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16. Abstract

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A COMPREHENSIVE EXAMINATION OF HEAVY VEHICLE EMISSIONS FACTORS

by

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ABSTRACT

This report summarizes the findings from reviewing the literature on several topics that are related to heavy vehicle emissions including engine and fuel types, vehicle technologies that can be used to reduce or mitigate vehicle emissions, the factors that affect vehicle emissions, vehicle emissions modeling, and current and future policy requiring accurate accounting of heavy vehicle emissions. The pollutants present in diesel exhaust are known to have undesirable effects on both human health and the environment. There are many engine and fuel alternatives for current and prospective vehicle owners to consider that have differing effects on a vehicle's pollutant output. In addition, new technologies, such as diesel particulate filters, auxiliary power units, and selective catalytic reduction, are being used in the production of new vehicles, and can often be installed on used vehicles, to reduce emissions and/or improve fuel economy. Accurate heavy vehicle emissions modeling is important in forming policies designed to reduce pollutants from heavy vehicle operation at both the vehicle and regional level. Such policies can include cap-and-trade schemes, carbon taxing, and road user charging. All of these policy types have been implemented in the European Union to varying degrees, but only some have been implemented in the United States. However, all of these are now being considered in the U.S., and could be implemented in the future.

EXECUTIVE SUMMARY

Vehicle exhaust has been shown to be directly and indirectly harmful to human and environmental health. Diesel exhaust in particular has been linked to health problems. While not a significant contributor to CO and HC emissions, diesel exhaust contains relatively large amounts of PM and NOx. PM emissions can reach the lungs and have adverse affects on the respiratory system. NOx can form smog, acid rain and PM after reacting with other chemicals in the atmosphere. U.S. heavy-duty vehicle emissions standards for PM and NOx are becoming progressively strict, reducing both in new vehicles by about 90% by 2010. Heavy-duty vehicles also contribute significantly to GHG emissions, which are believed to contribute to climate change. This report summarizes the findings from reviewing the literature on several topics that are related to heavy vehicle emissions including engine and fuel types, vehicle technologies that can be used to reduce or mitigate vehicle emissions, the factors that affect vehicle emissions, vehicle emissions modeling, and current and future policy requiring accurate accounting of heavy vehicle emissions.

The majority of heavy-duty vehicles employ a conventional diesel engine that is either turbocharged or naturally aspirated. Turbocharged engines allow for downsizing the engine while maintaining the same power. In addition, turbocharged engines recover exhaust energy that would have been wasted with a naturally aspirated engine. Both of these characteristics contribute to increased fuel economy of turbocharged engines relative to naturally aspirated engines, and as a result are more common for use in HDV. They also are effective in reducing NOx and PM emissions by 30%.

Passenger vehicle electric hybrids are of the series variety, and the electric motor directly powers the wheels. Heavy duty vehicle electric hybrids are of the parallel variety, and both the diesel engine and electric motor power the wheels. Electric hybrid engines have not yet been used in combination trucks, but have been used in many bus and package delivery truck fleets (e.g. UPS and FedEx). Despite the increased fuel efficiency and air quality benefit, electric hybrid engines are not a popular choice for heavy-duty vehicles because they are more expensive than conventional engines. Lead-acid batteries are no longer used in hybrid vehicles and were replaced with Nickel Metal Hydride (NiMH) batteries that have higher energy density and are safer (though more expensive). It is expected that Lithium-ION batteries will replace NiMH batteries in the future due to greater longevity and lower cost.

Hydraulic hybrids, vehicles powered by a diesel motor and hydraulically stored energy, are an inexpensive alternative to electric hybrids for large vehicles. Though still in the development stage, these vehicles improve fuel economy 50-70% and reduce GHG, HC, and PM emissions by roughly 50%. Costing only 15% more than a comparable conventional vehicle, it is estimated that the payback period is between 1 and 3 years.

The majority of fuel used to power heavy-duty vehicles is diesel, while gasoline and liquefied petroleum gas also provide fuel for a significant portion (10% and 0.3%, respectively). Gasoline vehicles are responsible for the majority of CO and HC emissions, while diesel vehicles are known for emitting large amounts of NOx and PM. Diesel is more common for use in heavy-duty vehicles because the engines are more powerful and efficient. Ultra-low sulfur diesel (ULSD) is now required in the U.S., which can reduce PM emissions by 90% when used with PM exhaust filters. Emulsified diesel, a mixture of petroleum diesel and water, is effective in reducing PM and NOx for only 20 cents more per gallon, making it an attractive option for school bus fleets trying to reduce their emissions. One drawback of emulsified diesel is that if it sits for long periods of time, it can separate and damage the vehicle.

Biodiesel can reduce emissions of GHG (lifecycle, not tailpipe), PM, HC and CO. Most fleets prefer not to use 100% biodiesel because it would require altering the vehicle to avoid maintenance issues. B20, a mixture of 20% biodiesel and 80% petroleum diesel, still reduces emissions without the need to alter vehicles. Ethanol is another biofuel that is commonly used in place of, or blended with, gasoline. The way that ethanol is produced has a large impact on its ability to reduce emissions. Ethanol made from corn offers the least emissions benefits, while sugarcane and cellulosic ethanol offer 2-3 times the benefit of corn ethanol. However, cellulosic ethanol is still in developmental stages and is not being commercially produced. It should be noted that biofuels only offer GHG emissions benefits if no agricultural land conversion is required to produce the fuel.

Relative to diesel fuel, natural gas reduces emissions of PM, NOx, and HC by 50%, and CO2 by 25%. However, it is necessary to invest in a private fueling storage and distribution system. It is a good alternative fuel for fleets that return to their point of origin on a daily basis (e.g. intracity buses and delivery trucks). Natural gas vehicles can cost twice as much as their diesel equivalent, but there are an increasing number of subsidies available to help offset this cost. Fischer-Tropsch (or Gas-to-Liquid diesel) is diesel fuel typically derived from natural gas. California has been mixing Fischer-Tropsch diesel with petroleum diesel to reduce PM emissions. Table X shows the costs and savings (both capital costs and emissions) associated with heavy-duty vehicle alternative fuel and engine choices.

The best engine and fuel option for heavy vehicles really depends on the vehicle type and the desired performance of the engine and fuel combination. For example, hybrid vehicles are a good option for smaller short-haul vehicles when fuel economy is a concern. In addition, many alternative fuels are effective in reducing emissions of some pollutants, but not effective in reducing others.

To meet EPA's 2007 and 2010 emissions standards for PM, most, if not all, trucks will utilize diesel particulate filters. When used with ultra-low sulfur diesel, PM emissions can be reduced by 90%. There are a few options to reduce NOx emissions. Most manufacturers will be using selective catalytic reduction (SCR) to meet 2010 NOx standards. Navistar is the exception, and they plan to rely on exhaust gas recirculation. NOx absorbers are a newer technology that reduces NOx emissions by 90%, but will probably not be fully developed early enough for the 2010 model year. In addition to these technologies, methods of optimizing engine and exhaust temperature can decrease NOx and PM emissions caused by cold starts. Improved fuel injection can also further improve NOx emissions.

Truck idling wastes approximately 1 gallon of fuel per hour and can cost approximately $2000 per truck depending on fuel prices. In addition to the fuel waste, excess emissions are being released into the atmosphere. Auxiliary power units, automated engine idle systems, and direct-fire heaters are all on-board devices aimed at eliminating the need for a truck to idle during extended rest periods. These can reduce fuel use by 3-10% and cost between 2 and 8 thousand dollars. Auxiliary power units cost more, but also save more fuel and have a shorter payback time. Electrified truck stops are a method of reducing engine idling without an on-board device. These stops either provide climate control for the cabin or provide the truck with electricity from which to run its own climate control system and other accessories. For this to be cost effective, it is necessary for the per-gallon price of fuel to be more than the hourly rate of the stop. Driver training and idle restriction policies can be an effective method of reducing fuel consumption and emissions from idling at pick up and drop off locations and in congested traffic.

Aerodynamic drag has decreased by 40% in the last 30 years, and the add-on devices available today can offer further reduction of 25%. Unfortunately, many of these devices infringe on the operational performance of the vehicle, making them undesirable. Low-resistance tires and super single tires are designed to reduce the rolling resistance between vehicle tires and the road surface, and can improve fuel economy by 3%. Low rolling resistance tires can be used on any truck, but require high pressure and frequent monitoring. Super singles are lower maintenance, but can only be used on newer model trucks.

The operating factors that affect heavy-vehicle emissions can be classified into roadway characteristics, traffic characteristics, driver characteristics and vehicle characteristics. As many of these factors act in tandem, it is very difficult to isolate the individual effect of each operating factors. In general, emissions increase with increase in grades, increase in congestion, aggressive driving, powerful acceleration/deceleration and stop and go traffic. These factors are important in developing and evaluating vehicle emissions models. These emission estimation models can be classified as either static emission factor based models or dynamic instantaneous emission models. Static emission factor based models calculate emission based on average traffic conditions such as average speed. There are fewer data requirements for these models, but they cannot be used to evaluate the impact of various traffic management strategies. Dynamic emission models can capture the impact of acceleration and deceleration and can be used to evaluate the impact of various traffic management strategies. However they have high data requirements such as detailed vehicle trajectory data.

Various levels of the U.S. and European heavy vehicle emissions standards are used in much of the world and are based on emissions per unit of energy expended. Japan has its own standards based on emissions per unit of distance traveled. Japan has also implemented the world's first heavy-duty vehicle fuel economy standards in 2006. In the U.S., emissions standards for PM and NOx are becoming more stringent with EPA's 2007 and 2010 heavy-duty vehicle standards.

The test cycles used to enforce these emissions standards are somewhat inadequate because engines can be designed to pass the test, yet frequently exceed the standards in real driving conditions (and is referred to as cycle beating). As a result, vehicle emissions may not be decreasing at the rate implied by the standards. To prevent test cycle beating, supplemental test cycles that are less predictable, and could potentially test a larger portion of an engine's operating range, are now being used.

It is only recently that greenhouse gases have been regulated. In 1997, several countries agreed to adhere to the maximum GHG emissions level that applied to them according to the Kyoto Protocol, and since then the United Kingdom and the European Union have implemented GHG cap and trade schemes to meet these targets. The U.S. has yet to set national GHG emissions targets, but several states have done so. Groups of states are planning future regional emissions trading schemes. At the federal level, several plans to control greenhouse gas emissions have been proposed that include targets, cap-and-trade, and carbon taxing to various degrees.

Future transportation policies related to vehicle emissions include cap and trade, carbon taxing, and road user charging. Despite numerous legislations, cap and trade and carbon taxes have not been implemented in the transportation sector, and road user charging is currently the most widespread of the three policy types. In the United States, high-occupancy toll (HOT) lanes are being implemented in multiple states, and truck only toll (TOT) lanes are also being considered in several corridors. Europe has three main types of emission related tolling strategies: (i) distance based truck tolling which vary depending on truck emission classes (ii) low emission zones where trucks have to pay a daily rate for entering based on emission class (iii) eurovignette tolls. It has been shown that HOT lanes are effective in reducing fuel consumption and GHG emissions at a corridor level. Though very few studies to date have investigated impacts for TOT lanes, it is reasonable to expect similar results. However, it is expected that much greater savings can be achieved with vehicle-centered strategies (e.g. FE standards, retrofits) than operational strategies. In addition, tolling structure can impact travel choices in such a way that may actually increase overall emissions. Distance-based charges may encourage fewer trips with heavier vehicles, while weight-based charges may encourage more trips with lighter vehicles.

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INTRODUCTION

In the US, heavy trucks are a major source of air pollutants including carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter. Trucks are also a major source of carbon dioxide (CO_2) emissions. Although CO_2 does not cause the negative health impacts associated with other mobile emissions, its performance as a greenhouse gas in excess in the environment has made its regulation a primary international concern. A number of regulatory changes are currently being debated in both the energy and transportation arenas. Carbon taxes and cap and trade systems are being considered for limiting carbon emissions. New methods for direct user charging are being considered to replace existing fuel taxes. Vehicle size and weight regulations are being reconsidered because of the energy savings and environmental benefits that might be achieved through operation of higher productivity vehicles. In order to understand the changes that might result from new forms of regulation applying to heavy trucks, it will first be necessary to gain a thorough understanding of heavy vehicle engine and fuel types, pollutants resulting from their use, vehicle design characteristics and technologies that might mitigate impacts, and the influence of operating conditions on emissions rates.

With energy concerns moving to the forefront of politics nationally and internationally, the need to accurately measure and model heavy vehicle emissions is becoming increasingly important. Currently, in the US, air pollution is regulated by the Clean Air Act. This act defines National Ambient Air Quality Standards for a variety of pollutants; any region that is not in compliance with these standards is designated as a non-attainment area. Non-attainment areas are required to submit a State Implementation Plan outlining measures that will be taken to reach the required levels within a reasonable timeframe. A failure to develop and implement such a plan could lead to loss of federal funding for the region found to be in non-compliance. With carbon emissions now recognized as a pollutant, there is much discussion concerning how it should be regulated. New regulations may come in the form of a direct carbon tax or a cap and trade system, where a maximum threshold value for carbon emissions is set, beyond which a polluter must pay a fee. Emission related variables are being introduced in several pricing schemes. As transportation, energy, and environmental policy in the US continue to evolve, it is clear that these issues can no longer be treated independently. In formulating new forms of regulation, it will be necessary to understand all of the pollutants that result from heavy vehicle emissions, the variables that contribute to emissions levels, how these variables can be controlled and mitigated, and how these variables relate to policy goals. The purpose of this study is to provide a comprehensive review of variables impacting heavy vehicle emissions, including engine types, vehicle design variables, mitigation technologies, and operating conditions.

This study first identifies the different types of heavy vehicle engines and fuel types currently in use or development. The pollutants resulting from heavy vehicle operations using different engine and fuel types are identified and their potential economic and health impacts are studied.
A review of existing and future technologies available to mitigate emissions impacts is conducted. A detailed review of heavy vehicle regulations worldwide is then conducted with specific focus on the methods and the type of pollutants regulated. The impact of various operating conditions such as vehicle and load size and weight, speed, altitude, acceleration, idling, tire pressure, on heavy vehicle emission is analyzed followed by a detailed analysis of the models used for estimating heavy vehicle emissions. The future transportation and energy policy decisions that will require accurate measurement of heavy vehicle emissions for the future is then discussed.

HEALTH AND ENVIRONMENTAL EFFECTS OF DIESEL EMISSIONS

Exhaust from heavy-duty vehicles (HDVs) contains many pollutants, including greenhouse gases (GHG) (e.g. carbon dioxide [CO2] and methane [CH4]), carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NOx), and hydrocarbons (HC). These pollutants are known to have many negative health and environmental effects, bringing importance to the regulation and reduction of such emissions. The South Coast Air Quality Management District in California estimated that 71% of the cancer risk from air pollution in the South Coast Air Basin is from diesel exhaust (SCAQMD 2000).

Evidence has shown that diesel truck emissions are more harmful to human health than gasoline vehicle emissions. Children living near roads with heavy truck traffic have decreased lung function relative to children living near roads with little truck traffic. Several studies have estimated that these kids are 60-90% more likely to experience wheezing, phlegm, bronchitis, pneumonia and allergies (Bailey and Soloman 2004). Westerdahl et al (2005) found that concentrations of ultrafine particles (less than 0.1 μm in diameter), PM, NO, and BC increased with the proportion of truck traffic. Concentrations of CO and CO2 increased with higher volumes of traffic, but showed no relationship with proportion of trucks.

Marine ports are especially harmful to regional air quality. Trucks, ships, locomotives and off-road equipment all operate on diesel fuel. Moreover, the diesel fuel used in all but trucks has high sulfur content, resulting in higher emissions per unit energy. Without further regulation, these emissions are only going to increase. Port traffic doubled between 1990 and 2001, and increased by 8.5% between 2001 and 2002 (Bailey & Soloman 2004). Encouraging idle reduction policies and the use of ULSD fuel are both inexpensive and effective ways to reduce air pollution from ports. It is estimated that a policy allowing at most 10 minutes of truck idling at the Los Angeles port would save 400 tons NOx and 2 million gallons of fuel per year, while costing approximately $800,000 per year for signage and other methods of enforcement (Bailey & Soloman 2004).

DE in general is likely to be carcinogenic to humans via inhalation. It has been shown in occupational studies that DE exposure is associated with lung cancer, but there is not definitive evidence supporting a claim that DE is carcinogenic. In addition, the level of exposure of certain occupations is probably higher than environmental exposure that most will be subjected to, so it cannot be said that these effects are average (EPA 2002).

Small (1995) has estimated the health costs associated with mobile source emissions of NOx, VOC, PM10, and SO2 in urban areas using Los Angeles Data, and Haling and Cohen (1995) have estimated these costs for rural areas in the U.S. These costs were updated to 2009 dollars and used with current heavy-duty vehicle emissions rates to estimate that the health cost of heavy-duty diesel exhaust per year in the U.S. is $28 billion. Table 1 shows the updated cost per ton of each pollutant in 2009 dollars for rural and urban areas.

Table 1: Cost Per Ton of Diesel Exhaust Pollutants ($2009/ton)

	VOC	**NOx**	**SOx**	**PM10**
Urban	4,438	16,218	167,048	155,040
Rural	764	423	523	7,832

CONTRIBUTION OF DIESEL EXHAUST

Heavy-duty vehicles contribute significantly to PM emissions. In the U.S., on-road mobile sources account for 10% of PM, while non-road mobile sources are 18%. Of that 10%, 72% are from diesel HDVs and 3% are from gasoline HDVs (EPA 2007). When natural and miscellaneous sources are left out, diesel vehicles are responsible for 23% of PM that are less than 2.5 μm in diameter, and can be as high as 35% in urban areas (EPA 2002). These particles are small enough to penetrate deep into the lungs and cause short and long-term health problems. On average, the exposure rate in the U.S. is 0.5-0.8 μg diesel PM (DPM)/m^3 of inhaled air, and is approximately 4 μg DPM/m^3 in some urban areas (according to mid-1990s estimation; EPA 2002).

Short term exposure can cause acute symptoms such as eye, throat, or bronchial irritation, lightheadedness and nausea, coughing and phlegm. There is not sufficient information available to recommend safe levels of exposure to avoid acute symptoms. It has been shown that long term exposure at levels higher than 5 μg DPM/m^3 is associated with chronic respiratory problems, but sufficient evidence is lacking to make definitive conclusions.

42% of NOx emissions from on-road mobile sources (34% of total) are from diesel HDVs and 5% are from gasoline HDVs. Once emitted, NOx can react with other chemicals in the air and form PM. In addition, NOx and HC together form smog, which can hinder visibility (EPA 2007). Congested roads with high proportion of diesel vehicles contributes significantly to SO2 emissions (Kalandiyur 2007). Both SO2 and NOx contribute to the formation of acid rain. Long term exposure to SO2 can also shrink the lungs.

Only small amounts of mobile source CO (7%) and HC (4%) emissions are from HDVs. The majority of these pollutants are emitted from light-duty gasoline vehicles. CO can be harmful to those with heart and respiratory diseases, and can cause headaches and reduced strength for all people (EPA 2007). In addition to contributing to smog formation, some HCs are toxic or carcinogenic (EPA 2007).

There are four main GHGs emitted by human activities: CO2, CH4, nitrous oxide (NO2) and fluorinated gases. In general, HDVs are responsible for the emission of 19% of mobile source and 5% of total GHGs in the U.S. While not a significant contributor to CH4 and fluorinated gases, emissions from heavy-duty vehicles are a significant source of CO2 and NO2. However, it is interesting to note that the second largest anthropogenic source of methane is natural gas systems. In processing the natural gas (composed of nearly 100% CH4) used for electricity production and other uses, methane is inevitably emitted accidently during production, transport and use of the fuel (EPA 2008). If natural gas were to become a primary fuel for transportation, methane emissions could increase as a result.

Greenhouse gases are believed to be the cause of the global rise in temperature, and if GHG emissions remain at current levels, or increase, the temperature will continue to rise (IPCC 2007). In addition to the overall rise in temperature, precipitation patterns are expected to change. The effects of these changes may be beneficial or troublesome depending on geographic region, and severity will also differ by region. However, globally speaking, the consequences of climate change are expected to be negative and impose substantial societal costs (IPCC 2007). On April 17th, 2009, the EPA announced that CO2, methane, nitrous oxide, and hydrofluorocarbons are harmful to public health (Miller, 2009). This declaration requires federal regulation of these pollutants under the Clean Air Act. Though the details are still unclear, the regulation will likely take the form of either a cap-and-trade system or taxing.

Table 2 summarizes the causes, effects, and heavy-duty vehicles' share of mobile source and total emissions from each pollutant. Because of the high proportion of PM and NOx coming from heavy vehicles, it may be especially important to reduce emissions of these pollutants from heavy vehicle exhaust.

Table 2: Cause and Effect Summary of Diesel Exhaust Pollutants.

Pollutant	Cause	Effect	HDVs' Share
PM	High sulfur content of fuel,	Acute and chronic respiratory problems, dizziness, nausea	75% (mobile) 7.5% (total)
NOx	Excess oxygen present	Forms PM, forms smog (with HC), forms acid rain	50% (mobile) 17.5% (total)
CO	Acceleration, enriched fuel-air ratio	Harmful for those with heart/respiratory disease; can cause headache and reduced strength	11% (mobile) 7% (total)
HC	Low temperature/Incomplete combustion	Forms smog (with NOx), some are toxic and carcinogenic	12% (mobile) 4% (total)
SOx	Fuel with high concentration of sulfur	Forms acid rain	1.8% (total)[1]
GHG	Directly proportional to fuel use	Contributes to climate change	19% (mobile) 5% (total)

Note: 1) 1.8% of SOx in the U.S. is from all on-road vehicles; a smaller percentage is from HDVs.

RECENT EMISSIONS POLICY

To avoid further health and environmental complications caused by pollutants found in heavy-duty vehicle exhaust, it has become a national objective to reduce these emissions, and several regulations are in place to accomplish this goal. The U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) have placed limits on grams emitted of CO, HC, NOx, and PM per unit energy. In 2000, the EPA passed new diesel emissions standards that began in 2007 and implementation will be finished in 2010. Details of these emissions regulations are discussed in the section "Heavy-Duty Vehicle Emissions Regulations". The end result of these standards, with respect to NOx and PM emissions, will be equal to eliminating 90% of heavy-duty vehicle miles (EPA 2000).

In addition to these stricter emissions standards, in 2006 the EPA required that refineries produce low sulfur diesel containing no more than 15 parts per million of sulfur, which reduces PM emissions relative to conventional diesel. When used alone, ULSD fuel reduces PM by 5-9%. Using ULSD also allows PM exhaust filters to be effective, and when used together PM can be reduced by 90%. By 2010 when all vehicles will be required to emit no more than 0.01 g/bhp-hr of PM, nearly all diesel sold in the U.S. will be ULSD.

The state of California utilizes vehicle idle limits and retrofitting requirements to reduce emissions even further than the levels obtained by new vehicle emissions standards. In 2002, California prohibited ports from operating in a manner requiring trucks to idle longer than 30 minutes. The fine for exceeding this limit is $250 per truck, and the fine for trying to avoid abiding by this policy is $750 per truck (Lowenthal 2002). In addition, California has recently tightened their diesel emissions standards by requiring existing heavy-duty vehicles to be retrofitted, taking full advantage of EPA's low sulfur and 2010 emissions standards. Beginning in January 2011, HDV owners will be required to install PM exhaust filters on all vehicles by 2014 and replace all pre-2010 engines prior to 2022 (CEPA 2008). Long haul trucks will need to have rolling resistance tires and aerodynamic devices installed to reduce fuel consumption and GHGs. These requirements will apply not only to vehicles registered in California, but also to vehicles registered elsewhere that travel within California. Exemptions will be made for low-use, emergency, military and personal use vehicles. In addition, school buses will only be required to install the PM filters and will be exempt from replacing old engines.

CONCLUSIONS

Vehicle exhaust has been shown to be directly and indirectly harmful to human and environmental health. Diesel exhaust in particular has been linked to health problems. While not a significant contributor to CO and HC emissions, diesel exhaust contains relatively large amounts of PM and NOx. PM emissions can reach the lungs and have adverse affects on the respiratory system. NOx can form smog, acid rain and PM after reacting with other chemicals in the atmosphere. U.S. heavy-duty vehicle emissions standards for PM and NOx are becoming progressively strict, reducing both in new vehicles by about 90% by 2010. Heavy-duty vehicles also contribute significantly to GHG emissions, which are believed to contribute to climate change. The EPA has recently recognized select GHGs as public health threats, and federal regulation can be expected in the near future.

HEAVY-DUTY VEHICLES, ENGINES, AND FUELS

The focus of this section is to describe features of heavy duty vehicles (HDV) that affect emissions. First, the different heavy vehicle classification schemes are presented and the FHWA and EPA vehicle classification schemes are described in detail. The engine type used by a heavy vehicle has a significant impact on the emission characteristics. Three types of engines (turbo charged, naturally aspirated and hybrid engines) are compared and contrasted with respect to the resulting emissions. Finally, the various fuel types used in heavy vehicles and the resulting emissions are described.

HEAVY VEHICLE CLASSES

Multiple vehicle classification schemes have been used in the U.S, each categorizing vehicles based on vehicle characteristics such as number and spacing of axles, total vehicle length, body or trailer type, vehicle weight, and engine or fuel type (Hallenbeck and Weinblatt, 2004). For example, the Environmental Protection Agency (EPA) and California Air Resources Board (CARB) vehicle classification systems are based on gross vehicle weight rating (GVWR) whereas the Federal Highway Administration (FHWA) classifies vehicles based on axle and vehicle configuration. Since different vehicle classification schemes are based on different vehicle characteristics, vehicle categories defined by each of the vehicle classes are not consistent with each other.

FHWA's system, Table 3, consists of 13 classes that are defined by vehicle purpose (i.e. passenger or freight transport), vehicle type/configuration (e.g. single unit, combination), number of axles and axle spacing. Light-duty vehicles are classes one, two and three, and heavy-duty vehicles are classes 4 through 13. Buses are in class 4, and the remaining HDV classes are for trucks. As HDV class increases from 5 to 13, number of axles and units also increases. Classes 5 through 7 are single unit trucks. Classes 8 through 10 are double unit trucks while classes 11 through 13 are multiple unit trucks (FHWA 2008).

Table 3: FHWA Truck Classification

FHWA Class	Truck Description	Truck Type
5	Two axle, six tire single-unit trucks	Light Duty Trucks
6	Three axle single-unit trucks	
7	Four or more axle single-unit trucks	
8	Four or fewer axle single-trailer trucks	Heavy Duty Trucks
9	Five axle single-trailer trucks	
10	Six or more axle single-trailer trucks	
11	Five or fewer axle multi-trailer trucks	
12	Six axle multi-trailer trucks	
13	Seven or more axle multi-trailer trucks	

EPA's vehicle classification system consists of 28 vehicle classes which are consolidated into 16 vehicle types that include both gasoline and diesel vehicles in a given class. Classes 2 through 5 are comprised of light duty trucks with GVWR less than 8500 lbs, whereas classes 6 through 13 are heavy duty trucks with GVWR ranging from 8500 lbs to greater than 60,000 lbs (DoE 2008). The American Automobile Manufacturers Association (AAMA) and California Air Resources Board (CARB) also classify vehicles based on GVWR. In the AAMA classification, classes 2 and 3 correspond to light duty trucks with a GVWR of less than 14,000 lbs; classes 4 through 6 correspond to medium duty trucks with GVWR ranging from 14,001 through 26,000 lbs; classes 7 and 8 correspond to heavy duty trucks with GVWR greater than 26,001 lbs (Yoon, 2005). Note that the number in the EPA abbreviation (for example HDV2b) corresponds to the AAMA truck class. The CARB classification is based on vehicle emission characteristics and it classifies vehicles into 7 classes of which classes 1 through 3 (GVWR < 8500 lbs) are light and medium duty trucks and classes 4 through 7 correspond to heavy-duty trucks. Heavy-duty trucks are further classified into light heavy-duty trucks in classes 4 and 5, medium heavy-duty trucks in class 6 and heavy heavy-duty trucks in class 7 (ARB, 2007). The USDOT also classified trucks into eight classes based on GVWR for the Vehicle Inventory and Use Survey (VIUS) data. Only trucks with a GVWR of greater than 19,501 pounds were considered heavy-duty trucks. Table 4 shows how VIUS, AAMA, and CARB classification systems compare with EPA's classification system.

