,585,935	$1,585,935	[32, 33]
TDM	G and D	Encourage participation in an Automobile Maintenance Organization	NO_X	-	0.9	-	$85,800	$85,800	[32, 33]
TDM	G and D	Encourage participation in an Automobile Maintenance Organization	ROG	-	0.8	-	$88,900	$88,900	[32, 33]
TDM	G and D	Develop and fund a program for neighborhood electric vehicles	NO_X	-	0.0	-	$2,948,754	$2,948,754	[32, 33]
TDM	G and D	Develop and fund a program for neighborhood electric vehicles	ROG	-	0.1	-	$2,790,821	$2,790,821	[32, 33]
TDM	G and D	Shuttles, Feeders, Paratransit	NO_X + VOC	-	-	$12,300	$1,970,000	$991,150	[34]
TDM	G and D	Bicycle/Pedestrian	NO_X + VOC	-	-	$4,200	$345,000	$174,600	[34]
TDM	G and D	Subsidies and Discounts	NO_X + VOC	-	-	$900	$550,000	$275,450	[34]
TDM	G and D	Park-and-Ride Lots	NO_X + VOC	-	-	$8,600	$70,700	$39,650	[34]
TDM	G and D	Employer Trip Reduction Programs	NO_X + VOC	-	-	$5,800	$176,000	$90,900	[34]
TDM	G and D	Vanpool Programs	NO_X + VOC	-	-	$5,200	$89,000	$47,100	[34]
TDM	G and D	Charges and Fees	NO_X + VOC	-	-	$900	$50,000	$25,450	[34]
TDM	G and D	Telecommute	NO_X + VOC	-	-	$13,300	$8,230,000	$4,121,650	[34]
TSM	G and D	Re-evaluate the traffic volumes that trigger ramp-metering lights	NO_X	-	1.0	-	$1,206	$1,206	[32, 33]
TSM	G and D	Re-evaluate the traffic volumes that trigger ramp-metering lights	ROG	-	1.0	-	$2,218	$2,218	[32, 33]
TSM	G and D	HOV Facilities	NO_X + VOC	-	-	$15,700	$333,000	$174,350	[34]
TSM	G and D	Freeway/Incident Management	NO_X + VOC	-	-	$2,300	$544,000	$273,150	[34]
TSM	G and D	Traffic Signalization	NO_X + VOC	-	-	$6,000	$128,000	$67,000	[34]

Many project-level CMs are costly because they involve expensive marketing tactics along with cooperation from the public, employers, and the trucking industry. The effectiveness of each program can vary by region, and also depends on the agency/industry who is implementing the CM. It may be more costly for smaller businesses to implement employer-based rideshare programs, therefore the cost effectiveness will decrease due to their limited resources [16]. Also, it is more complicated to estimate the cost effectiveness of project-level CMs. In some cases, these CMs will cause unexpected benefits, such as a rideshare program reducing congestion as well as providing a reduction in trips. Project-level CMs must be thoroughly evaluated before implementation, and may not initially be a cost-effective solution. However, if these CMs are properly promoted and contain incentives for participation, the benefits (including cost-effectiveness) have the potential to increase over time.

Conclusions

Control measures can reduce vehicular emissions directly, or indirectly, and are essential strategies to reduce negative health effects due to vehicular emissions exposure. In areas where there are potential NAAQS violations, control measures must be evaluated, and their cost-effectiveness quantified to effectively reduce vehicular emissions. A control measure is successful when it reduces a specified vehicular pollutant in a cost effective manner; therefore, CMs must be thoroughly evaluated before implementing. To successfully implement a control measure, it must first be determined if the pollution problem is regional one or if it is a project-level (or hot-spot) problem. Although some project-level CMs can be successful on the region-level (such as ridesharing), the inverse is not always true (retrofitting is not a cost-effective project-level CM). Also, the control measure’s effectiveness at controlling the targeted pollutant must be carefully evaluated. Because some CMs only work for specific pollutants (i.e. RFG can decrease VOCs, but potentially increase NO_X), the applicability of the CM must be investigated [30]. Additionally it is also necessary, especially for TSMs, to thoroughly market the CM to make it successful [16]. For programs that involve changing the behavior of a driver, incentives can help make SOV driving less desirable and will lead to a reduction in vehicle trips and a decrease in emissions. When CMs are implemented successfully, they can reduce vehicular emissions on a regional- and project-level scale, and provide a way to meet NAAQS standards in a cost-effective manner.

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