Table 4: EPA Truck Classification and comparison with VIUS, AAMA, CARB

<table>
<tr><th rowspan="2">EPA Class</th><th rowspan="2">Abbrev-iation</th><th rowspan="2">GVWR In lbs</th><th rowspan="2">Description</th><th colspan="3">Other Classifications</th></tr>
<tr><th>VIUS</th><th>AAMA</th><th>CARB</th></tr>
<tr><td>2</td><td>LDT1</td><td>0-6000</td><td>Light Duty Trucks 1</td><td rowspan="5">LDT</td><td rowspan="6">LDT</td><td rowspan="2">LDT</td></tr>
<tr><td>3</td><td>LDT2</td><td>0-6000</td><td>Light Duty Trucks 2</td></tr>
<tr><td>4</td><td>LDT3</td><td>6001-8500</td><td>Light Duty Trucks 3</td><td rowspan="2">MDT</td></tr>
<tr><td>5</td><td>LDT4</td><td>6001-8500</td><td>Light Duty Trucks 4</td></tr>
<tr><td>6</td><td>HDV2b</td><td>8501-10,000</td><td>Class 2b Heavy Duty Vehicles</td><td rowspan="2">LHDT</td></tr>
<tr><td>7</td><td>HDV3</td><td>10001-14000</td><td>Class 3 Heavy Duty Gasoline Vehicles</td><td rowspan="3">MDT</td></tr>
<tr><td>8</td><td>HDV4</td><td>14001-16000</td><td>Class 4 Heavy Duty Gasoline Vehicles</td><td rowspan="3">MDT</td><td rowspan="4">MHDT</td></tr>
<tr><td>9</td><td>HDV5</td><td>16001-19500</td><td>Class 5 Heavy Duty Gasoline Vehicles</td></tr>
<tr><td>10</td><td>HDV6</td><td>19501-26000</td><td>Class 6 Heavy Duty Gasoline Vehicles</td><td>LHDT</td></tr>
<tr><td>11</td><td>HDV7</td><td>26001-33000</td><td>Class 7 Heavy Duty Gasoline Vehicles</td><td rowspan="3">HHDT</td><td rowspan="3">HDT</td></tr>
<tr><td>12</td><td>HDV8a</td><td>33001-60000</td><td>Class 8a Heavy Duty Gasoline Vehicles</td><td rowspan="2">HHDT</td></tr>
<tr><td>13</td><td>HDV8b</td><td>> 60000</td><td>Class 8b Heavy Duty Gasoline Vehicles</td></tr>
</table>

Note that the EPA and CARB HDV classification systems are similar. Both are used to determine proportion of vehicle miles traveled for input into the emissions models MOBILE 6 and EMFAC, respectively. Trucks belonging to FHWA classes 5 through 13 also correspond to EPA's heavy duty trucks class. The EPA provides guidelines on converting vehicle miles traveled data classified by FHWA truck types to EPA truck types for use in emission models. Recently, Yoon (2005) developed a methodology to convert FHWA truck class based VMT data into EPA HDV class based VMT data by using physical characteristics of trucks (e.g. number of axles, the number of tires, gross vehicle weight ratings, horsepower ranges, vehicle activity characteristics, and tractor-trailer configuration).

ENGINE TYPES

The majority of heavy-duty trucks are powered by diesel engines. There are two types of diesel engines commonly in use: turbocharged and naturally aspirated diesel engines. The principle behind a turbocharged engine is increasing the cylinder's air intake to increase power. The turbocharger comprises of a turbine and a compressor. The turbine converts the exhaust gas flow into power which is then used by the compressor to compress air into the engine. In a naturally aspirated engine, the downward stroke of the piston creates an area of low pressure, allowing air to be drawn in naturally. Due to its increased efficiency, turbocharged engines are more common among heavy duty vehicles than naturally aspirated engines.

Turbocharged engines provide better fuel economy and reduce NOx and PM emissions by 30% compared to naturally aspirated engines (Schweikert and Johnson 1973, Clean Air Initiative). The increased fuel efficiency is due to the improved engine efficiency achieved by recovering exhaust energy that would otherwise be wasted. Turbocharged engines also have a higher power to weight ratio and require less space for installation. The smaller size of turbocharged engine also results in less noise, thermal and frictional losses. Because of better torque characteristics at lower speeds, a turbocharged engine is more efficient in hilly terrain. At higher altitudes, the performance of naturally aspirated engines deteriorates due to lower atmospheric pressure resulting in significant power loss. However, turbocharged engines do not experience any additional power loss at higher altitudes (Borg Warner Exhaust and Turbo Emission Systems, 2009).

Hybrid Engines

In recent times, increasing attention has been paid to using hybrid heavy-duty vehicles, which are vehicles driven by power from multiple sources. Two types of hybrids are common for heavy-duty vehicular usage: diesel-electric hybrid engines and hydraulic hybrid engines.

Diesel-electric hybrid vehicles contain an internal combustion engine (that typically uses gasoline or diesel fuel), an electric motor powered by an alternator or generator, and an energy storage device. Note that the electric hybrid system for a light-duty vehicle is significantly different from the hybrid system for a heavy-duty vehicle. Lightweight passenger vehicles employ a series hybrid system in which the engine energy is used to drive an electric motor which provides torque for the wheels. Heavier vehicles employ parallel hybrids where both the electric motor and diesel engines can be used to drive the vehicles through separate independent connections. For optimal performance, diesel engine power is used to drive the vehicle during high speeds while the electric motor is used to power the vehicle during low speeds, and both sources power the vehicle during acceleration. Benefits of diesel-electric hybrid engines include smaller engine size, regenerative braking (converting heat energy from braking to electrical energy), power-on-demand (not using combustion engines during idle or coasting modes), constant engine speeds and power output. Presence of an electrical power source enables the diesel engine to operate at an optimal speed thus increasing fuel efficiency and reducing emissions.

Despite its obvious environmental benefits, diesel-electric trucks are not used because they are much more expensive than conventional diesel trucks. In addition, there are concerns that the battery will need replacement after the warrantee has expired. While economies of scale bring the price down for hybrid passenger vehicles, only a fraction of vehicles produced per year are heavy vehicles. Moreover, heavy vehicles are available in dozens of configurations, and each is not produced in bulk (DOE 2006). Table 5 shows the estimated incremental cost of a variety of heavy-duty diesel-electric hybrid systems. In general, a series system is more expensive than a parallel system, and utilizing lead-acid (PbA) batteries is less expensive than Nickel Metal Hydride (NiMH) batteries. In addition, as a vehicle becomes less reliant on the conventional engine (CV-like) and more reliant on the electric engine (EV-like), expense increases. An et al (2000) estimate that the average payback time for a heavy-duty diesel-electric vehicle is 6 years.

Table 5: Incremental Cost of HDV Hybridization (An et al, 2000).

$	CV-like parallel, PbA	CV-like series, PbA	CV-like parallel, NiMH	CV-like series, NiMH	EV-like series, PbA
Class 3-4	5,750	11,458	9,720	15,613	26,333
Class 6-7	7,149	12,211	12,843	18,092	44,789

Lead-acid batteries, though cheaper, are more toxic and have lower energy density than Nickel Metal Hydride and Lithium Ion (Li-ION) batteries. NiMH batteries are the most common type used in hybrid-electric vehicles because of higher energy density, proven longevity and safety. Li-ION have even higher energy density and are more suitable for plug-in hybrid-electric vehicles, but are not yet as safe or long-lasting as NiMH (Axsen et al 2008). With further development, Li-ION batteries will likely last as long (or longer) than NiMH and cost less per kWh. In mid-2008, production of NiMH batteries couldn't keep up with the demand for hybrid-electric vehicles. Customers waited for months to purchase a Toyota Prius, and new plants are not expected to be operational until 2010 (Szczesny 2008).

Diesel-electric hybrid vehicles have been used for transit buses and in medium sized trucks used for urban delivery. These vehicles are more efficient in congested urban environments with lots of stop-and-go traffic. New York City Transit (NYCT) purchased an initial fleet of 10 diesel electric hybrid vehicles in 1997. The initial purchase cost of diesel electric hybrid buses was found to be 60 % higher and maintenance cost around 75-150 % higher than conventional diesel vehicles. Even though the initial purchase cost has reduced in recent years, diesel electric hybrid buses cost 30 % more. The hybrid-electric buses that were purchased in 2006 by the Toronto Transit Commission were originally equipped with lead-acid batteries that failed after just two years and are being replaced with Li-ION batteries (Gray 2008).

FedEx has experimented with using diesel electric hybrid vehicles for medium duty urban delivery trucks and is thinking of replacing a significant portion of their fleet with hybrid vehicles. They have experienced 42% fuel economy gains, and reduction of greenhouse gases by 30% and PM by 96% from their diesel-electric hybrid fleet (FedEx 2008). To date, diesel electric hybrid engines have not been used for long haul freight.

A new and more promising technology for heavy-duty trucks is the hydraulic hybrid. These engines have a radically different mechanical system for powering a vehicle and contain two pump motors. The energy from the diesel engine is used to drive a hydraulic pump motor. The hydraulic pump motor charges a high pressure accumulator which propels the vehicle through a bent-axis pump on the rear wheels. A reservoir circulates fluid between the two pump motors.

Even though most hydraulic hybrid technologies are still in developmental stages, hydraulic hybrids are low cost and are potentially the most effective type of engine for heavier vehicle classes such as heavy duty trucks. Hydraulic hybrids potentially have the same advantages of diesel electric hybrids including regenerative braking.

While electric hybrids and plug-ins seem to be the best hybrid technology for passenger vehicles, hydraulic hybrids are better suited for heavy-duty vehicles. Hydraulic hybrid vehicles can achieve 50-70% fuel economy improvement, 30-40% GHG reduction, 50% HC reduction, and 60% PM reduction (EPA 2008, Galligan 2008). These vehicles cost approximately 15% more than a comparable conventional vehicle. When factoring in gas savings, the technology pays for itself within 1 to 3 years, and a savings of $50,000 is estimated for a 20 year vehicle lifetime (EPA 2008). Current models exhibit negligible NOx reductions. However, the technology is currently utilizing off-the-shelf parts and substantial NOx reductions are expected from future optimized hydraulic hybrids (EPA 2008, Kutz 2000). The first operational hydraulic hybrids are part of the UPS fleet. Two were purchased for use in Minneapolis and will be deployed in 2009, and five additional vehicles will be deployed by 2010 (Galligan 2008).

FUEL TYPES

In 2006, heavy-duty vehicles in the U.S. consumed 19.4% of energy and emit 23% of greenhouse gases within the transportation sector (Davis & Diegel 2008). Of that, 89.6% of BTUs consumed by heavy-duty trucks were diesel, 10.1% gasoline, and 0.3% liquefied petroleum gas (Davis & Diegel 2008). Other heavy-duty vehicle types currently in use include natural gas and hybrid vehicles. Diesel vehicles dominate the heavy vehicle fleet because they are more powerful and more efficient (relative to gasoline engines) (OHVT 2000). On average, single unit HDVs achieve 8.2 miles per gallon (mpg) and combination trucks get 5.1 mpg.

Nearly all of CO and HC, 58% of NOx, and 28% of PM mobile source emissions are from gasoline vehicles (EPA 2007). Of course, more gallons of gasoline are consumed per year, and when accounting for this, a gallon of gasoline emits roughly 7 times more CO and 5 times more HC than a gallon of diesel. A gallon of diesel emits 2 times more NOx and 8 times more PM than a gallon of gasoline. Diesel fuel is more carbon intensive per gallon[1] and slightly more per unit energy. Of course, diesel vehicles are more efficient and emit fewer GHGs per mile than their gasoline counterparts.

While diesel is the dominant fuel used to power heavy-duty vehicles, other fuels such as natural gas, biodiesel and emulsified diesel are also commercially available. In 2006, ultra-low sulfur diesel (ULSD) replaced regular diesel fuel (sulfur levels at 500 parts per million weight [ppmw]) when the EPA required sulfur levels in diesel fuel to be less than 15 ppmw. Switching to ULSD can reduce PM emissions by 5-9%, and using ULSD with a PM exhaust filter can reduce PM emissions by 90% (EPA 2003). In addition, the diesel fuel containing sulfur at levels greater than 15 ppmw inhibits the performance of catalyst-based diesel particulate filters.

Emulsified diesel is a mixture of petroleum diesel and water that can be used in any compression-ignition engine. This mixture can separate if a vehicle is unused for long periods (i.e. 2+ months) and become harmful to the vehicle. Relative to pure diesel, emulsified diesel can reduce PM by 20-50% and NOx by 5-30% (EPA 2003). While it is effective in reducing emissions, the added water reduces the energy content of the fuel, and thus reduces power and fuel economy. In addition, the fuel is about $0.20 more per gallon than pure diesel.

Production of biofuels has increased in recent years due to efforts to reduce oil consumption and GHG emissions. From 2005 to 2007, biofuel production increased 40% and is expected to increase an additional 100% by 2015 (McDonnel and Lin 2008). Many state and federal initiatives are encouraging this trend, including former President Bush's Twenty in Ten plan that aims to increase production of biofuels to five times that mandated for 2012 by 2017, resulting in 15% of 2017 gasoline and use displaced with biofuels (White House 2007).

Biodiesel, a fuel made from vegetable oil and animal fat, is an alternative to diesel fuel and can be used interchangeably with petroleum-based diesel to power compression-ignition engines. Currently biodiesel is approximately 10% of the biofuels market, with the majority being

[1] The average gallon of gasoline contains 19.4 lbs CO2/gallon and diesel contains 22.2 lbs CO2/gallon (EPA 2009)

produced from soybeans (McDonnel and Lin 2008). Because crude oil is not required for production, increased use of biodiesel could decrease U.S. reliance on foreign sources of energy.

Biodiesel is available in pure form (100% biodiesel, known as B100) and in blends with petroleum diesel (e.g. 20% biodiesel and 80% petroleum diesel, known as B20). B20 reduces HC emissions by 13-21%, CO by 7-11%, PM by 10-20%, and increases NOx slightly by 1-2% (Van Gerpen et al 2007). Graham et al (2008) show that B20 is not effective in reducing tailpipe GHG, relative to petroleum diesel. However, Van Gerpen et al (2007) have found that biodiesel reduces GHG by 78% when considering the fuel's lifecycle, not just tailpipe, emissions. Of course, as the proportion of biodiesel in the mixture increases, emissions of HC, CO, PM, and GHG decrease, while NOx emissions increase.

While B100 is more effective than B20 in reducing emissions (of PM, CO and HC), it may cause issues such as exterior paint chipping, plugged filters, reduced power and fuel economy, and transformation of the fuel over time (Van Gerpen et al 2007, EPA 2003). B100 is a good solvent, causing paint to deteriorate if the fuel is spilled. This property also loosens deposits in used vehicles that will plug filters. To fix this, the tank, fuel lines and filters need to be cleaned. Storing a vehicle for long time periods leaves the fuel susceptible to chemical changes. Excess oxygen or water in the tank can react with the fuel and cause it to transform. Attempting to power a vehicle with this transformed fuel can be damaging. Lastly, the energy content of biodiesel is lower than petroleum diesel, lowering the power and fuel economy of biodiesel. To use pure biodiesel without experiencing the maintenance side effects, engine modifications would be necessary, deterring many fleets from using B100. In addition, biodiesel is more expensive than petroleum diesel, with B20 approximately $0.15-0.30 more per gallon, and B100 $0.75-1.50 more per gallon (EPA 2003). Incentives at the state and federal level are making biodiesel increasingly competitive with petroleum diesel (Van Gerpen et al 2007).

Another downfall of biodiesel is the massive amount of land required to produce it in quantities large enough to satisfy U.S. yearly diesel consumption. In 1995, it was estimated that 65% of total U.S. agricultural land is needed to completely replace petroleum diesel (Van Gerpen et al 2007). If all current U.S. soybean production was used to make biodiesel, only 6% of demand for diesel would be met (Hill et al 2006). In addition, recent studies have shown that converting land to grow feedstocks of biofuels can actually increase emissions (Searchinger et al 2008, Fargione et al 2008). To achieve GHG savings from biofuels, they must be produced without necessitating (direct or indirect[2]) land conversion. Yellow grease[3] is a biodiesel feedstock that doesn't require land conversion, but this method of production requires 1.7 times the energy required for soybean biodiesel (EPA 2007b).

Ethanol is a biofuel that is blended at various levels with gasoline (e.g. E10, E85). E10, also known as gasohol, is a blend of 10% ethanol and 90% gasoline. This blend is commonly found at fueling stations and can be used in most spark-ignition vehicles without negative consequences. Blends with higher ethanol content, such as E85, can only be used in spark-ignition vehicles equipped to handle this fuel (e.g. flexible fuel vehicles).

Using ethanol in place of gasoline reduces oil consumption and reliance on foreign sources of energy, and can also reduce GHG emissions depending on the method of production. The EPA estimates that relative to gasoline, on average, corn ethanol reduces GHG emissions by 22%, sugarcane ethanol reduces GHG by 56%, and cellulosic ethanol reduces GHG by 91% (EPA 2007). Facanha and Simiu (2008) compared the results of studies reporting the GHG emissions associated with ethanol production from various feedstocks in an attempt to deduce which type of ethanol (sugarcane, corn or cellulosic) will provide the greatest GHG benefit. Even after considering the additional transportation required for sugarcane ethanol (from Brazil to the U.S.), it offers a greater GHG benefit than corn-based ethanol. Of course, cellulosic ethanol, which is made from grasses and unused portions of plants, can also reduce GHGs substantially, relative to gasoline and ethanol produced from other feedstocks. However, this type of ethanol is in early stages of development, and estimates of GHG benefit and maximum production volume are uncertain. Figure 1 shown below shows the GHG emissions associated with gasoline and ethanol. Like biodiesel, any production of ethanol causing agricultural land-use changes will result in a net GHG increase.

[2] Direct land conversion would be converting land solely to produce biofuel feedstocks. Indirect land conversion would be using existing supplies of biofuel feedstocks (e.g. corn, soybeans), thus causing land conversion to meet the demand of the feedstocks' previous use (food production, in most cases).
[3] Used cooking oil, typically from restaurants.

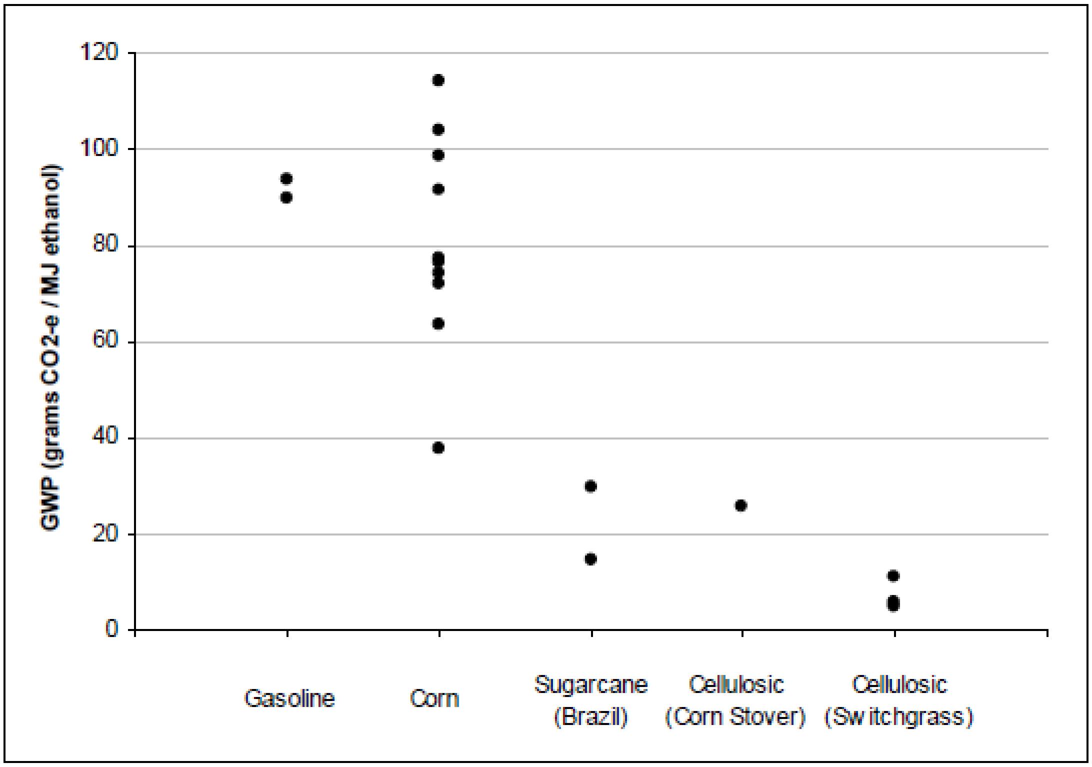

Figure 1: Comparison of Global Warming Potential Across Gasoline and Ethanol Feedstocks (Source: Facanha and Simiu (2008), Figure 1).

Liquefied Petroleum Gas (LPG) is the most popular alternative fuel in the world, and is the third most common fuel used to power heavy-duty vehicles. It is cleaner burning than gasoline (20% NOx reduction, 60% CO reduction), 85% of LPG consumed in the U.S. is domestic, and it is cheaper than gasoline (DOE 2003, EPA 2009). However, the fuel is not typically available at fueling stations and most production vehicles cannot use the fuel without being properly converted.

Natural gas is another fuel used to power heavy duty vehicles, and the majority consumed in the U.S. is produced in North America (EPA 2003). Bus fleets are attracted to natural gas because of its substantial reduction in PM emissions. Buses are often running idle waiting for passengers to load or unload in densely populated areas (urban cities and schools), making it especially important to reduce PM and its adverse health effects.

Natural gas is available in two forms: compressed natural gas (CNG; 85-95% methane), and liquefied natural gas (LNG; nearly 100% methane). LNG is produced by liquefaction of CNG, which consists of cooling CNG to -259° F. CNG must be stored in high pressure tanks, while LNG must be stored in insulated containers to maintain its cold temperature (DoE 2008). Converting from CNG to LNG condenses the fuel, allowing for cost-effective transport. Typically, natural gas vehicles are just as efficient as gasoline vehicles, on an energy basis. However, LNG has lower heat content than gasoline, meaning that 1 gallon of gasoline contains the same amount of energy as 1.5 gallons of LNG (DoE 2008). In addition, fuel costs are comparable with diesel on a per-mile basis (EPA 2002).

The advantages of natural gas, relative to petroleum diesel, are its 50% reduction of PM, NOx, and HC, and 25% reduction of CO2. Compression is less energy intensive than liquefaction, so the savings resulting from CNG is slightly higher than LNG. Of course, since natural gas contains so much methane (which has a higher global warming potential than CO2), a spill or leak would contribute substantially to GHG emissions. In addition, CNG vehicles are quieter than diesel vehicles, making them an attractive option where noise pollution is a concern (Kiel 2008), while LNG is cleaner burning, reducing engine maintenance costs and prolonging engine life (EPA 2002).

The cost of a LNG heavy-duty vehicle can cost twice that of its diesel equivalent ($207,000 versus $110,000), but these premiums are expected to decrease over time, assuming the market matures and vehicles are produced in larger quantities (Kiel 2008, EPA 2002). Many subsidies are also available. For example, Los Angeles and Long Beach ports offer $105,000 for each LNG vehicle purchased as a means of improving regional air quality (Kiel 2008). The private fuel distribution and storage systems add $15,000-20,000 per vehicle. Of course, as LNG vehicles become a larger share of the market, the number of public refueling facilities will probably increase.

As of 2008, only one manufacturer, Cummins Westport, produces heavy-duty LNG engines, and only two truck manufacturers, Kenworth and Sterling, are producing trucks with these engines (Kiel 2008). Two engine sizes are available (8.9L and 15L), and the 8.9L engine already meets

EPA's 2010 NOx emission requirements (Kiel 2008). During summer 2009, Clean Energy opened the largest natural gas fueling station in the world at southern California ports (Transport Topics 2009a).

Widespread use of natural gas faces challenges similar to hydrogen fuel: fuel storage, transport, lack of distribution infrastructure, and educating users. LNG's extremely cold temperature could cause frostbite while refueling a vehicle. LNG vehicles being stored indoors for a week or longer could be a fire hazard because of the flammable gas vented by the vehicle. Training would be necessary to prevent both of these incidents.

Biogas is a renewable form of natural gas that comes from the anaerobic decomposition of sewage sludge, agricultural waste, industrial waste, animal by-products, and municipal solid waste. In 2005, anaerobic digestion plants had to capacity to generate 600 MW of electricity, equivalent to 6% of natural gas and 7% of gasoline consumption in the U.S. (DoE 2008). Without being used for fuel, these sources of biogas (methane) would otherwise contribute substantially to GHG emissions.

Another form of transport fuel derived from natural gas is called Fischer-Tropsch (F-T), or gas-to-liquid (GTL) diesel, and can also be made from coal or biomass. This fuel can be used alone, or blended with conventional diesel. California has been using F-T as an additive to conventional diesel as means of reducing PM emissions (DOE 2006). Depending on the production process, GHG emissions from GTL diesel can be equal to or greater than that of conventional diesel (Jaramillo et al, 2008). The fuel is, however, successful in reducing emissions of HC, PM, CO and NOx by 30%, 30%, 35%, and 8% respectively (CEC 2006).

FUEL PROPERTIES

Diesel fuel consists of a mixture of hydrocarbons, such as paraffins and aromatics, to which additives like sulfur are added. The cetane number measures the combustion properties of the diesel fuel with higher cetane number corresponding to a more easily ignitable fuel. Usage of diesel fuels with a higher cetane number than the one recommended for a particular engine will not necessarily increase the performance of the engine. However, the engine efficiency can decrease if the diesel fuel being used has a lower cetane number than the recommended minimum cetane number. Using fuels with optimal cetane numbers will decrease emissions during cold starts, improve fuel economy and reduce smoke. The properties of diesel fuel used in the U.S. are shown in Table 6.

Table 6: Comparison of Diesel Fuel Properties (Source: Hydrotex)

Properties	ULSD Requirements	California (2004)	Rest of USA (2004)
Cetane Number	55 min	48	43
Cetane Index	52 min	45	40
Density kg/m3	820-840	844	847
Sulfur, ppm	<15	< 300	< 500
Lubricity, ASTM D975-04c SBOCLE Minimum load gram Or HFRR Max scar diameter, microns	3100 520	NR	NR

The primary pollutants from diesel fuel are oxides of nitrogen and particulate matters (PM). The amount of emissions from a diesel fuel engine is affected by a number of properties of the diesel fuel such as density, cetane number, aromatic content, distillation properties and sulfur content. Determining and identifying generic trends in emissions as a function of the diesel fuel composition is very difficult as the emission characteristics also depend on the engine characteristics and operating conditions. Also identifying the individual effects of each diesel fuel properties is a difficult process due to correlations.

A recent study of impact of fuel modifications on heavy duty diesel engines reveal that the emissions of older engines tend to more sensitive to changes in fuel than newer engines. The primary reason for this is that older engines have a higher emission rates and therefore even minor improvements in fuel composition results in significant reduction in emissions from the base value. In general, increasing cetane, reducing total aromatics, density, polyaromatics and the distillation temperature resulted in a small reduction in NOx whereas sulfur reduction had no impact on NOx emissions. Reducing sulfur had a significant impact on PM emissions. Increasing cetane, reducing aromatics and distillation temperature had no impact on PM emissions.

Reducing density and polyaromatics had no impact on low emission engines whereas it caused significant reduction of emissions in high emission engines (ADB).

Sulfur. Of all diesel fuel components, sulfur is receiving increasing attention due to its impact on PM emissions. In PM emissions, oxides of sulfur and water coat a carbon core and the resulting particles are carcinogenic. Reduction in sulfur content results in a reduction in PM emissions due to a reduction in SOx formation. An almost linear relationship was found to exist between PM emissions and sulfur reduction. The PM emissions were reduced by 0.87 %, for every 100 PPM reduction in sulfur. Sulfur was also found to inhibit the performance and durability of catalytic converters, NOx adsorbers and diesel particulate filters causing increased emissions. Decreasing sulfur content was also found to reduce the amount of corrosion wear in piston rings, cylinder lines and exhaust tailpipes and reduce deposition due to acidification of engine oils. EPA estimates the maintenance savings due to low sulfur diesel fuel usage expressed as savings per gallon to be 0.7 cents/gallon (ADB).

Aromatic Hydrocarbons. Aromatic Hydrocarbons which are hydrocarbons with benzene rings create soot due to poor ignition properties. Diesel fuel which is created by catalytic cracking have higher aromatic content and have lower cetane numbers (around 40-45) when compared to regular straight run diesel (around 50-55). Higher aromatic content causes inefficiency in burning during cold starts and increases the amount of hydrocarbon and NOx emissions. Increase in aromatic content also results in increase in soluble organic fraction emissions.

One of the most dangerous aromatic hydrocarbon related emissions are polycyclic aromatic hydrocarbons (PAH). A linear relationship was found to exist between the amount of PAH emitted and the amount of PAH present in the fuel. For example when the amount of PAH in the diesel fuel was restricted to less than 1 g/liter, PAH exhaust emissions reduced y around 80 % (ADB).

Fuel Additives. Fuel additives such as cetane enhancers, smoke suppressants and detergent additives are added to fuels to improve self-ignition during cold starts, inhibit soot formation and preventing deposits on engine components respectively. Cetane enhancers improve the ignition property of the fuels and therefore reduce the amount of hydrocarbons and PM emissions. Smoke suppressants reduce soot formation but cause increase in sulfate emissions. Detergent additives cause reduced PM and HC emissions by improving the mixing characteristics of the engine (ADB).

Volatility and other fuel properties. Distillation temperature curves are used to characterize the volatility of the diesel fuel mixture. From the distillation curve one can read the temperature at which a pre-specified amount of hydrocarbons have burned away. A diesel fuel with a lower distillation temperature is expected to generate higher hydrocarbon emissions due to increased hydrocarbon content. In contrast a diesel fuel with a higher distillation temperature generated higher amount of PM emissions. Other fuel properties which may affect emissions include fuel density and viscosity. Highly corrosive fuels are expected to increase emissions due to reduction in engine performance.

CONCLUSIONS

Vehicle classification schemes categorize vehicles by the number and spacing of axles, vehicle length, trailer type, engine type and fuel type. Five classifications exist in the U.S. from FHWA, EPA, CARB, American Automobile Manufacturers Association (AAMA), and Vehicle Inventory and Use Survey (VIUS). EPA and CARB classifications are used to determine the proportion of miles traveled for input to MOBILE6 and EMFAC vehicle emissions models, respectively. EPA provides guidelines for converting FHWA classification to EPA classification for use with the emissions model.

The majority of heavy-duty vehicles employ a conventional diesel engine that is either turbocharged or naturally aspirated. Turbocharged engines allow for downsizing the engine while maintaining the same power. In addition, turbocharged engines recover exhaust energy that would have been wasted with a naturally aspirated engine. Both of these characteristics contribute to increased fuel economy of turbocharged engines relative to naturally aspirated engines, and as a result are more common for use in HDVs than naturally aspirated engines. They also are effective in reducing NOx and PM emissions by 30%.

Passenger vehicle electric hybrids are of the series variety, and the electric motor directly powers the wheels. Heavy duty vehicle electric hybrids are of the parallel variety, and both the diesel engine and electric motor power the wheels. Electric hybrid engines have not yet been used in combination trucks, but have been used in many bus and package delivery truck fleets (e.g. UPS and FedEx). Despite the increased fuel efficiency and air quality benefit, electric hybrid engines are not a popular choice for heavy-duty vehicles because they are much more expensive than conventional engines. Lead-acid batteries are no longer used in hybrid vehicles and were replaced with Nickel Metal Hydride (NiMH) batteries that have higher energy density and are safer (though more expensive). It is expected that Lithium-ION batteries will replace NiMH batteries in the future due to greater longevity and lower cost.

Hydraulic hybrids, vehicles powered by a diesel motor and hydraulically stored energy, are an inexpensive alternative to electric hybrids for large vehicles. Though still in the development stage, these vehicles improve fuel economy 50-70% and reduce GHG, HC, and PM emissions by roughly 50%. Costing only 15% more than a comparable conventional vehicle, it is estimated that the payback period is between 1 and 3 years.

The majority of fuel used to power heavy-duty vehicles is diesel, while gasoline and liquefied petroleum gas also provide fuel for a significant portion (10% and 0.3%, respectively). Gasoline vehicles are responsible for the majority of CO and HC emissions, while diesel vehicles are known for emitting large amounts of NOx and PM. Diesel is more common for use in heavy-duty vehicles because the engines are more powerful and efficient. Ultra-low sulfur diesel (ULSD) is now required in the U.S., which can reduce PM emissions by 90% when used with PM exhaust filters. Emulsified diesel, a mixture of petroleum diesel and water, is effective in reducing PM and NOx for only 20 cents more per gallon, making it an attractive option for school bus fleets trying to reduce their emissions. One drawback of emulsified diesel is that if it sits for long periods of time, it can separate and damage the vehicle.

Biodiesel can reduce emissions of GHG (lifecycle, not tailpipe), PM, HC and CO. Most fleets prefer not to use 100% biodiesel because it would require altering the vehicle to avoid maintenance issues. B20, a mixture of 20% biodiesel and 80% petroleum diesel, still reduces emissions without the need to alter vehicles. Ethanol is another commonly used biofuel that is used in place of, or blended with, gasoline. The way that ethanol is produced, and the feedstocks used, has a large impact on its ability to reduce emissions. Ethanol made from corn offers the least emissions benefits, while sugarcane and cellulosic ethanol offer 2-3 times the benefit of corn ethanol. However, cellulosic ethanol is still in developmental stages and is not being commercially produced. It should be noted that biofuels only offer GHG emissions benefits if no agricultural land conversion is required to produce the fuel.

Relative to diesel fuel, natural gas reduces emissions of PM, NOx, and HC by 50%, and CO2 by 25%. However, it is necessary to invest in a private fueling storage and distribution system. It is a good alternative fuel for fleets that return to their point of origin on a daily basis (e.g. intracity buses and delivery trucks). Natural gas vehicles can cost twice as much as their diesel equivalent, but there are an increasing number of subsidies available to help offset this cost. Fischer-Tropsch (or Gas-to-Liquid diesel) is diesel fuel typically derived from natural gas. California has been mixing Fischer-Tropsch diesel with petroleum diesel to reduce PM emissions.

FUTURE MITIGATION TECHNOLOGIES

To regulate the emissions from diesel engines for heavy duty trucks, the US EPA will implement rigorous emissions standards (described in detail in the chapter "Heavy-duty Vehicle Emissions Regulations") in three stages. Phases 1 and 2 were implemented in 2004 and 2007 while phase 3 will be implemented in 2010. The primary focus of the rules was to reduce sulfur content in diesel fuel by around 97% and emissions from heavy duty vehicles by 95%. The EPA rule will ensure that every heavy duty truck will use some variety of NOx and PM reduction technology by 2010. Other than PM standards which will be fully implemented in the year 2007, standards of NOx and NMHC will be implemented in a phased manner by sales with 50 % of the engines sold expected to meet standards in the year 2007-2009 and all of them meeting the standards by the year 2010. Some of the recommended strategies by EPA include cooled exhaust gas recirculation, oxidation catalysts, injector timing particulate filters, NOx adsorbers and selective catalytic reduction.

Most major engine manufacturers have agreed upon particulate filters as the most effective way of reducing PM emissions. However, no single technology has been found to be significantly better than the others in controlling NOx emissions. One possibility for existing fleet owners is to convert existing engines to natural gas engines. However such a process, which involves discarding the diesel engines, is prohibitively expensive for fleet owners. Therefore, the most common techniques are retrofitting technologies such as exhaust gas recirculation and urea selective catalytic reduction.

DOE's 21st Century Truck Partnership is focused on improving the energy efficiency of trucking, reducing the dependence of the industry on foreign oil and reducing pollutant emissions. The goals of this program are outlined in Table 7 below.

Table 7: DOE 21st Century Truck Partership Goals.

Improvement Area	Goals:
Parasitic Losses	• Develop technology that reduces aerodynamic drag of class 8 combination vehicles by 20% (c_d=0.625 to 0.5) • Reduce class 8 auxiliary loads by 50% (from 20 hp to 10 hp) • Reduce tare weight by 15-20%
Idle Reduction	• Offer incentives/regulations to encourage vehicle owners to invest in idle reducing technology and driver training • Develop codes and standards for on-board and stationary electrification technologies • Develop add-on idle reduction equipment that has payback within 2 years and is less emitting than 2010 PM and NOx standards by 2009 • Produce trucks equipped with idle reducing equipment that also reduces truck component duplication (relative to add-ons) by 2012 • Develop a fuel cell APU that runs on jet fuel (JP-8) with 35% efficiency by 2015
Engine Losses	• Class 7-8 engines will comply with emissions standards while improving engine efficiency by 20% (from 42% thermal efficiency to 50%) by 2010 • Reach 55% thermal engine efficiency by 2013 • Identify an alternative fuel that is efficient and low-polluting to replace 5% of petrol fuels
Heavy-duty Hybrids	• Develop drive unit with 15 year design life and costs less than or equal to $50/kW by 2012 • Develop energy storage system of 15 year design life that "prioritizes high power rather than high energy" and costs less than $25/kW • Develop hybrid propulsion system that achieves 60% improvement in FE and meets 2007/2010 emissions regulations

REVIEW OF EMISSION CONTROL STRATEGIES

There are several vehicle technologies available and in development to increase energy efficiency and reduce pollutant emissions. Those improving average vehicle fuel economy include idle reduction technologies, tractor and trailer modifications to improve aerodynamics, tires reducing rolling resistance, lightweight materials reducing overall vehicle mass, and engine modifications to improve efficiency. In addition to these, many strategies are available to meet EPA's 2007/2010 NOx and PM requirements including diesel particulate filters (DPF), ultra-low sulfur diesel (ULSD), lean NOx traps (LNT), and selective catalytic reduction systems using urea (SCR).

Exhaust Gas Recirculation

The most common engine based technique to control NOx emissions is exhaust gas recirculation (EGR). In diesel engines with EGR, up to 50% of the exhaust gas comprising largely of carbon dioxide and water vapor is re-circulated back to the engine after passing through a heat exchanger. The excess air reduces the peak combustion temperature resulting in a reduction in NOx formation and improves the efficiency of diesel engines by reducing heat wastage. However, the presence of excess air during the power stroke causes a reduction in fuel combustion and increases the amount of PM. To account for the increased PM emissions, particulate matter filters must be fitted in the exhaust pipes causing a reduction in fuel economy. When properly implemented, EGR causes a NOx emission reduction of 50-60% or more, and needs to be complemented with other after treatment measures to comply with the 2007 or 2010 standards. Navistar is the only manufacturer relying on EGR technology to meet 2010 standards. They have managed to meet a level of 0.5 g/bhp-hr using only EGR, which is just above the 2010 standard of 0.2 g/bhp-hr (Rhomba 2009). They will be using credits earned in previous years from exceeding the standard to make up for the difference, until they have further developed their technology to meet 2010 standards. They estimate their 2010 models will achieve the same fuel economy as their 2007 models, and the price will increase by approximately $8,000.

Selective Catalyst Reduction

One of the primary reasons for the difficulty in controlling NOx emissions is that the nitrogen atom must be detached from the oxygen molecule and combined with another nitrogen atom. This process is very difficult in diesel engines as the exhaust fumes are rich in oxygen. Therefore special catalysts and reducing agents must be used to initiate the process. One of the most common after treatment measures is selective catalyst reduction (SCR) where nitrous oxides are converted to nitrogen and water using a catalyst and a reductant. The most commonly used reducer for heavy duty diesel engines is an aqueous solution of urea. The urea water solution is called diesel exhaust fluid (DEF) in the USA and Adblue in Europe. In urea-SCR, the urea is stored onboard the truck and is injected into the exhaust gas stream just upstream of the SCR catalyst. The urea SCR has been shown to reduce NOx emissions in stationary diesel engines by up to 99% and running diesel engines from 75% to 90% and PM emission from 20-30%.

In 2008, around half a million trucks in Europe use urea SCR and the number is expected to grow by 5% every year (Hargrove, 2008). The biggest advantage of urea SCR is that it has the potential to improve fuel economy and lower operating cost when compared to other technologies. The cost of a single unit of urea SCR system can vary from $ 11,000 to $ 50,000. However this amount is expected to reduce significantly as the number of urea SCR equipped trucks increase due to economies of scale. Volvo expects their SCR-equipped 2010 vehicles to increase in price by just under $10,000 (Transport Topics 2009b).

The biggest issue in urea SCR is to make the system portable and compact so that it can be used for a wide range of truck engines. Another problem in usage of urea SCR technology in heavy diesel trucks is ammonia slip where the unreacted ammonia escapes through the emission pipes. Recently advanced urea injection technologies have been developed which release urea based on the engine characteristics. Vehicles fitted with urea SCR technology need constant refilling of the urea tanks. In light vehicles the frequency is similar to that of an oil change. However, for heavy vehicles the frequency with which urea tanks have to be refilled will vary depending on the size and configuration. Another issue with Urea SCR is prevention of freezing when temperature drops below 12 F.

Diesel Oxidation Catalysts

Diesel Oxidation Catalysts (DOC) use catalysts to oxidize harmful chemicals in the exhaust stream to carbon dioxide and water. The mechanism uses a stainless steel canister with a honeycomb structure whose surface is coated with catalytic metals such as platinum or palladium. DOCs help reduce PM emissions by around 20%, carbon monoxide emissions by around 40% and hydrocarbon emissions by around 50%. DOC devices for large trucks cost around $1000 and can be used for around 7 to 15 years. DOC has been used in vehicles since 1980s and therefore is the most mature of retrofit technology with over 3 million trucks and buses in the US equipped with DOC. DOCs are reliable and do no impact engine efficiency and cause a minor statistically insignificant increase in fuel consumption. DOCs are also compatible and can be used with other NOx retrofitting technologies. DOCs are the most popular diesel retrofit technologies as they are easy to install, compatible with older diesel engines and require very little maintenance.

Diesel Particulate Filters

Another promising technology identified by the EPA is that of diesel particulate filters (DPF). DPF is a device with porous ceramic walls which traps and oxidizes PM in the exhaust stream. DPFs have a filter device which traps solid and liquid emission particles and lets the exhaust gas pass through the system. Some of the common filter materials used includes ceramic monoliths, woven silica fiber coils, ceramic foam, wire mesh and sintered metal filters. The collection efficiencies of the different materials vary significantly but most modern filters are designed to capture greater than 80 % of the PM. Latest advanced filters have the ability to trap greater than 99% of the fine carbon nano particles emitted through exhaust (MECA, 2009). Apart from reducing PM emissions by 60 to 90%, DPFs also reduce the emissions of hydrocarbons and carbon monoxides by the same amount. DPFs can cost up to $10000 depending on the vehicle specification and entails usage of ultra low sulphur diesel fuel. Use of regular diesel can clog up the filter resulting in engine damage due to back pressure. The device needs to be cleaned every 100,000 miles and typically lasts around 7 to 15 years (EPA, 2003).

One of the common ways in which the filters are cleaned is by burning the collected PM. However the issue with combusting the collected PM is that it entails an ignition temperature of around 650 C which is not available in the exhaust pipes. Therefore catalysts are used to lower the ignition temperature to combust the collected PM and the resulting filters are called catalyst-based diesel particulate filters (CBDPF). CBDPF has been installed on around 20,000 trucks and buses in Europe and have found to be very effective. However presence of sulfur inhibits the performance of CBDPF and the performance may deteriorate significantly if > 15 ppm amount of sulfur is present in the fuel. However with the widespread use of ultra low sulfur diesel for heavy duty trucks, the complications caused due to presence of sulfur is expected to reduce. The performance of CBDPF also deteriorates under cold temperature (due to low exhaust temperature) and in high altitudes (due to decrease in the amount of the oxygen). Recently truck manufacturing companies such as Mack and Volvo have been selling trucks pre-fitted with diesel particulate filters.

Promising Technologies: NOx Adsorbers, Non-Thermal Plasma Traps and Lean Nitrous Traps

NOx adsorber is a technology under development for diesel engines. NOx adsorbers result in significant reduction in NOx emissions in gasoline engines and transferring the technology to diesel engines is a feasible in a number of years. Studies reveal that NOx absorbers potentially can reduce the NOx emissions by up to 90% in light duty diesel vehicle (DVECSE, 2000). NOx adsorbers use a chemical trap such as zeolite to convert NOx into NO_2 and store them as nitrates. Once the storage capacity of the chemical trap is reached the nitrates are released through a regeneration process where the nitrates are reduced to nitrogen by creation of a rich atmosphere through injection of diesel fuel (MECA, 2009). NOx adsorbers may reduce the fuel economy of diesel engines. Also the technology may not be mature enough for widespread usage by the EPA 2010 deadline. However, NOx adsorbers have been identified by the EPA as one of the promising technologies available to meet the requirements (MECA, 2009).

Another promising technology which is still in the developmental stage is using non-thermal plasma technology in which NOx are converted to nitrogen using electrically charged air called plasma combined with a catalyst. Tests conducted at the Oakridge National Laboratory show that up to 50 % reduction in NOx can be achieved through plasma technology. The non-thermal plasma system also has the ability to reduce to PM significantly by 90 % (Krishnan et al, 2005). However the technology may not be mature enough for implementation or testing by 2010.

Lean Nitrous Traps (LNT) is another promising technology which is being studied by a number of researchers for controlling NOx emissions. LNT works by converting the NOx to barium nitrates using barium carbonate or barium hydroxide during the lean phase of the engine operation. During the regeneration phase the engine is operated in a fuel rich mode to enable conversion of barium compounds to their original form and nitrates to nitrogen or ammonia. The LNT can be combined with SCR to further convert the ammonia to nitrogen.

Idle Reduction

An idling heavy-duty vehicle wastes approximately 1 gallon of diesel fuel per hour. In the U.S., trucks idle 1500-3000 hours per year, resulting in 500 tons of NOx emitted per day and 2 million gallons of diesel wasted daily, costing each truck approximately $1,790 per year (Lee et al 2008, Muster 2000). Using idle reducing technology reduces oil consumption and emissions, and saves money. In addition, many states (25, as of July 2008) are regulating or banning truck idling (ATRI 2008). These idle reduction devices include auxiliary power units (APU), direct-fire heaters, electrified truck stops (ETS) and automated engine idle systems.

APUs are diesel-powered units that can be used to power climate control and other in-cabin devices. Direct-fire heaters are also diesel-powered units, but only provide heat and cannot power other devices. Automated engine idle systems monitor the cabin temperature and shuts the idling engine off when power is not needed for climate control. TSEs electrify climate control and other in-cabin devices by either allowing the vehicle to plug into an electrical outlet or inserting a hose into the cabin that delivers climate controlled air (for an hourly fee). Ang-Olsen and Schroeer (2002) found that APUs, direct-fire heaters and automated engine idle systems can reduce fuel use by 9%, 3.4%, and 6% per truck, respectively. Automated engine idle systems and direct-fire heaters cost approximately $1,500 per unit and APUs cost $7,000 (DOE 2009). Despite the higher capital cost of APUs, the payback time is only two years.

The majority of TSE service is provided by IdleAire, Shorepower, or CabAire, and there are approximately 130 truck stops in the U.S. offering this service (DOE 2009). IdleAire offers basic service for $2.45-2.89 per hour, depending on membership type (IdleAire 2008). Assuming that a truck consumes 1 gallon of diesel per hour, this is only a cost effective idle reduction strategy if per-gallon diesel prices exceed this hourly fee.

In addition to these devices aimed at supplying energy to climate control devices and other accessories, driver training can reduce fuel consumption while idling in transit. A study undertaken at the Verkehrs-Sicherheitszentrum Veltheim (VSZV) in Switzerland concluded that shifting buses from drive to neutral while idling will reduce idling fuel consumption by 45% (Muster 2000).

In addition to fuel consumption, pollutant emissions are important to consider when comparing idle reduction strategies. Gaines et al (2008) utilized the GREET model to estimate total upstream (fuel production/power generation) and downstream (vehicle) emissions associated with idle reduction options including APUs, direct-fire heaters, and ETS. They found that, during periods of cab air conditioning, the APU has the highest NOx and CO2 emissions and the ETS emits the most PM. However, the PM emitted due to ETS occur upstream at the electricity generation site, which is potentially an area of lower population relative to a truck stop[4]. During heating days, the APU is more emitting of NOx, CO2, and PM than direct-fire heaters and ETS. The emissions of all idle reducing options proved lower than that of the idling truck.

It should be noted that these results assume the average U.S. electricity generation mix. Results differ in each region of the U.S. since methods of electricity generation differ in efficiency and emissions rates. This study assumed 500 sulfur-ppm diesel rather than ULSD fuel due to data availability. Estimating emissions using ULSD would likely reduce PM emissions from the idling truck, APU and direct-fire heater. It would have an even greater effect on the scenarios that included use of DPF on the truck and APU. In addition, the truck modeled in this study follows 2001 emissions regulations, rather than the stricter NOx and PM rates of the 2007 regulations.

Lee et al (2008) investigated the effect of idle-reducing devices on in-cab air quality delivered by air conditioning systems at a truck stop in El Paso, TX. The alternatives included using the truck to power its A/C, using the truck to power its A/C recirculation, using APU to power the truck's A/C, and TSE powering the truck's A/C. Overall, the using the TSE to power the A/C resulted in the best in-cab air quality.

[4] Percentage of truck stops in urban areas across the U.S.: 45% in CA, 47% in FL, 59% in IL, 41% in NY, 51% in TX, 25% in VA, and 9% in WV.

Aerodynamics

Over the last 30 years, aerodynamic drag has decreased by 40%, and the drag coefficient (c_d) is currently about 0.625 (Muster 2000, DOE 2006). Aerodynamic drag consumes 21% of the energy used by class 8 trucks traveling at 65 mph. The DOE's 21st Century Truck Partnership recommends a 20% reduction in aerodynamic drag (c_d=0.5) which would result in a 6.5-15% fuel economy improvement (DOE 2006, Vyas et al 2002). Add-on aerodynamic drag reduction devices currently available can reduce drag by up to 25%. However, many add-ons hinder operational performance of the vehicle, discouraging many truck-owners from utilizing them (DOE 2006). In addition, technologies that are intended for use by the tractor, rather than the trailer, will be more cost effective since there are approximately three trailers for every tractor. Future research and development will aim to reduce aerodynamic drag using less obtrusive devices that are effective without affecting vehicle performance.

Drag-reducing technologies include cab top deflectors, sloping hood, cab side flares, aerodynamic bumpers, increased curvature in tractor and trailer design, underside air baffles, wheel well covers, gap closure (between tractor and trailer), and pneumatic blowing. All of these methods are currently used on trucks to varying degrees with the exception of pneumatic blowing, which has a history of use on aircrafts.

Reduced Rolling Resistance

Rolling resistance is the energy consumed due to the friction between the tires and road surface, and increases with vehicle weight and speed. Because of this weight-speed relationship, class 8 trucks are likely to benefit the most from technologies combating rolling resistance. It is estimated that rolling resistance accounts for nearly 13% of the energy consumed by a truck (Vyas et al 2002). Currently, the rolling resistance coefficient (RRC) is typically 0.007, but 0.0054 is possible using currently available methods.

Two types of tires, low-resistance tires and super singles, are effective in improving vehicle fuel economy by 3% (Vyas et al 2002). Of course, these are mutually exclusive technologies. Low resistance tires can be used on any truck, but require high pressure and frequent monitoring which has deterred truck owners from using them. Super singles eliminate the maintenance burden of low-resistance tires, but can only be used in newer MY trucks.

Pneumatic blowing can also provide benefit for rolling resistance by reducing the load on the tires. However, this technology's research and development is in the early stages and the full effects on fuel economy are not yet known. Vyas et al (2002) assume that this will improve truck fuel economy by 1.2%.

Thermal Management

During cold starts, there is significant amount of hydrocarbons generated due to incomplete combustion. Therefore catalysts must be used to attain optimal operating temperature of the engine and associated power train components. Recently, double walled stainless steel exhaust pipes containing an air gap have been used to retain the exhaust gas heat. The exhaust gas temperature is also very important to the function of particulate matter. With respect to the regeneration process, higher temperature leads to more effective combustion of the trapped PM.

Engine Management

One of the primary focuses of engine management, with respect to emissions, is to develop a more efficient cold start procedure. Strategies aimed at reducing cold start emissions primary focus on allowing flow of hydrocarbons to flow through the engines by slowing down the ignition timer or through variable valve timing where exhaust gases are re-circulated back to reduce HC and NOx emissions. Better fuel injection methods such as direct injection of fuel into cylinders, common rail fuel injection, pilot and retarded injection strategies have resulted in significant reduction in NOx emissions due to optimal fuel air ratios over conventional diesel injection procedures. Common rail fuel injection or electronically controlled injection can be combined with other emission control technologies such as particulate filters, NOx adsorbers and LNT to achieve more fuel efficiency and reduced emissions (MECA 2009).

Optimal combustion rates achieved by controlling the fuel air mixture can result in reduced emissions by controlling for the mixing of fuel and air. Better mixing is achieved by increasing the turbulence by modifying the shape of combustion chambers and the spray pattern. One of the most promising technologies in reducing PM emissions is through variable geometry turbocharging where the quantity of air being delivered varies according to the driving conditions. Other researchers have focused on improving fuel efficiency and reducing emissions by proper design of fuel injectors and injection ports (MECA 2009).

CONCLUSIONS

To meet EPA's 2007 and 2010 emissions standards for PM, most, if not all, trucks will utilize diesel particulate filters. When used with ultra-low sulfur diesel, PM emissions can be reduced by 90%. There are a few options to reduce NOx emissions. Most manufacturers will be using selective catalytic reduction to meet 2010 NOx standards. Navistar is the exception, and they plan to rely on exhaust gas recirculation. NOx adsorbers are a newer technology that reduces NOx emissions by 90%, but will probably not be fully developed early enough for the 2010 model year. In addition to these technologies, methods of optimizing engine and exhaust temperature can decrease NOx and PM emissions caused by cold starts. Improved fuel injection can also further improve NOx emissions.

Truck idling wastes approximately 1 gallon of fuel per hour and can cost approximately $2000 per truck depending on fuel prices. In addition to the fuel waste, excess emissions are being released into the atmosphere. Auxiliary power units, automated engine idle systems, and direct-fire heaters are all on-board devices aimed at eliminating the need for a truck to idle during extended rest periods. These can reduce fuel use by 3-10% and cost between 2 and 8 thousand dollars. Auxiliary power units cost more, but also save more fuel and have a shorter payback time. Electrified truck stops are a method of reducing engine idling without an on-board device. These stops either provide climate control for the cabin or provide the truck with electricity from which to run its own climate control system and other accessories. For this to be cost effective, it is necessary for the per-gallon price of fuel to be more than the hourly rate of the stop. Driver training and idle restriction policies can be an effective method of reducing fuel consumption and emissions from idling at pick up and drop off locations and in congested traffic.

Aerodynamic drag has decreased by 40% in the last 30 years, and the add-on devices available today can offer further reduction of 25%. Unfortunately, many of these devices infringe on the operational performance of the vehicle, making them undesirable. Low-resistance tires and super single tires are designed to reduce the rolling resistance between vehicle tires and the road surface, and can improve fuel economy by 3%. Low rolling resistance tires can be used on any truck, but require high pressure and frequent monitoring. Super singles are lower maintenance, but can only be used on newer model trucks.

HEAVY VEHICLE EMISSION MODELS

INTRODUCTION

The focus of this section is to first identify the various factors that affect heavy vehicle emission rates. The factors, which affect emissions, are classified into roadway characteristics, traffic characteristics, driver characteristics and vehicle characteristics. In general it is very difficult to isolate the effect of each of the individual factors on emission volumes and composition. Many of these factors act in tandem to affect the emission process and therefore it is very difficult to conduct experiments where only one of the above-mentioned characteristics can be studied. This section then provides an overview of the various emission estimation models. The emission estimation models can be classified into: state emission factor based models and dynamic instantaneous emission models and the advantages and disadvantages of each type of models are analyzed.

FACTORS AFFECTING EMISSIONS

Kalandiyur (2007) provides a detailed analysis of various network, roadway and driver characteristics which affect vehicular emissions. Though his work did not focus exclusively on heavy duty vehicles, the factors analyzed are expected to have a similar impact on heavy vehicle emissions. There have not been enough studies conducted on analyzing and quantifying the impact of geometric characteristics of roads on heavy vehicle emissions. The geometric characteristics of roadways sections affect the vehicle operating speed and speed profiles which have significant impact on the emission volumes and composition (Kean et al., 2003). However it might be very difficult to isolate the effect of certain geometric characteristics as its impact on the emissions might be in correlation with other parameters. Some of the geometric characteristics which are expected to have an impact on vehicular emissions by affecting operating speed include number of lanes, lane width, sight distance, horizontal and vertical curves, grades and pavement quality.

Roadway Characteristics

As driving patterns vary depending on the number of lanes and the lane width, one can expect the emission characteristics also to be different. Higher operating speeds are found on roadway sections with wider lanes (Fitzpatrick, 2001; Gattis and Watts, 1999). The capacity of a road is expected to increase linearly as the number of lanes which affects the operating speeds, a key input for most emission models. Williams-Derry (2007) used a spreadsheet based analysis and calculated 50 year carbon dioxide emissions and suggested that lane widening or adding new lanes may increase the amount of greenhouse gas emissions due to induced traffic. The average operating speeds of the vehicles tend to be lower on roadways sections with lesser sight distance. Horizontal and vertical curves affect the emissions by affecting both the driving patterns and the engine performance. The radius of the horizontal and vertical curve affects the sight distance which affects the operating speed and thus the emissions. The extra power and acceleration generated by the engine to maintain the vehicle at the comfortable operating speed also has a significant impact on emissions (Barth and Tadi, 1996; Samuel et al, 2002). Speed limits are also found to have an impact on vehicular emissions (Qu et al, 2003).

Pavement quality and grades are found to have a significant impact on vehicular emissions. For example the vehicular emissions on roadway sections with potholes are expected to be at least 30% higher than well maintained roads. Poor quality pavements affect the speed and acceleration profiles and engine performance and significantly increase the amount of emissions. A study conducted in Brazil reveal that both fuel consumption and emissions increase significantly on badly maintained roads and it might be beneficial to have well maintained roads for better environmental impacts (Bartholomeu et al., 2008). In general, emission volumes increase with grades. Studies have found that the average speed of vehicles tends to be lower on grades but the hydrocarbons and nitrous oxides emissions were higher (Barth et al., 1996; Kean et al., 2003; Ericson, 1999) due to enriched fuel-air ratios needed for greater power (Joumard et al., 1995). Even though the nitrous oxides emissions levels are lower on descents they do no compensate for the increased emissions on upper grade (Ericsson, 1999).

Because of the combined impact of the above mentioned geometric features, different facility types are expected to generate different emission levels. A number of studies on the impact of facility types have focused on automobile emissions (Rosquist, 1998; Rainford et al, 1987; Braunsteins and Marshall, 1980; Redsell et al 1993; Hammarström and Karlsson, 1987). For example emissions are found to be higher in streets with greater number of intersections due to increase in stop and go traffic. Stop and go traffic was found to emit twice the amount of pollutants compared to free flow conditions (Rapone et. al., 2000). Since the truck operating characteristics such as acceleration and speed profiles vary with facility types, one can expect the emissions levels to vary across facility types. MOBILE 6 accounts for this by having different emission factors for different vehicles by facility type (FHWA, 2005). Signal coordination on arterial streets was found to reduce emission up to 50%. Other roadway characteristics which could potentially affect vehicular emissions include speed limits and presence of work zones (Kalandiyur, 2007).

Traffic Characteristics

Another reason for the variation in emission characteristics by facility type is the variation in traffic characteristics by facility type. Traffic characteristics such as volume, capacity and volume/capacity ratio vary significantly over facility type and affect the operational speed which affects emissions. In general when the volume/capacity ratio is greater than one, the roadway section is highly congested and hence there is significant increase in emission volumes. Congested conditions have been found to increase emission by up to 10 times (Sjodin et al., 1995). Another important characteristic which has not been studied very thoroughly is the impact of different vehicular mixes on emissions. In general driving patterns are found to be significantly different when the percentage of heavy duty trucks increases (Hallmark et al, 1999).

Driver Characteristics

Driver characteristics such as attitude, experience, gender, age and aggressiveness cause significant variations in driving patterns affecting emissions. Driver characteristics are important for predicting automobile emissions as there is significant heterogeneity in driving behavior among automobile driver population. Vlieger et al. (2000) found that aggressive driving increased fuel consumption by 40% and emissions by a factor of eight. During acceleration, the amount of carbon monoxides and volatile organic compounds emitted increases significantly by a factor of 14 and 15 times respectively, due to fuel enrichment. Barth et. al. (1996) found that for a short trip, single power acceleration generated as much carbon monoxide as the rest of the trip. Even though vehicles spent less than 2% in the power acceleration mode, it contributed to more than 40% of the total emissions (Kalandiyur, 2007). Holmen et. al. (1998) recommended that a lot of research needs to be conducted in understanding urban driving behavior as variability in driving modes (variation in duration, frequency and intensity of cruise, acceleration and deceleration) causes significant changes in emissions. Driver behavior can be more important than other factors such as VMT with respect to emissions. Since heavy duty vehicle operators are more trained and are professional drivers one can expect the variation in driver characteristics to be less.

Vehicle Characteristics

Vehicle characteristics such as age, weight, engine size, maintenance, acceleration and deceleration characteristics play an important role in emission volumes and composition. Older vehicles tend to have higher emissions. However, significant percentage reductions in emissions can be obtained by retrofitting older vehicles with emission management strategies such as exhaust gas recirculation. As discussed earlier, sudden bursts in acceleration increases the amount of hydrocarbons and carbon monoxide emissions due to the usage of an enriched fuel air mixture. Barth et. al. (1996) found that for a short trip, single power acceleration generated as much carbon monoxide as the rest of the trip. The carbon monoxide and hydrocarbon emissions were found to increase by up to 2500 and 40 times for heavy loads on the engines. Other studies which showed that acceleration increased emissions by a significant amount include Ahn, et al (2002) and Jourmard et al (1999). Osses et al. (2002) discovered that acceleration had less effect on NOx emissions than average speed.

Another factor which affects vehicular emissions is the driving mode. Carbon monoxide and hydrocarbon emissions are generally higher in the cold start mode due to inefficiency in fuel burning. When the engine reaches the stabilized mode, emissions are lower and are a function of vehicle characteristics and operating conditions and all other factors discussed in previous sections. Under high engine loads during situations when it is ascending, the fuel air mixture is enriched and therefore produces high amounts of hydrocarbons and carbon monoxides.

Recently Capiello et al. (1998) classified vehicle factors affecting emissions into vehicle technology specifications, vehicle operating conditions and vehicle status. Vehicle technology specification comprises of design characteristics such as weight and aerodynamics, engine type and cycle characteristics, fuel type and emission control devices. Vehicle status includes characteristics such as age, mileage and maintenance status of the engine and its propulsion devices. Vehicle operating conditions include engine specifications such as speed and power, air to fuel mass ratio, speed and acceleration characteristics, and presence of catalyst. The above parameters combined with individual driver behavior and environmental factors such as pavement conditions, traffic and weather affect the total emissions (Figure 2).

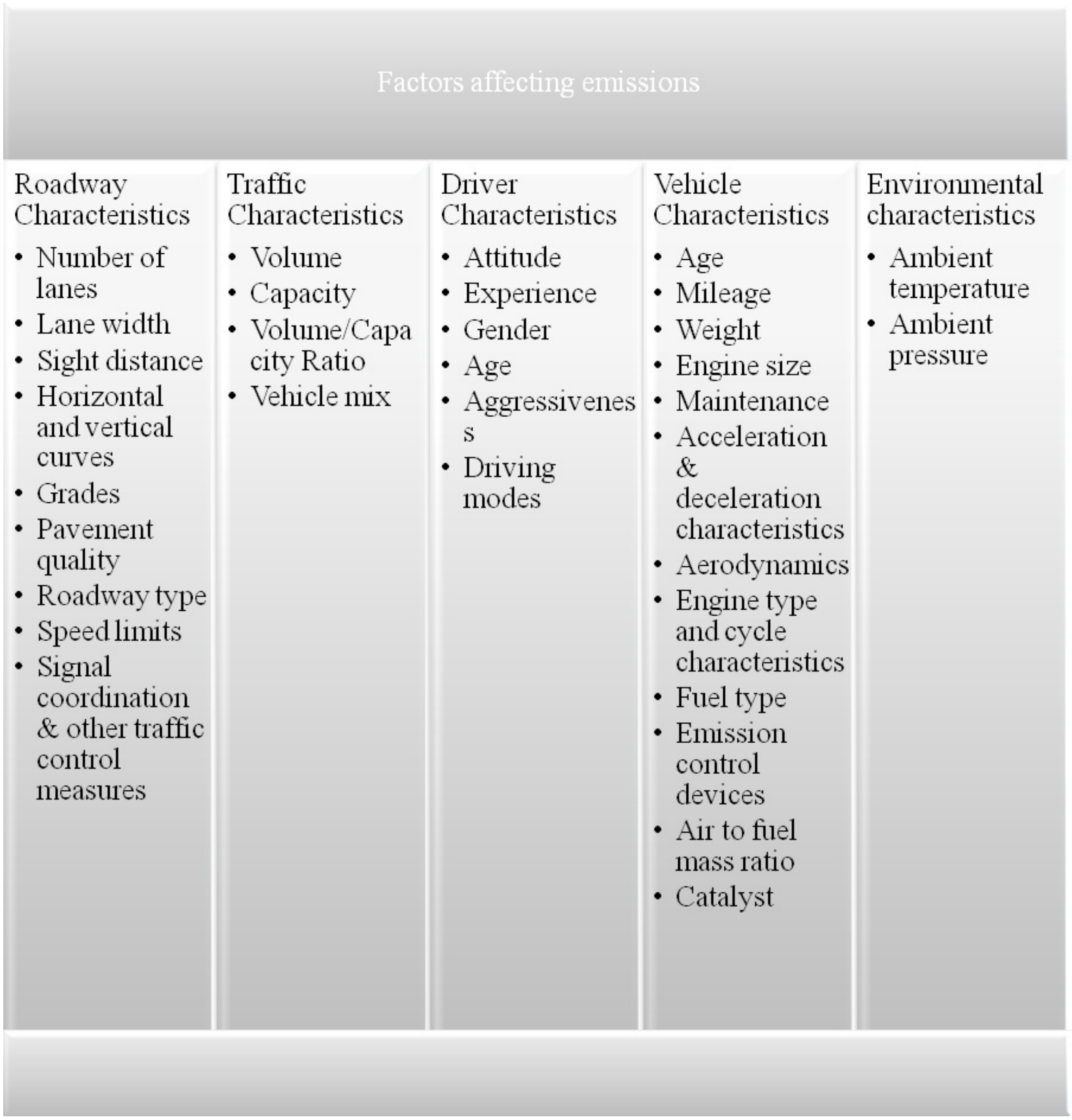

Figure 2: Overview of factors affecting emissions

EMISSION MODELS

Depending on the input parameters and the methodology used, emission models can be classified into static emission factor based models and dynamic instantaneous emission models. Emission factor based models use parameters such as average speed, vehicle mix as input and calculate emissions based on calibrated emission factors. Emission factors are obtained by measuring the amount of pollutants emitted during standard test cycles using a chassis or engine dynamometer. Emission factor based models do not account for speed and acceleration profiles and therefore cannot be used for studying the emissions impacts of traffic operation strategies such as ramp metering. Dynamic emission models which use time-varying parameters such as speed and acceleration profiles as input. They require far more disaggregate and detailed inputs but are more realistic in accounting for the impact of vehicle operating conditions on emissions. In contrast to emission factor based models, dynamic models can be used to estimate the air quality impacts of various operational strategies.

Emission Factor Based Models

As described above, emission factor based models calculate emissions based on average static traffic characteristics like traffic speed and vehicle miles travelled. Emission factor based models have separate emission factors based on the vehicle type and average operation conditions. Some of the most common emission factor based models are MOBILE 6, EMFAC and COPERT. The emission factor based estimation process is summarized in Figure 3.

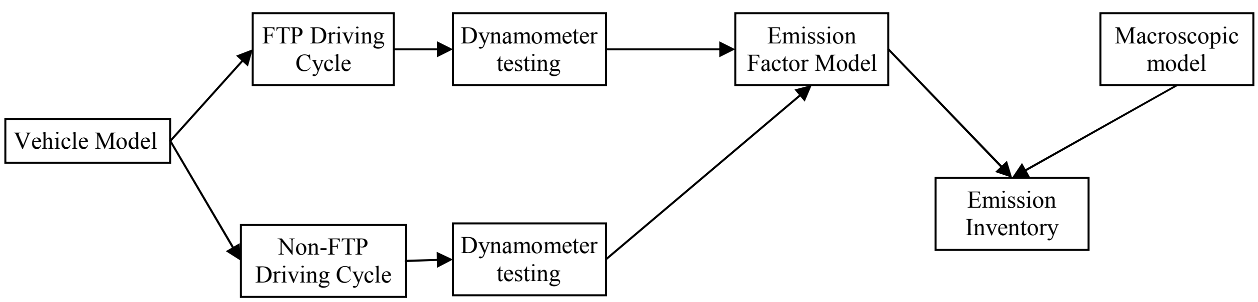

Figure 3: Overview of Emission Factor Based Models (Source: Barth et al, 1996)

MOBILE 6. MOBILE 6 is the most popular emission factor model and is used in almost all the states in the United States other than California. The first version of MOBILE was developed in 1978 and to date there have been six main releases. The base version of MOBILE 6 was released in 2002 and can be used to estimate emissions of nitrous oxides, hydrocarbons and carbon monoxides for a vehicle fleet from the years 1952 to 2000. The EPA then released an updated version, MOBILE 6.1 and 6.2, in which the capability to estimate air toxins and particulate matter were added. The air toxins which were produced include benzene, formaldehyde, acetaldehyde and acrolein (EPA,2003).

The vehicle fleet can comprise of all types of common and uncommon highway vehicles used in the U.S ranging from light-duty cars to heavy duty trucks. MOBILE 6 classifies the vehicles into eight major types and there is an option for further classification to 28 vehicle types. The model accounts for different maintenance levels and age of the vehicle by classifying the vehicles into tier 0, tier 1 and tier 2 vehicles with tier 0 vehicles being the oldest and tier 2 the newest. The model also accounts for fuel parameters, average vehicle operation parameters, environmental parameters and state maintenance programs. The detailed list of inputs needed for MOBILE 6 is given below in Figure 4. It provides emissions in grams/mile and accounts for exhaust emissions (cold start, hot start, hot stabilized and idle emissions) and evaporative emissions (diurnal, hot soak, running losses, resting losses, refueling losses and crankcase emissions) (EPA, 2003).

Generic Parameters

- Min/Max or Hourly Temperature
- Gasoline Volatility
- Calendar Year

Vehicle Activity Parameters

- VMT Mix
- Alternate VMT distribution by hour
- Alternate VMT distribution by facility type
- VMT by speed distribution
- Average Speed
- Starts per day
- Start Distribution
- Soak Time Distribution
- Hoat Soak Activity
- Diurnal Soak Acitivity
- Trip Length Distribution – Weekday vs Weekend

Fleet Characteristics

- Registration distribution
- Mileage
- Alternate diesel sales fraction
- Natural Gas Vehicle fractions

Weather Conditions

- Altitude
- Humidity
- Cloud Cover
- Peak Sun
- Sunrise/Sunset
- Month

Fuel Options

- Reformulated Gasoline
- Gasoline Sulfur levels

Figure 4: Inputs required for MOBILE 6 emission estimation (Source: EPA, 2003)

The emission factors are calculated based on the federal test procedure (FTP) driving cycle and the supplemental federal test procedure (SFTP). The federal test procedure simulates average urban driving conditions in Los Angeles in the 1960s over a distance of 11.1 miles traveling at an average speed of 19.6 mph. The supplemental federal test procedure (SFTP) comprises of two additional driving cycles US06 and SC03 which correspond to aggressive driving and rapid speed fluctuations. MOBILE 6 also estimates different emission factors based on different roadway facilities (freeways/ arterials/ urban streets) (EPA, 2003).

The emissions for pollutant type k for a given time period and a given region can be calculated as

$$E(k) = \sum_i \sum_n VMT_n \kappa_i ER_{i,n} CF_{i.n}$$

Where $E(k)$: emissions for pollutant type k for pre-specified time period

VMT_n: Vehicle Miles travelled in a specified set of links which has an average speed s_n

κ_i: Fraction of vehicles of type i

$ER_{i,n}$: Emission rate for vehicle of type i travelling at an average speed s_n

$CF_{i.n}$: Correction factors to account for non-standard operating conditions.

MOBILE 6 can be used to predict emissions for large scale planning models where average speed is a very accurate performance metric. As mentioned earlier it cannot be used to evaluate emissions under highly dynamic traffic conditions such as build up and dissipation of peak hour traffic. For a similar facility, MOBILE 6 generates the same emission levels irrespective of the actual driving conditions as long as the average speed is the same. For example, MOBILE 6 will predict the same emission level for a vehicle which travels at an average speed of 50 mph and other vehicles which travels half of the distance at 90 mph and the rest at 10 mph. This is a huge discrepancy as research has shown that acceleration and deceleration cycles can have a tremendous impact on emissions (EPA, 2003).

EMFAC. EMFAC2002 is the latest version of the emission factor based model used by California to calculate emission inventories. The inventories are calculated for a geographical region for a specific year by multiplying the emission factor, correction factor and the travel activity data. All the three factors vary based on vehicle population which depends on the area, fuel, class etc. The vehicle activity data is obtained by combining vehicle population data, regional estimates of VMT and number of trips per day. Vehicle population data is obtained by statistical forecasts of DMV data by vehicle class for the base year of 1999. Vehicle miles travelled which represents total distance travelled in a day is calculated based on the total number of miles the vehicle accrues in a year. This is obtained from regional transportation models. The number of trips per day is calculated from survey and vehicle instrumentation data or using engineering judgment. Calculating the emission inventory requires generation of a scenario which is characterized by the following parameters – geographical area, method, calendar year, season/month, model year and inspection and maintenance programs (Figure 5) (CARB, 2007).

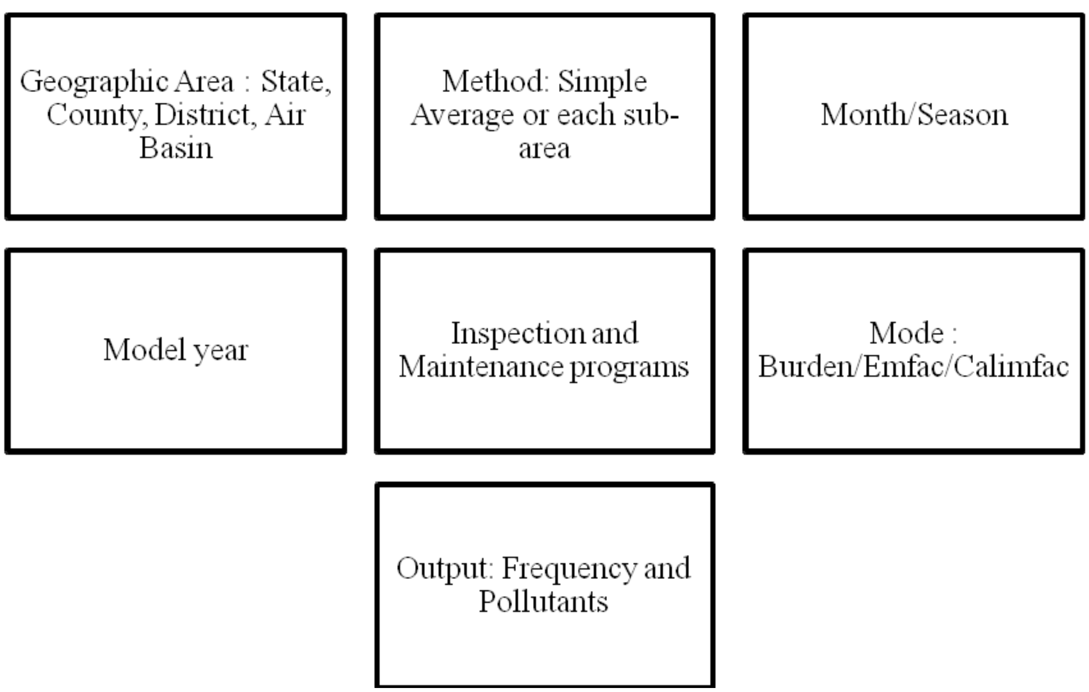

Figure 5: Inputs for EMFAC (CARB, 2007)

The model calculates exhaust emissions from running, starting and idling and evaporating emissions due to running, diurnal and resting losses and hot soak. In addition, the model estimates PM generated from tire wear and brake wear. The model calculates emission inventories from 1970 to 2040 and has the ability to model vehicle classes from 1965 to 2040. The model calculates emission inventories for hydrocarbons, carbon monoxides and dioxides, nitrogen and sulphur oxides and particulate matter. The model accounts for 22 vehicle classes and distinguishes between light heavy duty, medium heavy duty, heavy heavy duty and line haul vehicles. Note that the focus of this model is to calculate the emission inventories for geographical units based on average traffic, roadway and weather conditions and therefore cannot be used to calculate instantaneous emissions or impact of traffic management strategies such as ramp metering (CARB, 2007).

COPERT. COPERT stands for computer program to calculate emissions for road transport and is an emission factor based model used to calculate emission inventories for countries in Europe. The vehicle classes covered by the model include passenger cars, light duty vehicles, heavy duty vehicles, mopeds, motorcycles and buses. The heavy duty vehicles are further classified into eight rigid heavy duty vehicles with the weight ranging from less than 7.5 tonnes to 32 tonnes and six articulated vehicle classes ranging from 14 tonnes to 60 tonnes.

The emission inventory comprises of a fairly detailed mix of pollutants outside of the traditional emission pollutants such as oxides of nitrogen, sulfur, carbon monoxides and carbon dioxides. The pollutants are classified into four groups (Figure 6): (i) group 1 is pollutants which are well studied and emission factors exists for various traffic and engine conditions (ii) group 2 pollutants are pollutants dependent on fuel consumption (iii) group 3 pollutants are difficult to estimate due to lack of data and hence a simplified methodology is used (iv) group 4 corresponds to non methane volatile organic compounds (ETCACC, 2007).

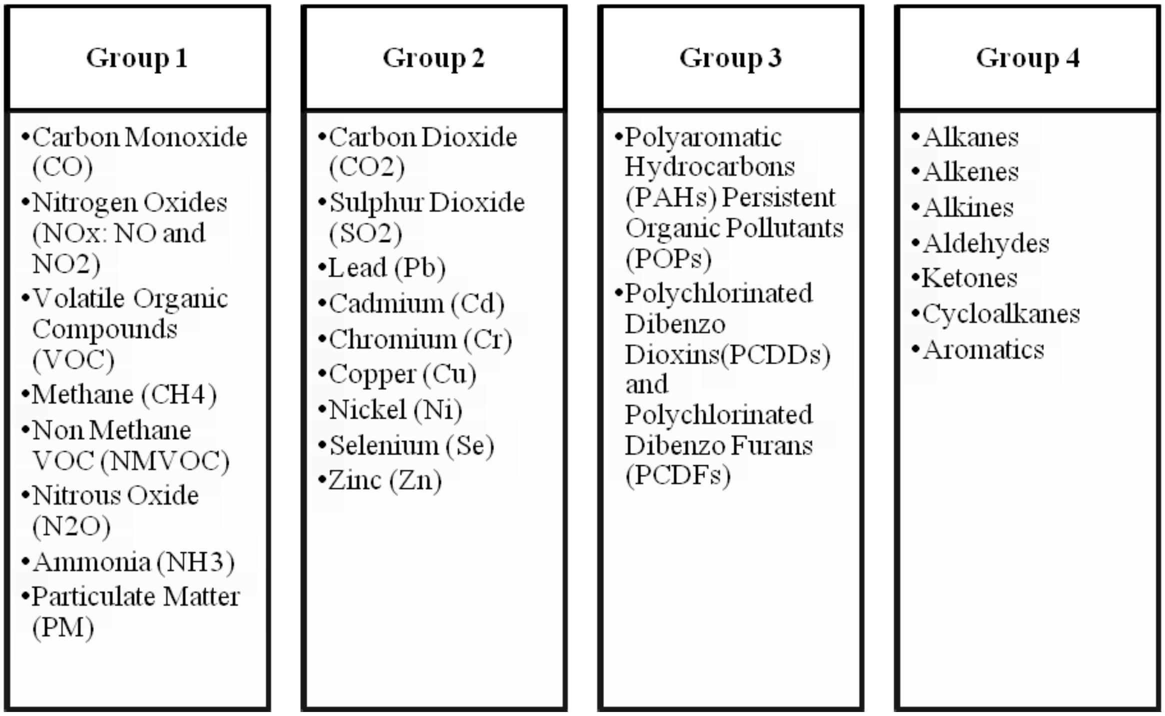

Figure 6: Emission Pollutants (ETCACC, 2007)

Baseline emission factors are estimated for every major pollutant for every country and region in mainland Europe. For regularly studied pollutants such as CO, VOC and NO_x and PM detailed emission factors are available whereas for other pollutants more simple bulk emission factors and equations are used. Correction factors are used to account for characteristics like vehicle age, gradient and vehicle loads. The input variables needed for the model are shown in Figure 7.

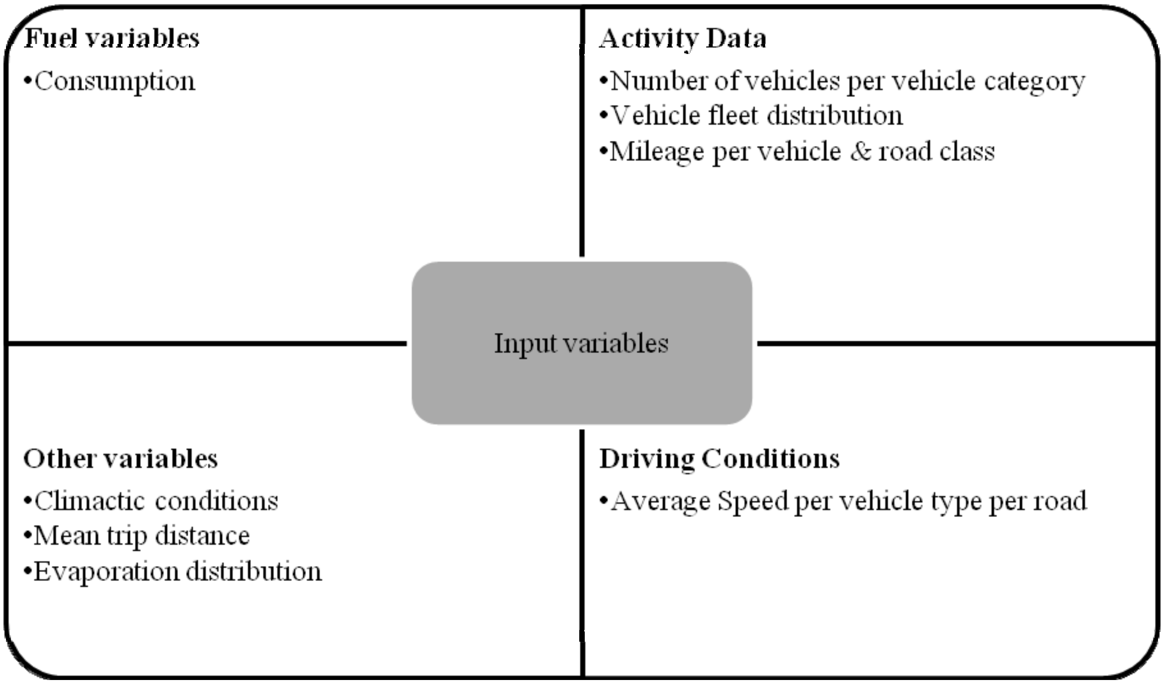

Figure 7: Input Variables for COPERT (ETCACC, 2007)

Dynamic Emission Models

This section we review some of the dynamic models available for emission estimation. Dynamic emissions models estimate instantaneous emissions based on input parameters such as vehicle speed, acceleration, engine power, etc. Many dynamic emissions models have been integrated with traffic simulation models and can be used to evaluate the impact of various traffic management strategies such as ramp metering or speed harmonization.

MOVES. MOVES stands for Motor Vehicle Emission Simulator is the latest modal emissions model developed by the EPA with the aim of replacing MOBILE 6. MOVES calculates emission inventories based on the amount of time spent in each operating modes rather than standard average operating parameters such as average speed. MOVES can be used to estimate emissions at four levels: macroscale, mesoscale lookup, mesoscale and microscale. Macroscale option is used when the focus is on estimating emission inventories within larger areas such as zones or counties. Mesoscale lookup is used when the focus is on estimating emission rates for roadways within a county whereas mesoscale is used to determine emission inventories for roadways within a county or zone. Microscale option is used to determine emission inventories when detailed user input data is available. Microscale option can be used to estimate emissions from traffic simulation software like TRANSIMS. As of now only the macroscale and mesoscale is available (EPA, 2009).

MOVES software estimates the emissions from the following process: running, start, extended idle, evaporative, crank case, tire wear, brake wear and life cycle process. Apart from estimating the volume of common pollutants such as carbon dioxide, methane, nitrous oxides, hydrocarbons and particulate matter, MOVES also estimates the total energy consumed by the vehicle fleets from petroleum and fossil fuels. The software has MYSQL database tables storing emission rates. The emission rate databases stores emission rates classified by vehicle characteristic (operating mode) and the driving characteristic (source bins). The emission rates are a function of vehicle specific power and instantaneous speed and therefore the total emissions are a function of the amount of time the vehicle spends in each of the bins. The amount of time spent in each of the bins can be determined based on average speed distribution on roadways, default driving cycles or can be entered directly by the user either from real world measurements or from a traffic simulation model. Thus a wide variety of driving conditions can be modeled and the variation in emissions caused due to the highly dynamic nature of traffic can be determined (EPA, 2009).

MOVES accounts for thirteen major vehicle classifications which is consistent with the Highway Performance Monitoring System (HPMS) classifications which eases the process of estimating emissions from real world data. Apart from vehicle classes, MOVES has separate bins for estimating emissions based on fuel types, engine technologies and sizes, age and model year and average loaded weight bins. MOVES has four major roadway classifications: rural unrestricted, rural restricted, urban unrestricted and urban restricted. Because of the detailed amount of inputs (Figure 8) used to determine emission volumes and composition, MOVES is expected to handle a wider variety of traffic scenarios than MOBILE 6 (EPA, 2009).

Scale

- Macroscopic
- Mesoscopic Lookup
- Mescoscopic – User Input Database
- Microscopic – User Input Database

Geographic bounds

- Macroscopic – Nation, State, County
- Meso and Microscopic – Zone and County

Time Spans

- Aggregation Level (Year/ Days/Month)
- Select Start Time and End Time

Vehicles/Equipment

- Fuel Type
- Source Type

Road type

- Off Road
- On Road – urban and rural, unrestricted and restricted

Pollutants/Processes

- Pollutants - carbon dioxide, methane, nitrous oxides, hydrocarbons and particulate matter
- Process - running, start, extended idle, evaporative, crank case, tire wear, brake wear and life cycle process

Additional Input datasets (corresponding to MOVES database schema)

Additional / existing emission control strategies

Output

- Specify Output database names
- Specify Time period and Units
- Uncertainty Analysis

Advanced Performance Features

Figure 8: Input files for MOVES (EPA, 2009)

CMEM. Comprehensive Modal Emission Model is an emission model developed at the University of California Riverside and University of Michigan based on second by second chassis dynamometer data. For heavy duty vehicles, the data was collected using the mobile emissions research laboratory (MERL) - trailer containing apparatus to measure exhaust emissions of the vehicle which pulls the trailer. The data was collected by conducting 442 testing cycles over 11 different vehicles. The testing cycles for which emissions data were measured for heavy duty vehicles include the California Air Resources Board test, urban dynamometer driving schedule, real-world driving with actual traffic and other modal emission cycles developed by the research team. For heavy duty vehicles, the model predicts emissions of carbon monoxides, hydrocarbons and nitrous oxides.

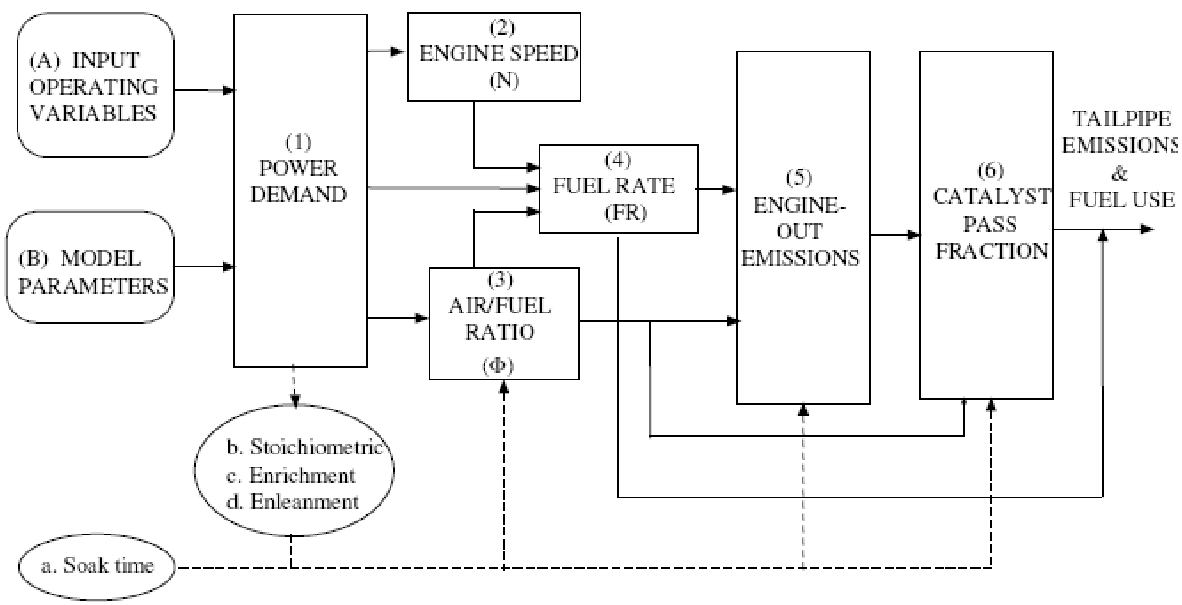

Figure 9: CMEM model (Barth et al, 1999)

The model comprises of six major modules as shown above in Figure 9. The engine power demand module determines second by second engine power output based on input parameters like speed, acceleration, grade, mass etc. The engine speed module determines the engine torque based on the engine power and engine speed which is approximated from the vehicle speed based on the gear ratio. The fuel rate module determines the diesel fuel consumption based on engine friction factor, engine speed, engine displacement and engine power. The engine out emission module calculates the emissions of carbon monoxides, hydrocarbons and nitrous oxides as a linear function of the fuel rate consumption. The CMEM module can be integrated with a microscopic traffic assignment module and can be used to evaluate and compare the emissions resulting from various traffic management strategies. Details of the input file is shown in Figure 10.

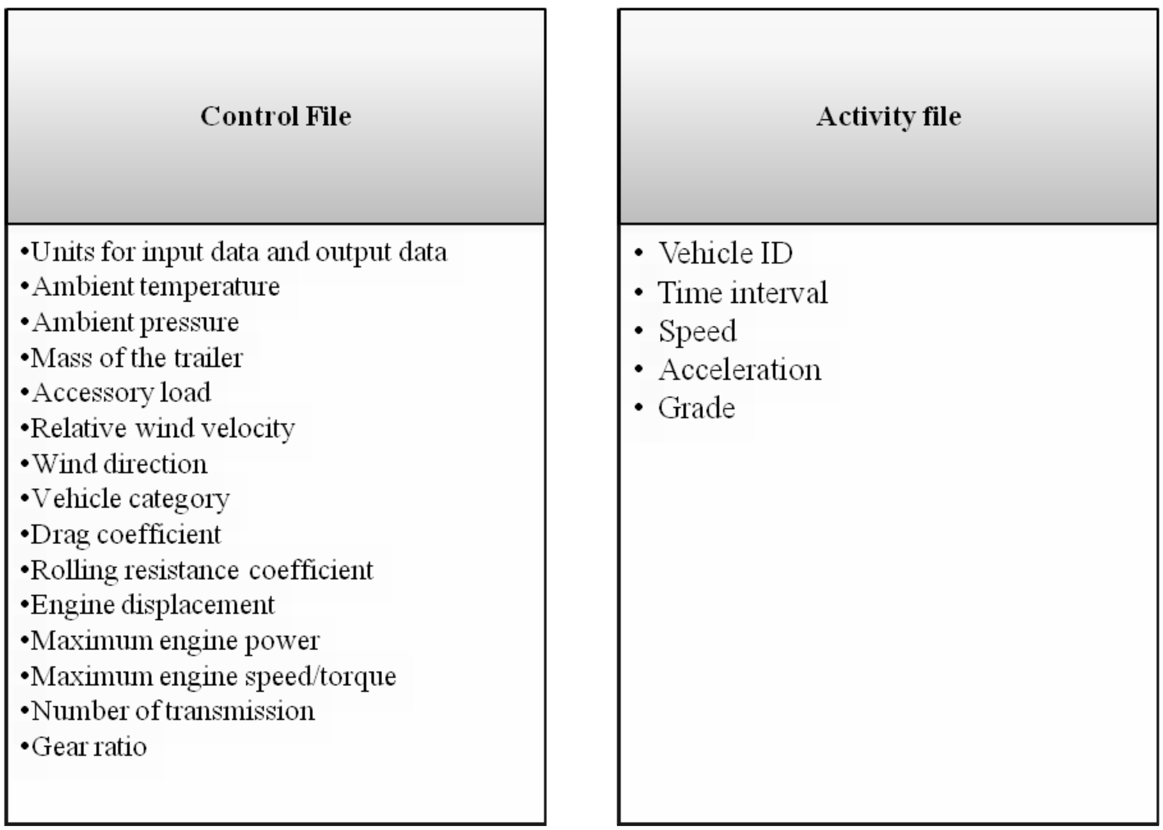

Figure 10: Input File for CMEM

MEASURE. Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) developed at Georgia Tech uses a GIS based framework to estimate regional emissions by applying emission rates calculated from fleet composition and vehicle activity (Bachman, 2000). The GIS framework has the following advantages:

(i) Effective in capturing spatial variations in input parameters affecting emissions
(ii) Easier to estimate individual vehicle activities and the resulting emissions from the vehicle's modal activities
(iii) Ability to interface emission estimates with photochemical models

(iv) Geocoding and visualization tools which aid in creating new databases and map making

(v) Easy to interface with statistical packages.

The inputs (Figure 11) to MEASURE can be classified into five major types: spatial, temporal, vehicle technology, modal activity and trip generation.

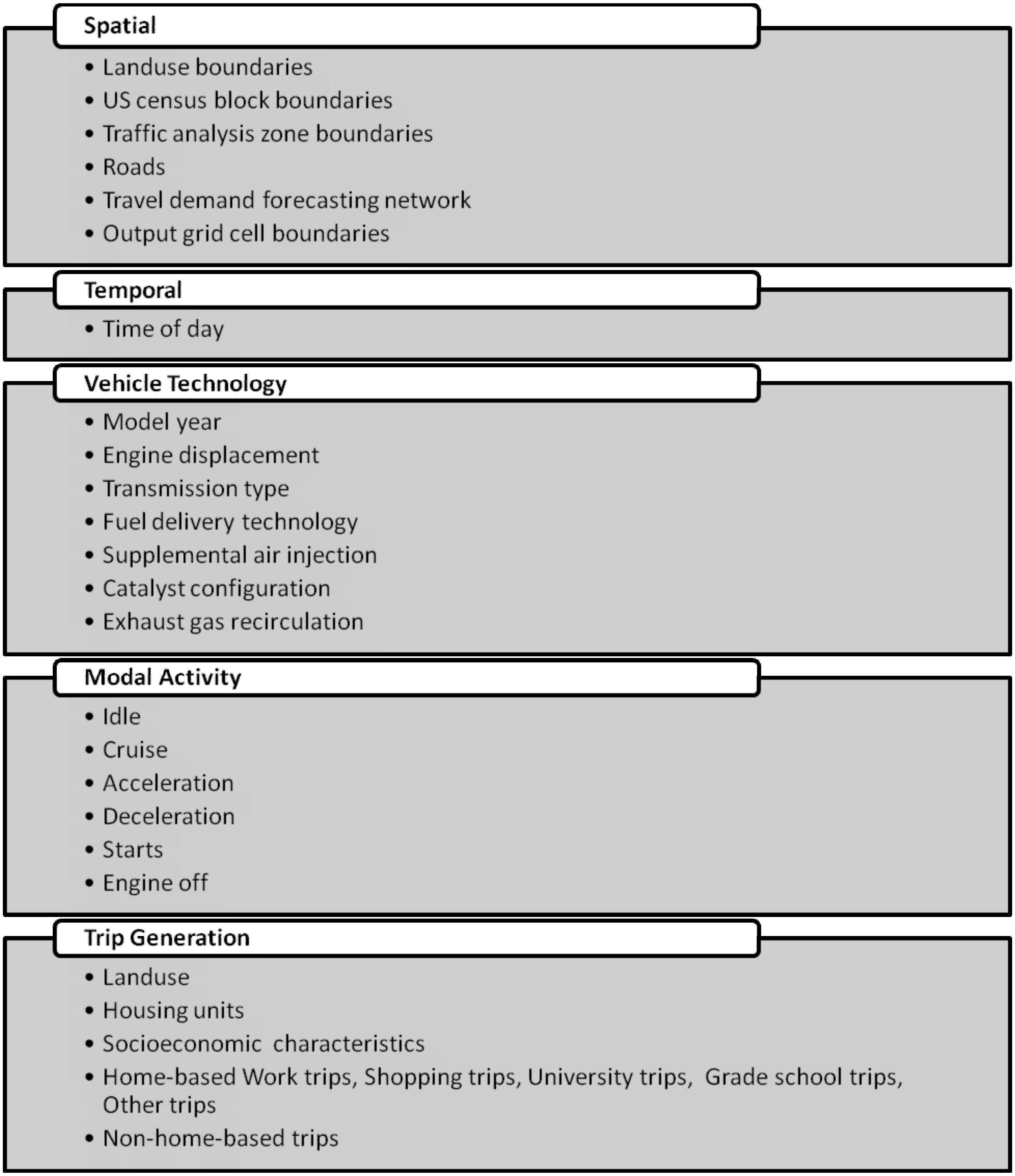

Figure 11: Input Variables for Measure

The model classifies vehicles into technology groups based on vehicle characteristics and average operating conditions. For each of the technology groups' baseline emission factors have been calibrated to determine emissions of CO, HC and NOx. The total emissions for a zone or a roadway section is determined by multiplying the average number of vehicles belonging to each technology group, baseline emission factors and instantaneous engine loads determined from average vehicle operating conditions and roadway geometry. The vehicle operating characteristics are based on speed and acceleration distributions which are determined to be a function of roadway classifications and other geometric parameters (Grant, 1996; Hallmark and Guensler, 1999).

HDDV-MEM. Heavy-Duty diesel vehicle modal emissions model (HDDV-MEM), developed at Georgia Tech, predicts emissions by applying vehicle technology group specific emission factors on dynamic engine power demand. The model uses a technique developed by Yoon et al. (2004) to classify heavy vehicles into different technology groups based on horsepower, GVWR, configurations and operating conditions. The relationship between the new visual classification scheme and the EPA and FHWA classification is shown in Table 8.

Table 8: New Heavy Vehicle Classification Scheme (Yoon et al., 2004)

Yoon classes	EPA	FHWA
X1	HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7	3,5
X2	HDV8a	6,8
X3	HDV8b	7,8,9,10,11,12,13

The model contains three main modules: Emission rate module, engine power module and vehicle activity module. The engine power demand predicts the second by second engine power for each vehicle technology group, hour of the day, facility type and link as a function of vehicle speed, acceleration, weight, gradient, rolling resistance, aerodynamic drag forces, drive train rotational inertial loss and auxiliary power demand. Positive tractive power corresponds to actual running time emissions and negative tractive power corresponds to idle emissions. Vehicle activity module predicts the hourly vehicle volume for each vehicle technology group, hour of the day, facility type and link as a function of the annual average daily traffic, number of lanes in each direction, hourly vehicle fraction, VMT and diesel vehicle fraction for each technology group, link length and average speed. The emission rate module estimates running and idle emissions based on the zero mile emission rate, diesel vehicle registration fraction, vehicle age, baseline emission deterioration rate and annual mileage. Hourly and daily emissions are generated for each transportation link for VOC, CO, NOx and PM. Running and idling emissions are estimated based on the EPA's MOBILE 6.2 and EMFAC2002 emission rates respectively. The output files are easily integrated into a GIS framework to conduct a comprehensive air quality analysis. The HDDV-MEM inputs are shown in Figure 12.

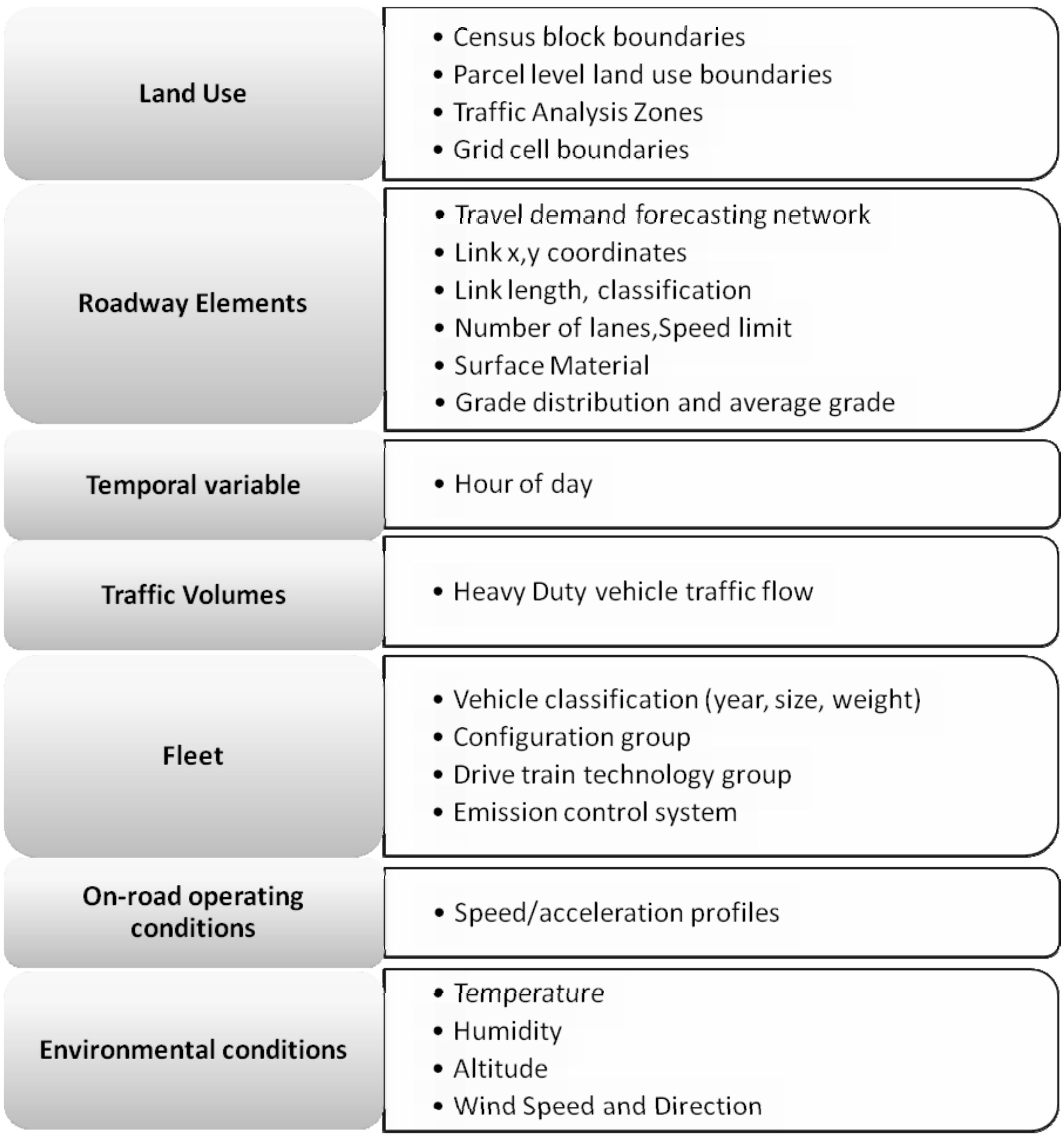

Figure 12: Input variables for HDDV-MEM

Other Emission Models

Outside of the emission factor and dynamic emission models reviewed in this chapter, several other models exist which use significantly different methodologies to prediction emission rates. VT MICRO is a dynamic instantaneous model developed at Virginia tech which predicts emissions of CO, HC and NOx emission rates as a function of instantaneous speed and acceleration (Ahn et al., 2002). VT MICRO is different from most other emission models as they use regression techniques to fit polynomial functions to emission data obtained from the tests conducted at Oak ridge National laboratory. The disadvantage of such an approach is that it can predict emissions only if the operating conditions are in the data used for calibrating the model. The statistical model does not have the ability to extrapolate beyond the region of application. The model also has sophisticated vehicle classification techniques which categorizes vehicles based on vehicle type, fuel and similarity in emission characteristics based on operating conditions. The above model has been integrated into the INTEGRATION traffic simulation software. Several other emission models such as AVL Advisor and GREET (ANL, 2007), attempt to simulate the engine operations in different operating conditions and predict the fuel consumption and emissions.

CONCLUSIONS

This section identifies the various operating factors affecting heavy vehicle emissions. The operating factors can be classified into roadway characteristics, traffic characteristics, driver characteristics and vehicle characteristics. As many of these factors act in tandem, it is very difficult to isolate the individual effect of each operating factors. In general, emissions increase with increase in grades and congestion, aggressive driving, powerful acceleration/deceleration and stop and go traffic. The chapter then reviews the various estimation models used for determining heavy vehicle emissions. The emission estimation models can be classified into static emission factor based models and dynamic instantaneous emission models. Static emission factor based models calculate emission based on average traffic conditions such as average speed. The data requirements are less. However they cannot be used to evaluate the impact of various traffic management strategies. Dynamic emission models can capture the impact of acceleration and deceleration and can be used to evaluate the impact of various traffic management strategies. However they have high data requirements such as detailed vehicle trajectory data.

HEAVY-DUTY VEHICLE EMISSIONS REGULATIONS

CRITERIA POLLUTANT STANDARDS

The two major vehicle criteria pollutant emissions standards were developed in the United States and European Union (EU). Some other countries have developed their own standards, but many follow U.S. and EU standards. Japan is the only country with heavy-duty vehicle emissions pollutants measured in weight per unit distance (g/km). All other countries measure HDV emissions in terms of weight per unit energy (g/kWh or g/bhp-hr). The graphs in figures 13 through 17 compare CO, HC, PM and NOx emissions standards around the world. Japan is left out of these graphs because their standards are in terms of distance and not energy consumption. In addition, Canada's standards are nearly the same as U.S. and can be represented with U.S. standards in the chart for simplification. In general, U.S. and Euro series have very similar NOx and PM standards after year 2000. During the 1990's, the U.S. had significantly lower PM standards than the European Union. U.S. CO and HC standards, however, have remained stagnant over the years while EU's have gradually lowered.

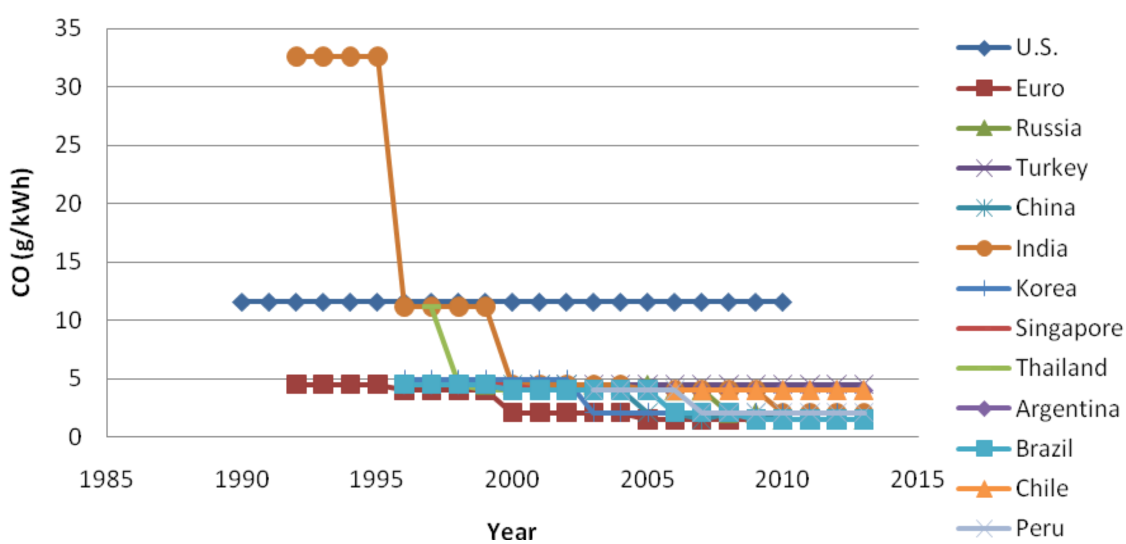

Figure 13: Carbon Monoxide HDD Emissions Standards Comparison.

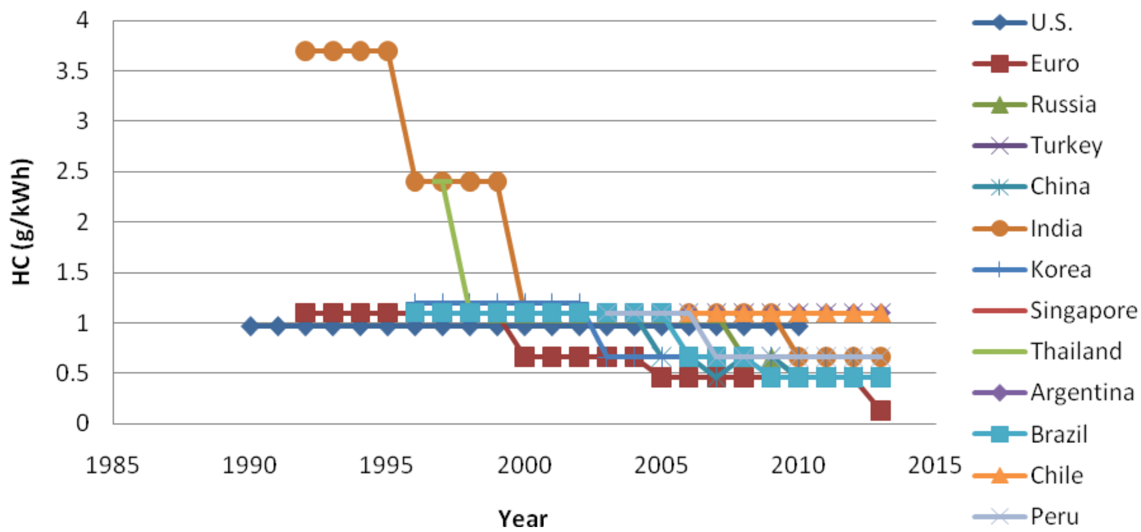

Figure 14: Hydrocarbons HDD Emissions Standards Comparison.

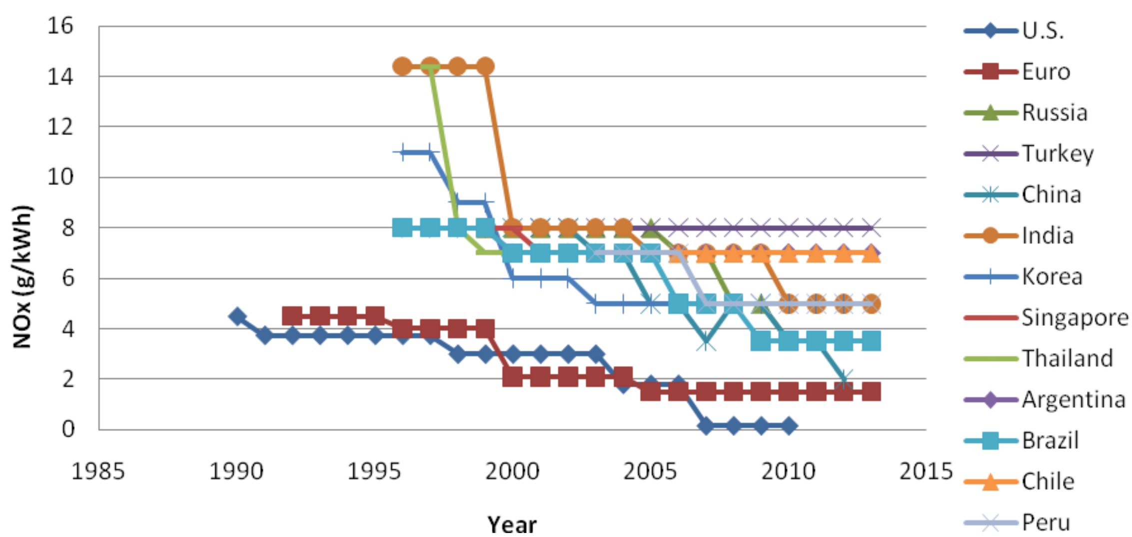

Figure 15: Nitrogen Oxides HDD Emissions Standards Comparison.

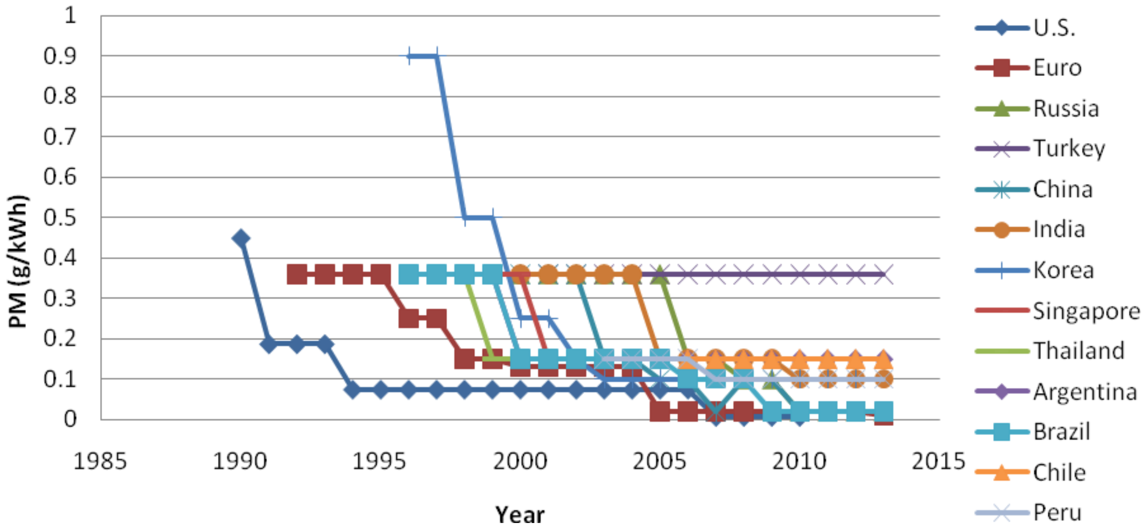

Figure 16: Particulate Matter HDD Emissions Standards Comparison.

Figure 6 shows 2009 global heavy vehicle emissions standards in terms of the Euro series. At present, the US and Canada have the most stringent heavy vehicle emissions standards. In 2013, the European Union's Euro VI standards will be in effect, and US, Canada, and EU standards will be very similar.

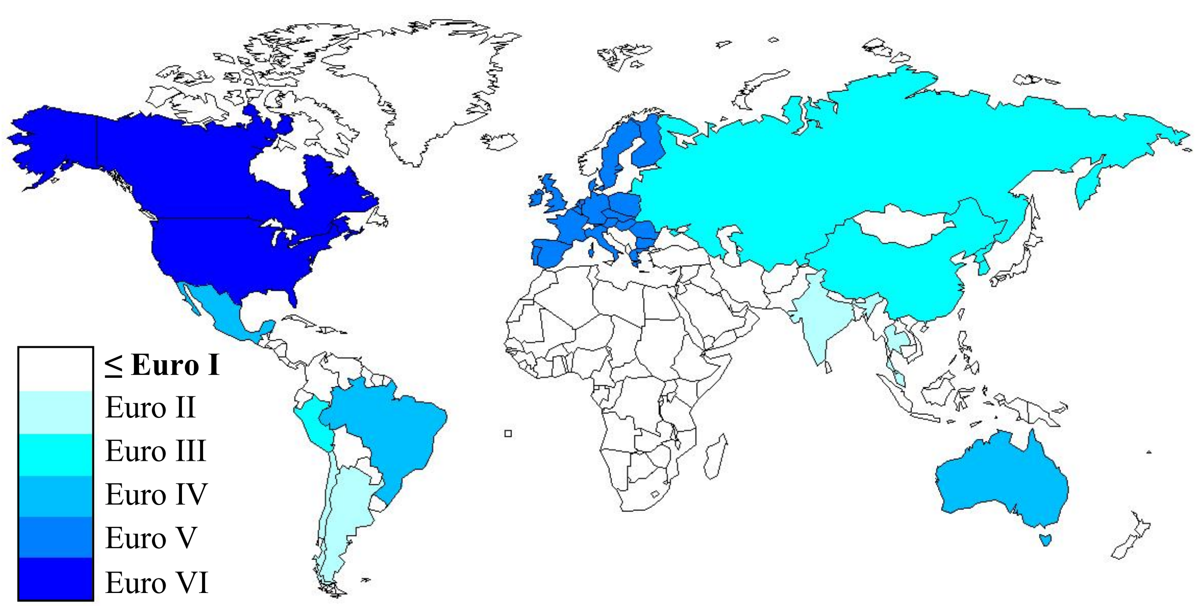

Figure 17: 2009 Heavy Vehicle Emissions Standards Around the World

North America

The Clean Air Act of 1970 authorized the regulation of stationary and mobile source emissions in the United States. Soon after, the Environmental Protection Agency (EPA) was established enforce these regulations. In 1990, Title II, Provisions Relating to Mobile Sources, tightened emissions of mobile sources starting in MY 1994 and regulated the sulfur content of diesel fuel by allowing no more than 0.05% by weight starting in 1993 (EPA 2008).

The U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) have placed limits on pollutants emitted from mobile sources. In 2000, the EPA passed new diesel emissions standards that began with phase 1 in 2004, phase 2 in 2007 and phase 3 in 2010. Table 9 summarizes CARB, 2004 EPA and 2010 EPA emissions standards. Phase 1 in 2004 reduced NOx emissions standard by 50%, and the end result of the 2010 standards will be equal to eliminating 90% of heavy-duty vehicle miles (EPA 2000). Other than PM standards which will be fully implemented in the year 2007, standards of NOx and NMHC will be implemented in a phased manner by sales with 50 % of the engines sold expected to meet standards in the year 2007-2009 and all of them meeting the standards by the year 2010.

Table 9: EPA and CARB Heavy Duty Diesel Emissions Standards (g/bhp-hr). (Sources: EPA 1997, USDOT 2004)

Standard	Year	NOx	PM	CO	HC	NMHC	NMHC + NOx	CH4
US EPA	1990	6	0.6	15.5	1.3	-	-	-
	1991	5	0.25	15.5	1.3	-	-	-
	1994	5	0.1	15.5	1.3	-	-	-
	1998	4	0.1	15.5	1.3	-	-	-
	2004	-	0.1	15.5	-	-	2.4	-
	2007	0.2[1]	0.01	15.5	1.3	0.14	-	-
	2010	0.2	0.01	15.5	1.3	0.14	-	-
CARB[2]	1987	6	0.6	15.5	1.3	1.2	-	-
	1991	5	0.25	15.5	1.3	1.2	-	-
	1994	5	0.1	15.5	1.3	1.2	-	-
	1998	4	0.1	15.5	1.3	1.2	-	-
	2004	2.4	0.1	15.5	1.3	1.2	2.5	-
	2007	0.2	0.01	15.5	-	-	0.14	-

Notes: (1) Only 50% of vehicles need to meet NOx between 2007-09, and 100% by 2010; (2) CARB also had more stringent optional standards during 2002-2006

In addition to these stricter emissions standards, in 2006 the EPA required that refineries produce low sulfur diesel containing no more than 15 parts per million of sulfur because higher levels of sulfur are shown to be damaging to pollutant reducing-technologies needed to meet 2007 and 2010 standards. When used alone, ULSD fuel reduces PM by 5-9%. Using ULSD also allows PM exhaust filters to be effective, and when used together PM can be reduced by 90%. By 2010 when all vehicles will be required to emit no more than 0.01 g/bhp-hr of PM, nearly all diesel sold in the U.S. will be ULSD.

The U.S. also regulates the pollutant concentration within a given geographic area under the National Ambient Air Quality Standards (NAAQS), which is summarized in Table 10. Areas classified as non-attainment are required to adopt strategies aimed at reducing the pollutant(s) for which the area is in non-attainment.

Table 10: NAAQS

Pollutant	Concentration	Averaging Time
CO	9 ppm (10 mg/m^3)	8 hours
	35 ppm (40 mg/m^3)	1 hour
NO2	0.053 ppm (100 μg/m3)	annually
PM10	150 μg/m3	24 hours
PM2.5	15 μg/m3	annually
	35 μg/m3	24 hours
Ozone	0.075 ppm	8 hours
	0.12 ppm	1 hour
SO2	0.03 ppm	annually
	0.14 ppm	24 hours
Lead	0.15 μg/m3	rolling 3-month average
	1.5 μg/m3	quarterly average

Vehicle emissions have been regulated since 1971 by Transport Canada until 1999 when Environment Canada was given the responsibility (Environment Canada 2007). In general, Canada's standards are in sync with U.S. standards. For U.S. standards that are phased in over a period of time, the Canadian standard doesn't change until the time when the U.S. phase-in is complete. For example, the new U.S. heavy-duty standards are requiring 50% of vehicles to meet NOx level of 0.20 g/bhp-hr by 2007 and 100% of vehicles to meet this by 2010. Canadian vehicles would not be subject to this requirement until 2010. Canada's heavy-duty vehicle emissions standards are shown in the tables below. Table 11 standards apply to vehicles of GVWR greater than 8,500 pounds, curb weight of greater than 6,000 pounds, or having a frontal area greater than 45 SFT (Environment Canada 2006). Table 12 standards apply to vehicles weighing less than 14,000 pounds with a load carrying device or container attached when it leaves control of the manufacturer.

Table 11: Canadian HDD Engine Emissions Standards (g/bhp-hr) (Source: DieselNet 2008)

	GVWR kg (lb)	NOx	NMHC	NOx + NMHC	CO	PM
Pre-2005	≤ 6,350 (14,000)	4.0	1.1	-	14.4	-
	> 6,350 (14,000)	4.0	1.9	-	37.1	-
Phase 1 (2005)	≤ 6,350 (14,000)	-	-	1.0	14.4	-
	> 6,350 (14,000)	-	-	1.0	37.1	-
Phase 2 (2008 - 2010)	≥ 3,856 (8,500)	0.2	0.14	-	14.4	0.01

Table 12: Canadian Complete Heavy-Duty Vehicle Emissions Standards (g/mile) (Source: DieselNet 2008)

	GVWR kg (lb)	NOx	NMHC	HCHO	CO	PM
Phase 1 (2005)	3,856 - 4,536 (8,500 - 10,000)	0.9	0.28	-	7.3	-
	4,536 - 6,350 (10,000 - 14,000)	1	0.33	-	8.1	-
Phase 2 (2008 - 2009)	3,856 - 4,536 (8,500 - 10,000)	0.2	0.195	0.032	7.3	0.02
	4,536 - 6,350 (10,000 - 14,000)	0.4	0.23	0.04	8.1	0.02

Mexico's heavy-duty vehicle emissions standards matched U.S. standards for years 1993-2003. When the U.S. upgraded their standards in 2004, Mexico's standards remained the same. ULSD is currently available in the large population centers and will be available throughout all of Mexico by the end of 2009 (Industrial Economics 2007). It has been proposed that during years 2008-2011, vehicles in Mexico must meet U.S. 2004 standards or Euro IV standard, and after 2011 they must meet U.S. 2007 or Euro V standards.

European Union

Regulation of pollutants from road vehicles in the European Union began in 1992 with the Euro series. It is mandatory for all new vehicles sold to meet these standards. The regulations have been tightened over time with six steps, Euro one through six. Euro 1 to 6 standards are for light duty vehicles while Euro I to VI regulate emissions from heavy duty vehicles. When the program began, the vehicles were tested using the ECE cycle until 1999. However, it was found that vehicle manufacturers were catering their designs to this cycle in order to pass. Because the cycle was not representative of true driving conditions, emissions of these pollutants remained stagnant despite the tightening standards. Starting in 1999, heavy gas (NG, LPG) vehicles were tested using the European Transient Cycle (ETC) and heavy diesel vehicles were tested using the ETC, the European Stationary Cycle (ESC) and European Load Response (ELR). The ETC and ESC cycles are used to test emissions of CO, HC, NOx, and PM while ELR is used to measure smoke. Table 13 shows the emissions standards for heavy-duty diesel vehicles using the ESC, ELR and ETC test cycles.

Table 13: European Union HDD Emissions Standards (g/kWh) (Source: DieselNet 2008)

Standard	Year	NOx	PM	CO	HC	NMHC	CH4
ESC Cycle							
Euro I	1992[1]	8	0.36	4.5	1.1	-	-
Euro II	1996	7	0.25	4	1.1	-	-
	1998	7	0.15	4	1.1	-	-
Euro III	1999[2]	2	0.02	1.5	0.25	-	-
	2000	5	0.1 0.13	2.1	0.66	-	-
Euro IV	2005	3.5	0.02	1.5	0.46	-	-
Euro V	2008	2	0.02	1.5	0.46	-	-
Euro VI	2013	0.4	0.01	1.5	0.13	-	-
ETC Cycle							
Euro III	1999[2]	2	0.02	3	-	0.4	0.65
	2000	5	0.16 0.21	5.45	-	0.78	1.6
Euro IV	2005	3.5	0.03	4	-	0.55	1.1
Euro V	2008	2	0.03	4	-	0.55	1.1
Euro VI	2013	0.4	0.01	4	-	0.16	0.5

Notes: (1) >85 kW ; (2) EEVs only.

Turkey, not part of the European Union, does not follow the EU schedule, but they have adopted the Euro I standards in 2001. Several other countries have adopted portions of the Euro series standards including China, Russia, Switzerland, India, Singapore, Thailand, Australia, Argentina, Brazil, Chile, and Peru (DieselNet 2008).

Asia

Japan's passenger vehicle emissions standards began in 1986 and heavy-duty standards, summarized in Table 14, began in 1988. Until 2005, the drive cycles being used for commercial vehicles were the 10-15 cycle and the 6 cycle, neither of which were representative of natural driving conditions. Starting in 2005, and fully phased in by 2011, a drive cycle (JC08) meant to mimic congested urban driving conditions has been used for emissions testing. Unlike U.S. and European standards, the Japanese emissions standards are measured per unit distance rather than per unit energy.

Table 14: Japan's Heavy-Duty Vehicle Emissions Standards (g/km; Ave (Max))
(Source: DieselNet 2008)

Year	NOx	PM	CO	HC
1988[1]	380 (500)	-	790 (980)	510 (670)
1993	1.30 (1.82)	0.25 (0.43)	2.1 (2.7)	0.40 (0.62)
1997	0.70 (0.97)	0.09 (0.18)	2.1 (2.7)	0.40 (0.62)
2003	0.49	0.06	0.63	0.12
2005	0.25	0.015	0.63	0.024
2009	0.15	0.007	0.63	0.024

Notes: (1) Measured in ppm.

In addition to new-vehicle emissions standards, Japan's Automotive NOx and PM Law regulates emissions of in-use diesel vehicles in the Tokyo, Saitama, Kanagawa, Osaka and Hyogo metropolitan areas. Every vehicle is required to be in compliance with 1997/98 MY regulations. If vehicles are not in compliance, the owner must replace the vehicle or retrofit with equipment that will reduce NOx and/or PM emissions. Vehicles are allowed between 9 and 12 years from initial registration to comply.

In addition to this, the Tokyo metropolitan area has additional requirements for in-use vehicles that began in 2001. Those in certain classes are required to be retrofitted with devices lowering PM emissions. Businesses owning greater than 30 vehicles are required to develop an environmental management plan to reduce pollution. Businesses owning greater than 200 vehicles are required to have a certain percentage of low emissions vehicles. Idling while parked or unloading is prohibited. Finally, the use of diesel fuel mixed with heavy oil is prohibited.

The remaining countries in Asia follow the European Union standards at various rates of adoption. Table 15 outlines the Euro-series adoption schedule for Russia, China, India, Korea, Singapore, and Thailand.

Table 15: Asian Emissions Standards Adoption Schedule for Heavy-Duty Vehicles (g/kWh) (Source: DieselNet 2008)

	Year	Standard	CO	HC	NOx	PM
Russia	1999	Euro I	4.5	1.1	8	0.36
	2006	Euro II	4	1.1	7	0.15
	2008	Euro III	2.1	0.66	5	0.10
	2010	Euro IV	1.5	0.46	3.5	0.02
	2014	Euro V	1.5	0.46	2	0.02
China	2000	Euro I	4.5	1.1	8	0.36
	2003	Euro II	4	1.1	7	0.15
	2008	Euro III	2.1	0.66	5	0.10
	2010	Euro IV	1.5	0.46	3.5	0.02
	2012	Euro V	1.5	0.46	2	0.02
India	1992		32.6	3.7	-	-
	1996		11.2	2.4	14.4	
	2000	Euro I	4.5	1.1	8	0.36
	2005	Euro II	4	1.1	7	0.15
	2010	Euro III	2.1	0.66	5	0.10
Korea	1996		4.9	1.2	11	0.9
	1998		4.9	1.2	9	0.5
	2000		4.9	1.2	6	0.25
	2002		4.9	1.2	6	0.15
	2003	Euro III	2.1	0.66	5	0.10
Sing-apore	1998	Euro I	4.5	1.1	8	0.36
	2001	Euro II	4	1.1	7	0.15
Thai-land	1997		11.2	2.4	-	14.4
	1998	Euro I	4.5	1.1	0.36	8
	1999	Euro II	4	1.1	0.15	7

In China, low-sulfur diesel fuel (≤500 ppm) is used, and in Beijing a blend containing at most 50 ppm is used (slightly higher than that of 15 ppm ULSD sold in the U.S.). India has its own standards for two- and three-wheeled vehicles, but follows an adoption of the Euro series for other varieties of light-duty vehicles and heavy-duty vehicles.

Australia

Australia developed its own heavy-duty vehicle standards for MY 1996 through 2001. Starting in 2002, standards followed either Euro or U.S. standards according to the schedule shown in Table

16. The smoke standards are ADR(30/01), or US 1994. The maximum allowance for sulfur content in diesel fuel has become progressively lower since 2002, from 500 ppm to just 10 ppm.

Table 16: Australian Heavy Trucks Emissions Standards Adoption Schedule. (Source: DieselNet 2008)

Veh Class	GVM (tons)	02/03 Diesel	03/04 Petrol	05/06 Petrol	06/07 Diesel	07/08 Diesel	08/10‡ Petrol	10/11 Petrol	10/11 Diesel
Trucks									
Light	≤ 3.5	Euro 2	Euro 2	Euro 3	Euro 4		Euro 4		
Med	3.5 ≤ 12	Euro 3 or US98	US96	US98		Euro 4 or US04, JE05		Euro 4 or US08	Euro 5 or US07, JE05
Heavy	> 12	Euro 3 or US98	US96	US98		Euro 4 or US04, JE05		Euro 4 or US08	Euro 5 or US07, JE05

South America

Most countries in South America follow European or U.S. emissions standards according to various adoption schedules. The exception, Brazil, began regulating emissions according to its own standards in 2006. The adoption schedules for Argentina, Brazil, Chile and Peru are summarized in Table 17.

Table 17: South American Emissions Standards Adoption Schedule for Heavy-Duty Vehicles (Source: DieselNet 2008)

Country	Year	Standard	CO	HC	NOx	PM
Argentina	1996	Euro I	4.5	1.1	8	0.36
	2000	Euro II	4	1.1	7	0.15
Brazil	1996	Euro I	4.5	1.1	8	0.36
	2000	Euro II	4	1.1	7	0.15
	2006	Euro III	2.1	0.66	5	0.1
	2009	Euro IV	1.5	0.46	3.5	0.02
Chile	2006	Euro II	4	1.1	7	0.15
Peru	2003	Euro II	4	1.1	7	0.15
	2007	Euro III	2.1	0.66	5	0.1

Brazil and Chile also have smoke opacity standards. In Brazil, the smoke limit for naturally aspirated engines is 0.83/m and 1.19/m for turbocharged engines. In Chile, the limit is 1.0/m for diesel engines.

EMISSIONS STANDARDS TESTING PROCEDURES

The U.S. EPA, European Union, and Japan have developed vehicle and engine emissions testing procedures that are used to determine if countries meet their respective emissions standards. A problem with these testing procedures is the ability of manufacturers to program the engine to identify the test cycles and adjust combustion to meet the standards. This method of cheating the emissions standards is referred to as cycle beating. The engines are designed specifically to pass the emissions test, but not necessarily to perform well (in terms of emissions rates) under real driving conditions. The catalytic converter is only effective for a certain portion of an engine's load and speed range, and in the case of cycle beating, only the portion covered by the test cycle. This is problematic because an engine can emit 10 to 100 times more when operating in a range not cleaned by the catalytic converter (Kageson, 1998). In addition to this, EU's test cycles have been known to have smooth acceleration and only using a small portion of an engine's operating range (Pelkmans and Debal, 2006). As a result, emissions reductions from mobile sources have not reduced as dramatically as is required by the gradually tightening standards (Pelkmans and Debal, 2006).

United States

In the U.S., there are three tests that currently apply to heavy duty vehicles. The transient Federal Testing Procedure (FTP) consists of four modes, with three that are modeled after New York and Los Angeles non-freeway driving, and a fourth that is representative of LA freeway driving. As the name suggests, this cycle attempts to mimic transient driving conditions for heavy-duty vehicles. The 4 mode cycle lasts 1200 seconds and is ran first with a cold start and then repeated for hot start. The average speed is 30 km/h.

The Supplemental Emissions Test (SET) tests steady-state driving emissions. The pollutant limits for this test are the same as FTP. The cycle itself has two parts, one of which is identical to the European Stationary Cycle (ESC), and the other is similar to ESC but has 20 second transition periods between each mode.

To prevent truck companies cheating the testing system with cycle beating, the Not-to-Exceed (NTE) test encompasses the portion of an engine's power curve (speed and load combinations) that is expected to be encountered during normal vehicle use (referred to as the NTE zone). The test is not a specific cycle, but requires that the engine remain in the NTE zone for at least 30 seconds, and the emissions are averaged over that time.

European Union

Prior to year 2000, the ECE R-49 test cycle was used for heavy-duty vehicles. The test was run on an engine dynamometer and the modes were equivalent to EPA's 13-mode cycle. However, EU weighted the modes differently, and placed more emphasis on the high engine load modes (i.e. 6 and 8) which resulted in average emissions results being higher than US results. This test cycle was replaced with the European Stationary cycle (ESC), European Transient Cycle (ETC) and European Load Response (ELR) cycle.

The ESC has 13 predetermined steady-state modes, as well as another random mode selected by the test proctor (to prevent cycle beating). The average load factors and exhaust temperatures are typically high. The ETC has a running time of 1800 seconds and features modes modeled after transient driving in urban, rural and motorway locations. The ELR test simulates the vehicle carrying loads for 10 seconds alternating from 10% to 100% of capacity at 3 different speeds. The total running time is 180 seconds, with 60 seconds spent on each vehicle speed.

Japan

Prior to 2005, Japan tested emissions on a 13-mode cycle with low average speeds, engine loads and exhaust temperature. After 2005, the JE05 transient test is used. The 1800 second test is based on transient Tokyo driving, with an average speed of 27 km/h and maximum speed of 88 km/h. Unlike the U.S. and EU test cycles, this cycle is defined by a speed versus time graph rather than engine power and speed (as is required for engine dynamometer).

FUEL ECONOMY REGULATIONS

Many countries also have fuel economy or CO2 emissions standards in addition to criteria pollutant emissions standards. The U.S., California, Japan, China, Taiwan, and South Korea all have mandatory FE standards while the European Union, Australia and Canada have voluntary FE standards (An and Sauer 2004). All standards are fleet- or industry-wide, with the exception of Japan and China where standards apply to vehicle classes designated by weight. However, unlike criteria pollutant standards, most fuel conservation standards only apply to passenger vehicles, leaving the FE of heavy vehicles without regulation. The exception to this is Japan, where heavy vehicle fuel economy standards became effective in 2006.

Because fuel costs are a significant proportion of a freight company's expenditures, it was thought that fuel-saving technologies would enter the heavy-vehicle market naturally, thus making fuel economy regulations unnecessary. In addition, it is much more difficult to test the fuel economy of heavy vehicles because they are used for many different purposes. However, time has shown that low fuel prices, low production numbers (limiting the benefit of economies of scale) and lack of information provided to the consumer regarding vehicle model fuel economy have prevented some technologies from penetrating a significant proportion of the market (Langer 2004, Onoda 2008). Fuel economy standards would create an artificial demand for these fuel-saving technologies and accelerate heavy vehicle fuel economy improvement (which has been nearly stagnant for 30 years). Of course, contrary to regulations are market-based options such as incentives for hybrid, natural gas or other vehicles that significantly reduce fuel consumption and/or CO_2 emissions relative to its diesel counterpart.

In a report prepared for the National Commission on Energy Policy, Langer (2004) recommends including pickup trucks, SUVs and vans weighing less than 10,000 lbs to be included in CAFÉ standards, offering incentives for the purchase of hybrid vehicles weighing between 10,000-30,000 lbs, and creating fuel economy standards (as well as effective testing procedures) for heavy vehicles greater than 33,000 lbs. The lighter heavy vehicles would be easy to include in CAFÉ standards because the same testing procedures could be utilized. However, based on typical use patterns, it would be inaccurate to include medium and heavy duty vehicles in CAFÉ. Because medium duty vehicles are often utilized for urban delivery and subject to stop-and-go traffic, they would benefit most from hybridization. Because heavy-duty vehicles are most typically used for long haul transportation, the benefit from hybridization would likely be insignificant. Of course, as mentioned previously, the key issue with heavy-duty fuel economy standards is developing a test procedure.

Japan's Heavy-duty Vehicle Fuel Economy Standards

Japan's HDV FE standard test procedure is essentially an extension of its criteria pollutant test procedure, which is based primary on engine performance. The simulation results are held to a standard of at most 0.4% error (Sato, 2008). Unfortunately, many other vehicle components affect fuel economy that are not captured by such a test. In general, the FE standards will force a 12% improvement by 2015 for vehicles weighing more than 3.5 tons (Goto 2007). The targets by weight class are shown in Table 18.

Table 18: Japan's Heavy-duty Vehicle Fuel Economy Targets. (Source: ECCJ, 2008).

GVW Range (tons)	**Max Load Range** (tons)	**Fuel Economy** (km/l)	**Fuel Economy** (mpg)
3.5-7.5	<1.5	10.83	25.5
	1.5-2	10.35	24.3
	2-3	9.51	22.4
	>3	8.12	19.1
7.5-8	-	7.24	17.0
8-10	-	6.52	15.3
10-12	-	6.00	14.1
12-14	-	5.69	13.4
14-16	-	4.97	11.7
16-20	-	4.15	9.8
20	-	4.04	9.5
<20*	-	3.09	7.3
>20*	-	2.01	4.7

GREENHOUSE GAS POLICY

The Kyoto Protocol was an international effort aimed at reducing GHG emissions via GHG reduction targets, research and education. The protocol was ratified in 1997 and became active in 2005. The reduction targets, Table 19, are to be met by 2012. The policy separates countries into Annex I (developed) and non-Annex I (developing) categories. Annex I countries are required to reduce their GHG emissions to the level assigned to them by 2012 (assuming they have signed the treaty). Non-Annex I countries are not subject to emissions reduction requirements, but are required to contribute to research, education, and technological advances related to climate change prevention (UNFCCC 2007). Annex I countries can modify their emissions targets by trading tons of carbon dioxide equivalents ($CO2_e$) with another country, investing in projects that reduce $CO2_e$ emissions, and enhancing carbon sequestration in another Annex I country (referred to as "joint implementation"), or non-Annex I country (called the Clean Development Mechanism).

Table 19: Kyoto Protocol GHG Emissions Targets Relative to 1990 levels. (Source: Pew Center on Global Climate Change, 2009)

Country	**By 2012**
Australia	+8%
Canada	-6%
New Zealand	0%
Japan	-6%
European Community:	-8%
Luxembourg	-28%
Germany	-21%
Denmark	-21%
Austria	-13%
United Kingdom	-12.5%
Belgium	-7.5%
Italy	-6.5%
Netherlands	-6%
Finland	0%
France	0%
Sweden	+4%
Ireland	+13%
Spain	+15%
Greece	+25%
Portugal	+27%

The Protocol was ratified by every developed nation except the U.S. and Australia. If the U.S. had ratified the protocol, its target would have been to reduce GHG emissions to a level 7% below that of its 1990 emissions level[5]. Instead of setting GHG targets, the U.S. focused on market based approaches to reducing GHG emissions. In 2002, the Bush Administration's Clear Skies and Global Climate Change Initiative set goals of reducing GHG intensity (tons of CO2e per dollar GDP) by 18% by 2012. However, it was estimated by the U.S. Department of State (2007) that meeting this 18% reduction in GHG intensity will still allow total emissions to increase by 11%.

In 2005, the California Energy Action Plan II established GHG targets of 1990 levels by 2020 and 80% below 1990 levels by 2050 (CEC & CPUC 2005). When put into the context of U.S.

[5] In 2005, U.S. GHG emissions were 8.1 billion tons, and Kyoto targets required 6.4 billion tons by 2012 (EPA 2008).

emissions, CA's 2020 target requires a 2 billion ton reduction (of 8 billion tons, total) which is roughly the same as Kyoto's 2012 target for the U.S. Since then, 19 other states[6] have followed California's lead and established statewide GHG targets, as seen in Figure 18 (Pew 2009). The American Clean Energy and Security Act (ACES) of 2009 has been passed by the House of Representative and, if passed by the Senate and President Obama, will set GHG targets for 17% below 2005 levels by 2020 and 83% below 2005 levels by 2050, also shown in Figure 5.

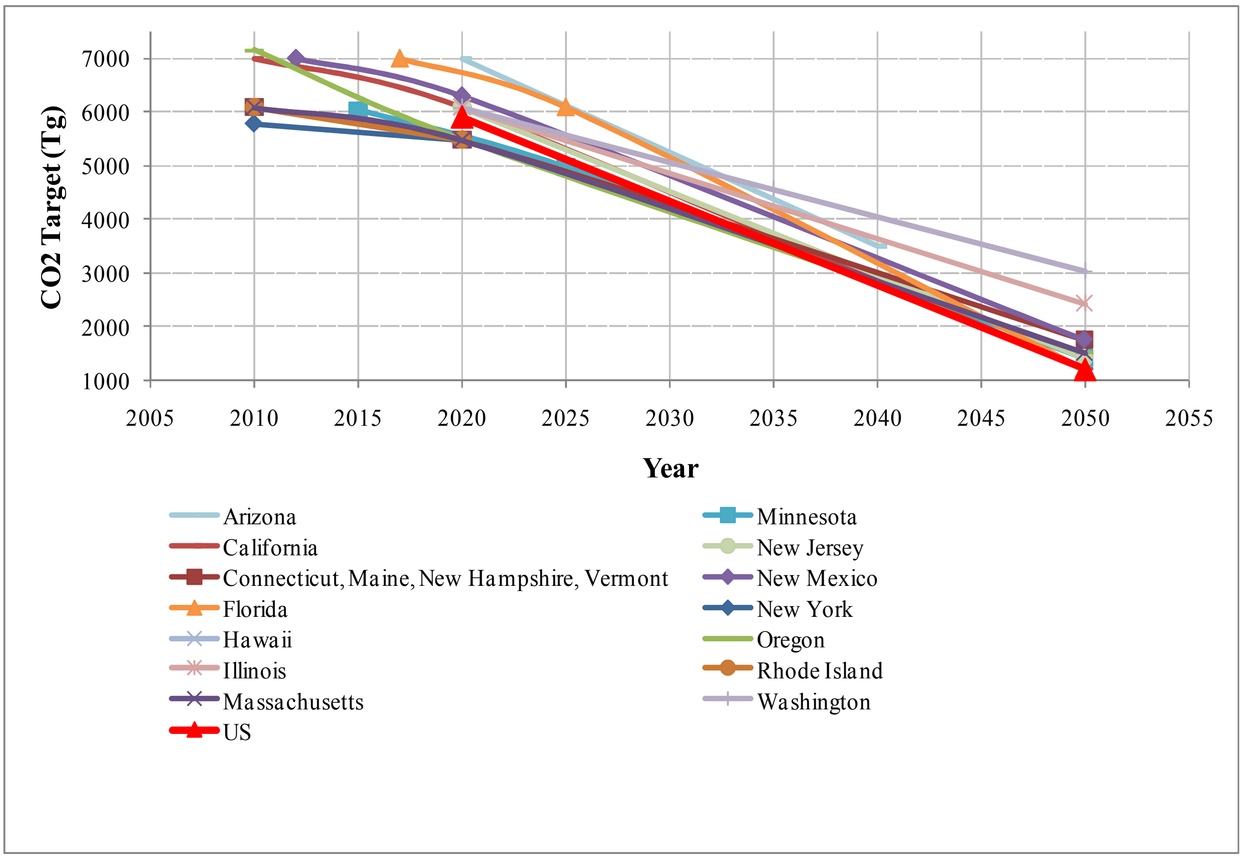

Figure 18: U.S. State GHG Targets.

RETROFITTING REQUIREMENTS AND INCENTIVE PROGRAMS

California has recently tightened their diesel emissions standards by requiring existing heavy-duty vehicles to be retrofitted, taking full advantage of EPA's low sulfur and 2010 emissions standards. Beginning in January 2011, HDV owners will be required to install PM exhaust filters on all vehicles by 2014 and replace all pre-2010 engines prior to 2022 (CEPA 2008). Long haul trucks will need to have rolling resistance tires and aerodynamic devices installed to reduce fuel

[6] Washington, Oregon, Arizona, Utah, Colorado, New Mexico, Montana, Minnesota, Illinois, Florida, Virginia, New Jersey, New York, Vermont, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine.

consumption and GHGs. These requirements will apply not only to vehicles registered in California, but also to vehicles registered elsewhere that travel within California. Exemptions will be made for low-use, emergency, military and personal use vehicles. In addition, school buses will only be required to install the PM filters and will be exempt from replacing old engines. Outside of California, the state of Arizona has prohibited heavy-duty diesel vehicles of model year 1987 or older from registering or operating in the Phoenix metropolitan area in 2006.

Many programs exist for voluntary retrofitting and offer financial incentives for doing so. The EPA's Federal Clean Diesel Program has been offering assistance since 2001 in the form of over 300 grants to efforts reducing diesel emissions. In Arizona, heavy-duty vehicles that have been registered in Phoenix or Tuscon for at least 24 months and are 12 or more years old can qualify for $1,000 to be used for repair or retrofits to reduce emissions. California's Lower Emissions School Bus Program provides funding for new school buses and retrofits (Industrial Economics, 2007).

CONCLUSIONS

Various levels of the U.S. and Europe vehicle emissions standards are used in much of the world that are based on emissions per unit energy expended, and Japan has its own standards based on emissions per unit distance traveled. Japan has also implemented the world's first heavy-duty vehicle fuel economy standards in 2006. In the U.S., emissions standards for PM and NOx are becoming more stringent with EPA's 2007 and 2010 heavy-duty vehicle standards.

The test cycles used to enforce these emissions standards are somewhat inadequate because engines can be designed to pass the test, yet frequently exceed the standards in real driving conditions. As a result, vehicle emissions are not decreasing at the rate implied by the standards. To prevent test cycle beating, supplemental test cycles that are less predictable and could potentially test a larger portion of an engine's operating range are now being used.

Only recently, have greenhouse gases been regulated. In 1997, several countries agreed to adhere to the maximum GHG emissions level that applied to them according to the Kyoto Protocol, and since then the United Kingdom and the European Union have implemented GHG cap and trade schemes to meet these targets. The U.S. has yet to set national GHG emissions targets, but several states have done so. Groups of states are planning future regional emissions trading schemes. At the federal level, several plans to control greenhouse gas emissions have been proposed that include targets, cap-and-trade, and carbon taxing to various degrees.

FUTURE TRANSPORTATION POLICIES

Future transportation and energy policy decisions that will require accurate measurement of heavy vehicle emissions for the future include GHG cap and trade, carbon taxes, and emission based road pricing strategies. This chapter provides a detailed review of current and potential implementations of above mentioned policies.

CAP AND TRADE POLICIES

Cap and trade policies attempt to control pollution using market forces and economic incentives to reduce emissions. With respect to greenhouse gases, every cap and trade policy involves identifying greenhouse gas emitters in a region and capping their emissions. GHG emitters are provided emission allowances which quantify the amount of pollutants which can be emitted. A company wanting to emit more pollutants than the allocated allowance needs to purchase credits from those companies which emit less and are willing to trade the emission allowances. Thus there is an economic incentive to reduce emissions. The total emission allowances in a region will correspond to the emission cap targeted by the policy. A successful cap and trade policy entails: (i) stringent and achievable total emission cap, (ii) determining baseline emissions and resulting allowances, (iii) good banking and trading system (iv)well defined performance criteria and (v) flexibility to emission emitters to achieve their emission targets without compromising productivity (EDF, 2009) .

Cap and Trade in United States:

Cap and trade was first introduced in the United States through the National Clean Act of 1990 with the aim of controlling SO2 levels. The SO2 cap and trade policy was implemented in two phases from 1995 to 1999 and from 2000 onwards. The focus of the cap and trade was controlling SO2 emissions from fossil fuel burning power plants in continental United States. The SO2 cap and trade policy was extremely successful in reducing SO2 emissions (Figure 19) without compromising economic efficiency.

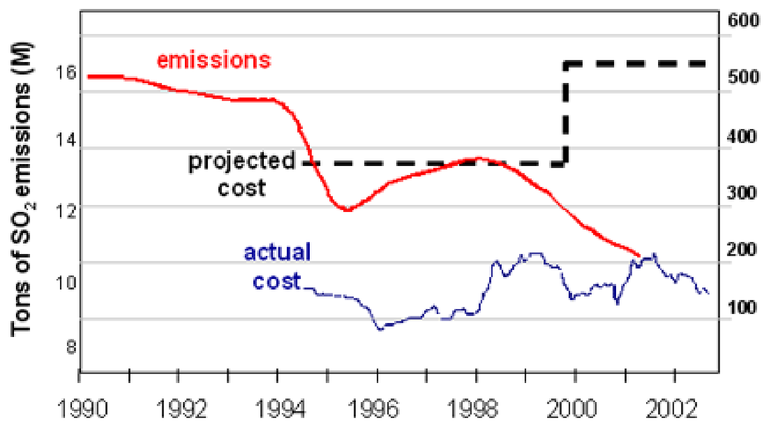

Figure 19: Reduction in SO2 (Source: EDF, 2009)

The state of Illinois implemented the Emission Reduction Market System (ERMS) to control volatile organic compound emissions in the Chicago region. The focus of ERMS is to control ozone levels in the region by capping the VOC emissions. ERMS distinguishes itself from other trading systems as it is active only during the Ozone season from May to September. Thus many VOC emitters have the option of shifting their operations which emit VOC's to outside the Ozone season (IEPA, 2007).

In 2003, ten Northeastern and Mid-Atlantic States initiated Regional Greenhouse Gas Initiative, which was the first GHG cap and trade policy implemented in the. The participating states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island and Vermont. The target of the RGGI is to reduce CO2 emissions from the power sector by 10% by 2018. The power generators in the ten states will purchase, sell and trade allowances and the profits will go to clean energy research/implementation efforts. The tightening of cap will be gradual in beginning, to allow companies to "clean" their grid to avoid sharp increases in consumer energy prices. The credits are auctioned quarterly, starting September 2008 (RGGI, 2009).

In 2007, seven US states and three Canadian states formulated the Western Climate Initiative with the aim of reducing GHG emissions by 15% below 2005 levels by 2020. The participating states are Arizona, British Columbia, California, Manitoba, Montana, New Mexico, Ontario, Oregon, Quebec, Utah and Washington. The WCI is a multi-sector system and if passed, encompasses 90% of region's emissions corresponding to 70% of Canadian economy and 20% of US economy. The initiative focuses on electricity generation, industrial, commercial and residential fuel consumption. The first phase will begin 2012 and will cover all of the above other than residential and transportation sources. The second phase in 2015 will cover all of above mentioned sectors. The WCI will be the first cross border cap and trade initiative in North America (WCI, 2009).

Recently ten Midwestern states signed the Midwestern Gas Accord which aims to reduce green house gas in the region through a multi-sector cap and trade system. The participating states are Wisconsin, Minnesota, Illinois, Indiana, Iowa, Michigan, Kansas, Ohio, South Dakota and Manitoba. Note that short term targets with respect to GHG such as CO2 have not been established and the details of the cap and trade plan have not been determined. The plan will most likely cover electricity production, industry (emissions from combustion), transportation fuels, and fuel consumption of buildings and will not cover agriculture, forestry or waste management (MGGRA, 2009). California recently passed the AB 32 or the Global Warming Solutions Act which identifies a number of measures to control GHG emissions. The act identified cap and trade as an important way of reducing emissions to 1990 levels by 2020 and to 80% of 1990 levels by 2050. The act directs the California Air Resource Board (CARB) to implement the program by 2012 (CARB, 2009).

Numerous legislative proposals where passed in the congress between January 2007 and January 2009 (Bean and White, 2009). However, even though the proposals have not been passed these legislations will act as the basis for future GHG emission regulations. The major legislative proposals include:

(i) Climate Stewardship and Innovation Act of 2007 (S.280), Lieberman-McCain focusing on capping emissions of downstream emitters in electrical, industrial and commercial sectors. Transportation emissions are capped upstream at petroleum refineries level.

(ii) Global Warming Pollution Reduction Act of 2007 (S.309), Sanders: Cap and trade system which enforces newer and more stringent emissions standards on vehicles.

(iii) Global Warming Reduction Act of 2007 (S.485), Sen. John Kerry: The proposed act is an amendment to the Clean Air Act which encourages the setting up of a cap and trade market system. The EPA will have control on identifying the sources and sectors which fall under the cap.

(iv) Low Carbon Economy Act of 2007 (S.1766), Bingaman: Unlike other acts which gives EPA the control to monitor the cap and trade system, the low carbon economy act gives the President the power to monitor and review the program. The revenue from the cap and trade system will be deposited in the Energy Technology Development Fund.

(v) Lieberman-Warner Climate Security Act of 2007 (S.2191) and Lieberman-Warner Climate Security Act of 2008 (S.3036): The act proposed one of the most popular cap and trade system covering all sectors of the economy. The act emphasizes the need for a "Clean Medium and Heavy-Duty Hybrid Fleets Program" and provides funding for emitters to purchase more environmentally friendly vehicles to replace the existing fleet.

(vi) Climate MATTERS Act of 2008 (H.R.6316), Doggett: The act establishes a cap and trade system with the secretary of treasury conducting the auctions.

Cap and Trade in Europe

A voluntary pilot carbon trading scheme was launched in the UK in 2002 involving 34 participants who were provided funding to reduce carbon emissions. The focus of this scheme was to study the feasibility of carbon trading and use the experience to refine the European Union Emissions Trading Scheme (EU ETS).The scheme ran till 2006 after which the mandatory EU ETS took over. The scheme did achieve reduction in carbon emissions though stricter emission requirements could have provided more benefits (DEFRA, 2006).

The EU ETS implements cap and trade and has three periods: Phase I: 2005-2007 trial period to build infrastructure, Phase II: 2008-2012 period to meet Kyoto Targets (target is 6% below 2005) and Phase III: 2013-2020 (target is 21% below 2005. The aim is to limit CO2 from 12,000 facilities in 27 EU member states and covers about 50% of GHG sources including power plants and five major industrial sectors (oil, iron and steel, cement, glass, and pulp and paper). Transportation may be included in the cap at the discretion of the member countries and is not mandatory. There is a chance that airline industry will be included in the cap in 2011 (Pew Center, 2009).

The price of credits fluctuated (especially in the first year) dramatically during the trial period, but EU feels this is typical of a new compliance market; due to weather, energy prices rising, and over allocation of allowances. Preliminary results indicate a reduction of 50-100 million tons of CO2. The initial targets were lenient as the objective was to refine the system during this phase and also due to the lack of historical emissions date in certain region to establish baseline emissions. The aim of the program is to reduce the emissions to 30% below the 1990 level by the end of phase III. The long term goal is to reduce emissions to 70% below the 1990 emission level. The EU experience provides invaluable lessons US policy makers in terms of how to implement cap and trade in US (Pew, 2009).

Cap and Trade in Transportation Sector

Ellerman et al. (2006) studied issues associated with implementing cap and trade in the transportation sector. The primary issue of implementing cap and trade is monitoring emissions at the individual vehicle level. To counter this proxies for emissions such as fuel consumption have been suggested. However the usage of proxies results in inequities among the sectors and vehicle owners depending on the type of vehicle being operated. Also lack of coordination between cap and trade and existing regulations can lead to prohibitively high cost for certain sectors which can affect economic productivity. Until now most efforts on incorporating cap and trade in the transportation sector have focused on regulating motor fuel related emissions upstream in the refineries and vehicle manufacturers with other regulations being imposed to control fuel economy and emissions. The analysis identified lifetime carbon burden of the new vehicle as the main mechanism of trading and exchange in the cap and trade system for the transportation sector (Ellerman et al., 2006).

CARBON TAX

Carbon tax can be viewed as a tax on usage of fossil fuels. Carbon taxes are levied with the aim of reducing CO2 emissions by charging fossil fuel (coal, gasoline, aviation fuel and natural gas) combustion. The economic principle behind carbon taxes is the Pigouvian principle- which is to charge the negative externality imposed by burning of fossil fuels on the society. Thus one of the key requirements in implementing an efficient carbon tax is estimating the social cost of carbon. The current estimate of the social cost of carbon emission is $ 43/ ton of carbon. (IPCC, 2007)

Table 20 shows existing taxes on fuel around the world. The revenue from carbon taxes can be used for promoting cleaner technologies such as solar and wind power.

Finland was the first country to implement a carbon tax in 1990. Sweden implemented a carbon tax in 1991 charging \$100/ton of CO_2 and increased the rates in 1997 to \$150/ ton of CO_2. In the same year Norway also implemented a carbon tax that averaged \$21/ ton of CO_2. Airline industry was exempt from the carbon tax. Finland, Netherlands, United Kingdom and Italy are other European countries which have implemented the carbon tax (Bryner, 2007).

In the United States, the Clinton administration proposed Btu based taxes. Btu corresponds to British thermal units and is a measure of the amount of heat generated and can be viewed as an energy tax. The act levies taxes on all fossil fuel usage and exempted all environmentally friendly energy producing technologies such as wind, geothermal etc. The residents of Boulder passed a municipal carbon tax on electricity usage. The revenues generated from the study will be used to promote GHG emission reduction programs. The tax is expected to increase the electricity utility bill of homeowners by \$16/year and industries by \$46/year (Bryner, 2007).

Table 20: Taxes on Petrol and Diesel (Source: Baranzini, Goldenber, Speck, 2001)

Country	Petrol		Diesel	
	$PPP/1000 l	$PPP/ ton Co2	$PPP/1000 l	$PPP/ ton Co2
Denmark	395	164	272	95
Finland	558	232	324	113
France	590	245	370	129
Germany	495	205	313	109
Netherlands	583	242	336	117
Norway	520	216	403	140
Spain	490	203	356	124
Sweden	456	189	295	103
Switzerland	356	148	371	129
UK	630	261	645	224
USA	101	42	116	40
Japan	320	133	124	43

The following legislations have been proposed in the congress to support carbon tax initiatives (Bean and White, 2009):

(i) Save Our Climate Act of 2007 (H.R.2069), Stark: The approximate estimate of taxes for highway freight operators would be $ 0.11 per gallon of fuel consumed.

(ii) America's Energy Security Trust Fund Act of 2007 (H.R.3416), Larson: The approximate estimate of taxes for highway freight operators would be $ 0.16 per gallon of fuel consumed.

A recent study by the congressional budget office reveals that climate change regulations such as carbon tax will not have significant impact on emissions from the transportation sector. This is because moderate increase in gas prices will not have significantly vehicle owners travel patterns or freight operations (CBO, 2008).

According to the Pew Center on Global Climate Change, main difference between cap and trade and tax is that cap and trade provides certainty of emissions levels, and tax provides certainty of carbon cost. Carbon tax would generate more revenue than cap-trade system (according to Parry and Pizer). An upstream cap-trade system would have the same effect as a carbon tax on freight shippers; the upstream energy producers pass on the cost of compliance to the energy users (Bean and White, 2009). Yale Professor, William D. Nordhaus, claimed carbon taxes were more efficient than cap and trade due to the following six reasons: (i) reduced volatility and increased predictability of energy prices, (ii) less complex to implement, (iii) increased transparency and easy to understand, (iv) difficult to exploit and manipulate, (v) addresses emissions from a diverse sector (vi) easy transference of revenue to the public through dividends.

ROAD USER CHARGING

A number of countries throughout the world have been looking at tolling as a way to control emissions. The basic premise behind most tolling mechanisms is to charge the user of a roadway facility, the negative externality he imposes on the system. A driver or trucker by using the roadway system is imposing a cost on the other users. The cost can be decomposed into congestion externality – by using the system a driver contributes to the congestion, infrastructure externality – by using the system driver causes deterioration of infrastructure, and environmental externality – contribution to the pollution. An ideal tolling methodology would be to quantify in monetary value, all the negative externality imposed by the user on other users and charge that amount as toll. Traditionally tolling has been used to recover and generate revenue for construction and maintenance of roadway infrastructure.

Emissions based tolling mechanism is increasingly being viewed as a way to charge the users of the system the pollution related negative externality. It is being considered as a way of controlling emissions by making environmentally friendly vehicles – a cheaper option to travel or transport goods. With the advancement in traffic monitoring technology, interests in tolling has increased as it is now feasible to collect tolls without disrupting the traffic flow. Figure 20 shows existing and proposed high occupancy toll lanes and truck-only toll lanes in the U.S. Some of the common ways of implementing emission based pricing are discussed below.

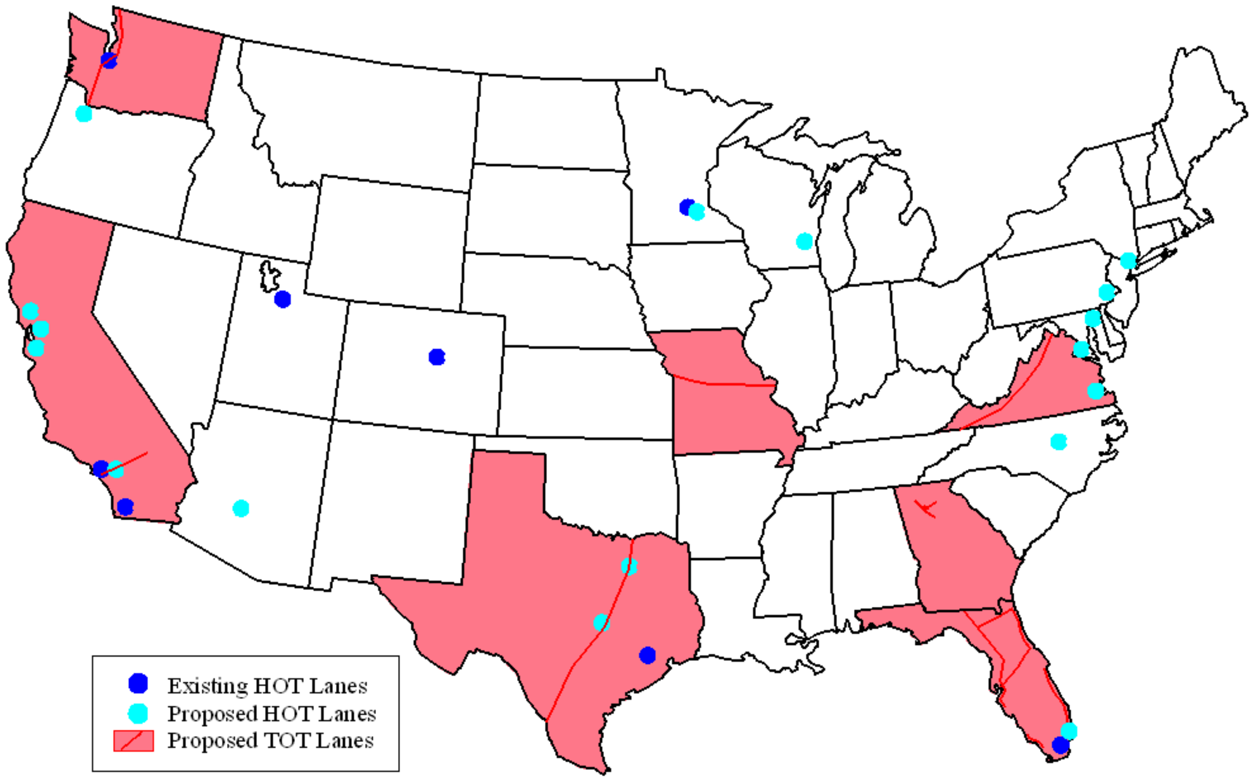

Figure 20: HOT and TOT Lanes in the U.S.

High Occupancy Toll Lanes

High Occupancy Toll lanes aim at reducing vehicle miles traveled (VMT) by encouraging people to carpool. HOT lanes are primarily aimed at reducing automobile VMTs and not heavy vehicles. To date HOT lanes have been implemented in the U.S. in California, Minnesota, Texas, Utah and Colorado. California and Texas are looking to expand their HOT corridors while further corridors are being planned in Washington, Virginia, Florida and Georgia. The popular HOT corridors in USA include the SR-91 corridor in Orange County (operating since 1995), I-394 in Minneapolis, I-15 in San Diego (operating since 1996), I-10 in Houston, I-25 in Denver and I-15 in Utah. Tables 21 and 22 lists the freeway facilities in the US where HOT lanes are in operation, development or are being considered.

Table 21 : Existing HOT lanes Project (Source: METRO, 2009)

State	City	Facility
Florida	Miami	I-95
Washington	Seattle	SR-167
Colorado	Denver	I-25
Utah	Salt Lake City	I-15
Minnesota	Minneapolis	I-394
California	San Diego	I-15
	Orange County	SR-91
Texas	Houston	US-290 NW Freeway
		I-10 Katy Freeway

Table 22: HOT Lane Projects in USA – Proposed or Under Development (Source: METRO, 2009, Poole and Orski, 2009; Vu, 2008)

State	City	Facility
Arizona	Phoenix	All freeways
California	Alameda	I-680, I-880
	Contra Costa	Various
	Los Angeles	I-10,I-110, I-210
	Oakland	I-680
	Orange County	SR 57
	Riverside	SR 91
	Santa Clara	SR 85, US 101
	Santa Cruz	SR1
	Sonoma	US 101
Florida	Fort Lauderdale	I-595
	Miami	SR 86
Maryland	Baltimore	I 95
Minnesota	Minneapolis	I 35 W, I 394
North Carolina	Raleigh	I 40
New Jersey		Lincoln Tunnel
Oregon	Portland	SR 217
Pennsylvania	Philadelphia	US 1
Texas	Austin/San Antonio	I 35
	Austin	Loop 1
	Dallas	I 30, I 636
Virginia	Hampton Roads	I -64
Washington D.C		I-95.I-393,I-495
Wisconsin	Milwaukee	I-94

Studies conducted by Cambridge Systematics on impacts of HOT lanes in the Minnesota region reveal a potential to reduce fuel consumptions by 0.9 % in 2010 to 2.5% in 2030. A similar study in the Seattle area reveals a potential reduction in fuel consumption of 0.1 % to 1.4 %. The study extrapolated the results to urban areas in the nation and estimated that HOT lanes could reduce national fuel consumption from 0.5% to 1.1 % (Cambridge Systematics Inc. and CH2MHLL, 2009).

The same study also concludes that improvements in fuel economy standards and emission controls are likely to be more effective in reducing emissions than roadway pricing. However, roadway tolling and pricing if implemented properly has significant potential to control emissions at the facility level. Emission pricing on its own may not be able to achieve the reductions in emission desired in many climate change plans (Cambridge Systematics Inc. and CH2MHLL, 2009).

Truck Only Toll Lanes

Several states in the United States are looking at implementing truck only toll (TOT) lanes with the objective of congestion and pollution management. Even thought there no existing TOT lanes in the United States or Europe, around seven states are planning to develop TOT corridors as summarized in Table 23 (Chu, 2007). Each state used its own criteria in selecting potential TOT lane corridors. California selected highly congested corridors (peak hour volume > 1800 vphpl and off peak hour volume > 1200 vphpl) with truck volumes greater than 30 % of total traffic volumes (CALTRANS, 2006). Florida selected truck only lanes by evaluating corridors based on a weighted metric consisting of truck volume, level of service, high truck related crashes, high truck percentages and proximity to ports/truck terminals and railroads. Georgia only considered corridors with combined truck volume > 30000 per day and level of service E or below with proximity to truck activity centers and existence of freight bottlenecks to be truck only toll lanes (Fowler, 2008). Both the ARTBA and Transportation Construction Coalition are in favor of TOT Lanes (Poole, 2003). Almost all the studies recommended usage of dynamic toll rates which vary depending on time of day and truck percentage levels. There has been very little work in identifying emission benefits of TOT Lanes. Chu and Meyer (2009) estimate using MOBILE 6.2

that voluntary and mandatory usage of TOT lanes would reduce total CO2 emissions on freeway sections by 62% and 60% respectively.

Table 23: Proposed TOT lanes in the United States (Source: Chu, 2007)

State	Proposed Corridors
California	SR-60, I-710 and I-15 Around 142 miles of 2 lane TOTL
Florida	Six Major Corridors I-95 from Miami to Titusville I-95 from Daytona to Jacksonville I-75 from Naples to Fort Meyers I-4 from Tampa to Daytona I-75 from Venice to Florida/Georgia Border I-10 from Lake City to Jacksonville
Georgia	Study conducted by Meyers, 2006 recommended TOT lanes on I-75, I-85 and I-285 in metro Atalanta region 15 mile TOT lanes also considered in I-75 in Cobb and Cherokee county
Missouri	2 lane TOT lanes considered in I-75
Texas	Trans Texas Corridor 600 mile long with 2 TOT lanes
Virginia	TOT lanes in 325 miles of I 81 through the Shenandoah Valley
Washington	Washington Commerce Corridor Considering 280 miles of 2 lane TOT lanes

Emission Related Truck Tolling in Europe

Europe has three main types of emission related tolling strategies: (i) distance based truck tolling which vary depending on truck emission classes (ii) low emission zones where trucks have to pay a daily rate for entering based on emission class (iii) eurovignette tolls . The main features of the emission based toll systems in various countries are described below.

Germany. Germany has implemented LKW-MAUT – a tolling system for trucks based on the number of axles and emission category. The toll rates in Euros for heavy good vehicles are shown below in Table 24. Three emission categories were derived from the Euro emission standards. The toll rates do not vary depending on the weight of the vehicle. The toll can be paid automatically using an on-board GPS unit, or through a booking on the internet or at a payment terminal.

Table 24: Germany HGV Toll Rates (Euros/Km) (Source: Federal Ministry of Transport, 2009)

Emission Category	<= 3 axles	>= 4 axles
Category A (Euro 5)	0.09	0.10
Category B (Euro 3 and 4)	0.11	0.12
Category C(other vehicles)	0.13	0.14

The truck tolls in Germany generated annual revenue of 2.9 billion Euros. Between 2005 and 2008, the percentage of trucks with the best emission exhaust technology (Euro 5) increased from less than 1% to 37 % while the percentage of trucks with highest emissions (Euro 2) decreased by one-third in the same period (Sorensen, 2008). Truck tolling did not cause any noticeable increase in freight tariffs or consumer prices and did not induce any significant modal shifts to rail or waterways or toll free routes. Loads were distributed more efficiently with decrease in the amount of backhauling by around 15% (Kosak, 2006).

Switzerland. Switzerland has implemented a distance based truck tolls, the LSVA, for all trucks weighing over 3.5 tons. The toll rates per kilometer vary depending on vehicle class which are adjusted based on tailpipe emissions. The LSVA also has a flat fee options for certain cross country routes. The distances are calculated based on on-board GPS units which are free for truckers. There are three fee categories: (i) Free Category 1: 3.07 centimes per ton-km corresponding to Euro 0 ,I and II, (ii) Fee Category 2: 2.66 centimes per ton-km corresponding to Euro III and (iii) Fee Category 3: 2.26 centimes per ton-km corresponding to Euro IV-VI. The above specified rates are multiplied by the distance travelled and the maximum permissible weight of the vehicle to determine the actual toll rates (Krebs, 2004).

The tolling system lead to decease in VMT of HGVs of up to 6.4% between 2001 and 2005 but increased goods transported measured in tone-kms by 16.4 %. Thus goods transportation lead to more efficient form of goods transport with little impact on consumer prices and no significant change in the labor market for the heavy vehicle freight industry (Krebs, 2004).

Austria. Austria currently has a distance based tolling system, Table 25, for vehicles with weight greater than 3.5 tons which depends on the number of axles of the vehicle and trailer. Two axle vehicles have to pay a toll of 0.158 Euros/km, three axle vehicles have to pay a toll of 0.2212 Euros/Km whereas four axle vehicles have to pay a toll of 0.3318/km. The toll value change annually based on the consumer price index. A new tolling scheme is being introduced starting in 2010 motivated by environmental issues which classified tariffs based on euro emission standards. All vehicles with weight > 3.5 tons will be required to have a small electronic device – GO box which will track the movement of the vehicle. The GO box communicates to around 400 toll stations in Austria and the toll charges can be paid electronically 9 (Fiala, 2009).

Table 25: Toll rates in Austria – Euros/Km (Source: Fiala, 2009)

Vehicle	**2 axle**	**3 axle**	**4 or more**
A (EURO VI)	**0.1420**	**0.1988**	**0.2988**
B (EURO IV-V)	**0.1520**	**0.2128**	**0.3192**
C	**0.1740**	**0.2436**	**0.3654**
Current	**0.1580**	**0.2212**	**0.3318**

Czech Republic. The Czech Republic is introduced distance based tolls classified by emission class on motorways for vehicles over 12 tons in 2007 and vehicles over 3.5 tons in 2008. There are plans to extend to current tolling system on to first second and third class roadways also. This is to prevent trucks from excessively using the minor roads to avoid tolls. The toll charges for the year 2008 are shown in Table 26 (MYTOCZ, 2009).

Table 26: Toll rates/km in Czech Kroner

Class	2 axle	3 axle	4 or more axle
Euro 0-II	1.10	1.80	2.60
Euro III-IV	0.8	1.40	2.00

London Low Emission Zone. London low emission zone charging scheme aims to discourage and reduce the usage of highly polluting vehicles in central London. The LEZ has been operating from February 4th 2008. Heavier lorries with operating weight greater than 12 tons have to pay a daily charge of 200 pounds if they don't meet Euro III PM emission standards starting February 4th 2008 and Euro IV PM emission standards by January 3rd 2012. Lighter lorries with operating weight between 3.5 and 12 tons have to pay a daily charge of 100 pounds if they don't meet Euro III PM emission standards starting July 7th 2008 and Euro IV PM emission standards by January 3rd 2012 (TFL, 2009).

London also has a congestion charge of 8 pounds per day for all vehicles entering the congestion charge zone in central London between 7 AM and 6 PM on weekdays. Certain classes of vehicles including buses, minibuses, alternate fuel vehicles etc. are exempt from the charge. In the first year of operation, the traffic entering the congestion zone reduced by 18% during charging hours. Significant environmental benefits were observed. NOx and PM emissions reduced by 13% and 15 % in 2005 compared to 2002 (Wedlock, 2007).

Milan Low Emission Zones. Milan have introduced a low emission zone, Table 27, on a on a one year trial basis in 2008-2009. Trucks can be charged up to 10 Euros/day based on emission class, euro type and presence of approved filters. Apart from a daily charge Milan also has the option of buying a multiple access card.

Table 27: Low Emission Zone Rates for Milan (Source: Green Car Congress, 2008)

Class	Vehicle	Daily	Multiple first 50	Multiple Successive 50	Annual Resident
I	Alt Fuel	Free	Free	Free	Free
II	Gasoline cars and trucks, Euro 3 and later; Diesel cars and trucks, Euro 4 and later	Free	Free	Free	Free
III	Gasoline cars and trucks, Euro 1, 2	2	50	60	50
IV	Gasoline cars and trucks, Euro 0; Diesel cars, Euro 1, 2, 3; Diesel trucks, Euro 3; Diesel Bus Euro 4, 5	5	125	150	125
V	Diesel cars, Euro 0; Diesel trucks, Euro 0, 1, 2; Diesel Bus, Euro 0, 1, 2, 3	10	250	300	250

Other Low Emission Zone in Europe. Several other cities in Europe have already introduced low emission zones or are in the process of introducing them. Figure 21 shows all the cities in Europe which already have implemented LEZs or are in the process of implementing them, and Table 28 lists the cities in Europe where LEZs have been implemented permanently or in a trial period.

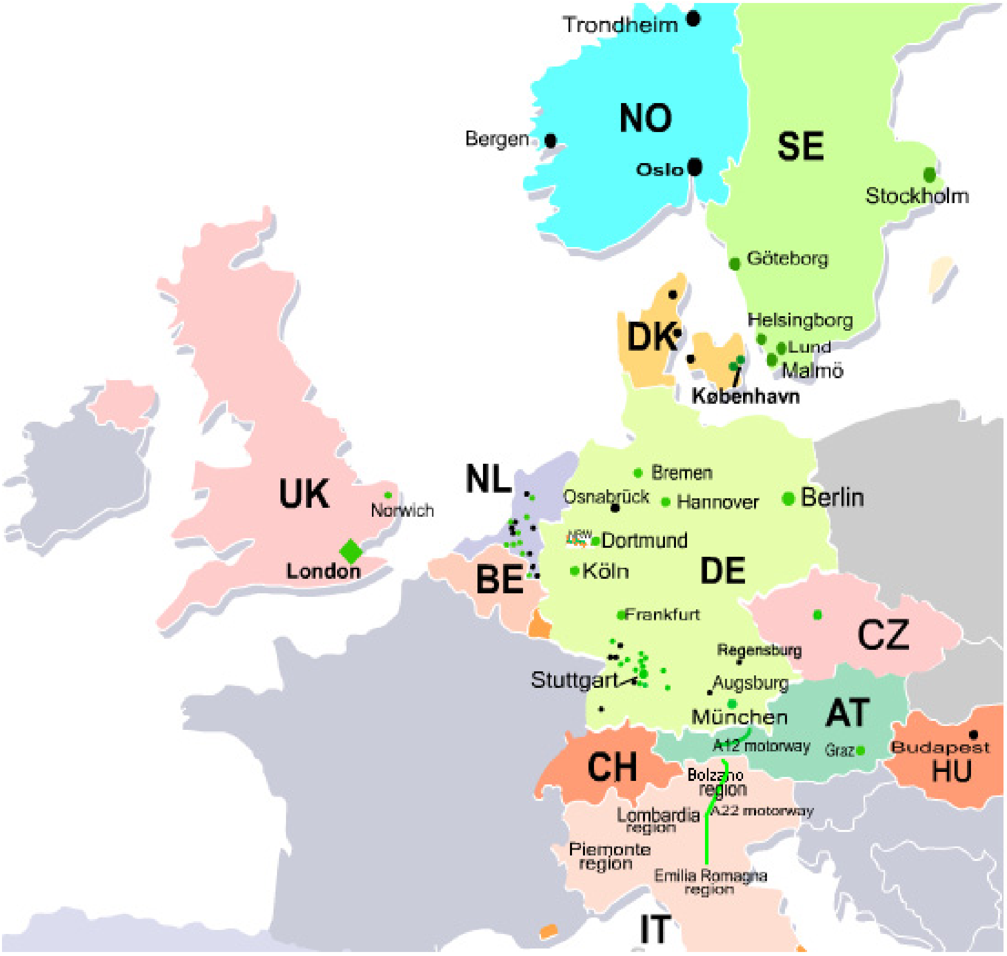

Figure 21: Low Emission Zones in Europe (Source: European LEZ, 2009)

Table 28 : Existing LEZs in Europe for Trucks (Source: European LEZ, 2009)

Country	City/Area	Start Date	End Date	Vehicles	Diesel
Austria	A12 motorway	01/01/2007	01/11/2008	Trailer and tractor trailers > 7.5 T	Euro 2
Austria	A12	01/01/2007		Lorries at night	Euro 4
Italy	A22	01/01/2007		Lorries	Euro 2
Italy	Emilia-Romagna, Piemonte	01/01/2007		All vehicles	Euro 2
Italy	Lombardia	15/10/2008	01/01/2010	All	Euro 2
Italy	Bolzano	01/11/2008	31/03/2009	All	Euro 2
Sweden	Gothenburg, Lund, Malmo, Stockholm	01/01/2007	01/01/2010	Vehicles over 3.5 T	Atleast Euro 2
Netherlands	Eindhoven, Utrecht, Hertogenbosch, Tilburg, Rotterdam, Maastricht, Breda Hague	1/07/2007	01/01/2010	Vehicles over 3.5T	Euro 2 + filter
Netherlands	Amsterdam	1/10/2008	01/01/2010	Vehicles over 3.5T	Euro 2 + filter
Netherlands	Leidschendam, Zaanstad	1/09/2008	01/01/2010	Vehicles over 3.5T	Euro 2 + filter
Czech	Prague	01/01/2008		Vehicles over 3.5 T	
Germany	Berlin, Hannover, Koln	01/01/2008	01/01/2010	All	Euro 2 PM
Germany	Dortmund	12/01/2008		All	Euro 3 PM
Germany	Illsfeld, Leonberg, Ludwigsburg, Mannheim,Reutlingen, Schwabisch, Stuttgart, Tubingen	01/03/2008	1/01/2010	All	Euro 2
Germany	Pleidelsheim	01/07/2008	01/01/2010	All	Euro 2
Germany	Bochum, Botrop, Duisburg,Essen, Frankfurt, Gelsenkirchen,	01/10/2008		All	Euro 2 PM

	Muhlheim, Munich, Oberhausen, Recklinhausen					
Germany	Bremen, Hannover, Heilbronn,Herrenburg, Muhlacker,Pforzheim, Ulm,Dussefldorf, Wuppertal, Auugsburg, Neu-Ul	01/01/2009	01/01/2010 01/01/2012	All	Euro PM	2
Denmark	Fredericksburg, Copenhagen	01/09/2008	30/06/2010	Vehicles over 3.5T	Euro PM	3
Denmark	Aalborg	1/02/2009	30/06/2010	Vehicles over 3.5T	Euro PM	3

EuroVignette Directive based Tolls. The Eurovignette directive encourages EU member states to set tolls to internalize the environmental and pollution costs of vehicles greater than 3.5 tons. The member countries are given freedom to determine the amount of tolls and the enforcement. The directive provides certain rules which all member countries have to follow.

Tolls have to be distance based and must vary depending on vehicle class. A toll and a user charge cannot be levied at the same time. Member countries are encouraged to cooperate so that there is no hindrance with respect to toll collection at national boundaries and there is free flow of traffic. Tolls and user charges can be levied on motorways or on multi-lane roadway sections similar to motorways. The maximum toll levied will depend on the infrastructure construction and maintenance cost and the level of pollution in the region. The toll charges can vary depending on time of day. The threshold for annual user charges is shown in Table 29.

Table 29: Threshold for Annual User Charges (Source: ECT, 2009)

Class	Max 3 axle	Min 4 axle
EURO 0	1332	2233
EURO I	1158	1933
EURO II	1008	1681
EURO III	876	1461
EURO IV and less polluting	797	1329

Belgium, Netherlands, Denmark, Sweden and Luxembourg have a common Eurovignette tolling system for heavy goods vehicles above 12 tons as shown in the Table 30.

Table 30: Eurovignette rates in Euros (Source: ECT, 2009)

Num Axle	Max 3	Min 4	Max 3	Min 4	Max 3	Min 4
Euronorm	0	0	1	1	2	2
Day	8	8	8	8	8	8
Week	26	41	23	37	20	33
Month	96	155	85	140	75	125
Year	960	1550	850	1400	750	1250

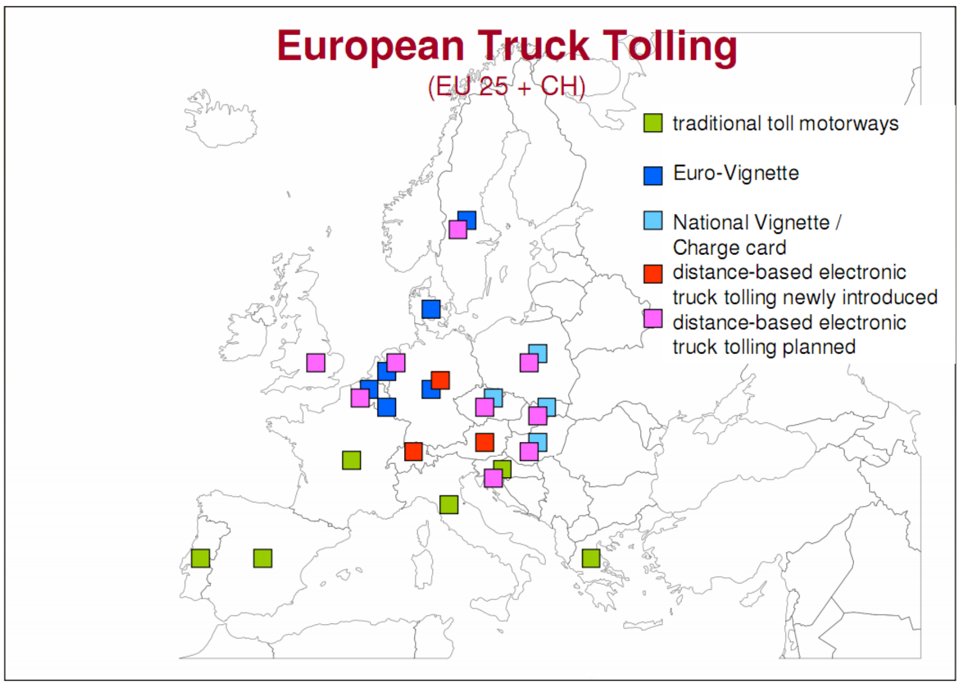

Figure 22: European Truck Tolls (Source: Kosak, 2006)

Apart from the countries discussed in this section several other countries in Europe are planning to levy tolls based on vehicle emission classes. Table 31 discusses some of their existing and planned tolling strategies on certain motorways.

Table 31: Other European, Existing or Planned Emissions based Tolls

Countries	Existing		Planned	
	Vehicle	*Toll Classification*	*Vehicle*	*Toll Classification*
France	All	Axles	> 12 t	Axle plus emission class
Sweden	> 12 t	EURO 0 to EURO IV, Axle	Distance based for > 3.5 t	Euro Class, Environmental Characteristics, Time of Day
Poland	> 3.5 t	Weight, Axle, Emissions	-	-
Romania	All	Axles, weight, emissions	-	-
Slovakia	All	Weight	> 3.5 t	Weight, Axle, Emissions
Slovenia	All	Vehicle height, axle	All	Emission characteristics

CONCLUSIONS

This section provided an overview of some of the existing and future transportation policies being considered or implemented in US and Europe. Some of the future energy policies reviewed include: cap and trade, carbon tax and emission based tolling. Despite numerous legislations cap and trade and carbon taxes have not been implemented in the transportation sector. Of the three emissions based tolling systems are the most widespread currently. In the United States, High-Occupancy Toll (HOT) lanes are being implemented in multiple states. Truck only toll lanes are also being considered in several corridors. Europe has three main types of emission related tolling strategies: (i) distance based truck tolling which vary depending on truck emission classes (ii) low emission zones where trucks have to pay a daily rate for entering based on emission class (iii) eurovignette tolls.

CONCLUSIONS

Vehicle exhaust has been shown to be directly and indirectly harmful to human and environmental health. Diesel exhaust in particular has been linked to health problems. While not a significant contributor to CO and HC emissions, diesel exhaust contains relatively large amounts of PM and NOx. PM emissions can reach the lungs and have adverse affects on the respiratory system. NOx can form smog, acid rain and PM after reacting with other chemicals in the atmosphere. U.S. heavy-duty vehicle emissions standards for PM and NOx are becoming progressively strict, reducing both in new vehicles by about 90% by 2010. Heavy-duty vehicles also contribute significantly to GHG emissions, which are believed to contribute to climate change. The EPA has recently recognized select GHGs as public health threats, and federal regulation can be expected in the near future.

The majority of heavy-duty vehicles employ a conventional diesel engine that is either turbocharged or naturally aspirated. Turbocharged engines allow for downsizing the engine while maintaining the same power. In addition, turbocharged engines recover exhaust energy that would have been wasted with a naturally aspirated engine. Both of these characteristics contribute to increased fuel economy of turbocharged engines relative to naturally aspirated engines, and as a result are more common for use in HDV. They also are effective in reducing NOx and PM emissions by 30%.

Passenger vehicle electric hybrids are of the series variety, and the electric motor directly powers the wheels. Heavy duty vehicle electric hybrids are of the parallel variety, and both the diesel engine and electric motor power the wheels. Electric hybrid engines have not yet been used in combination trucks, but have been used in many bus and package delivery truck fleets (e.g. UPS and FedEx). Despite the increased fuel efficiency and air quality benefit, electric hybrid engines are not a popular choice for heavy-duty vehicles because they are more expensive than conventional engines. Lead-acid batteries are no longer used in hybrid vehicles and were replaced with Nickel Metal Hydride (NiMH) batteries that have higher energy density and are safer (though more expensive). It is expected that Lithium-ION batteries will replace NiMH batteries in the future due to greater longevity and lower cost.

Hydraulic hybrids, vehicles powered by a diesel motor and hydraulically stored energy, are an inexpensive alternative to electric hybrids for large vehicles. Though still in the development stage, these vehicles improve fuel economy 50-70% and reduce GHG, HC, and PM emissions by roughly 50%. Costing only 15% more than a comparable conventional vehicle, it is estimated that the payback period is between 1 and 3 years.

The majority of fuel used to power heavy-duty vehicles is diesel, while gasoline and liquefied petroleum gas also provide fuel for a significant portion (10% and 0.3%, respectively). Gasoline vehicles are responsible for the majority of CO and HC emissions, while diesel vehicles are known for emitting large amounts of NOx and PM. Diesel is more common for use in heavy-duty vehicles because the engines are more powerful and efficient. Ultra-low sulfur diesel (ULSD) is now required in the U.S., which can reduce PM emissions by 90% when used with PM exhaust filters. Emulsified diesel, a mixture of petroleum diesel and water, is effective in reducing PM and NOx for only 20 cents more per gallon, making it an attractive option for school bus fleets trying to reduce their emissions. One drawback of emulsified diesel is that if it sits for long periods of time, it can separate and damage the vehicle.

Biodiesel can reduce emissions of GHG (lifecycle, not tailpipe), PM, HC and CO. Most fleets prefer not to use 100% biodiesel because it would require altering the vehicle to avoid maintenance issues. B20, a mixture of 20% biodiesel and 80% petroleum diesel, still reduces emissions without the need to alter vehicles. Ethanol is another biofuel that is commonly used in place of, or blended with, gasoline. The way that ethanol is produced has a large impact on its ability to reduce emissions. Ethanol made from corn offers the least emissions benefits, while sugarcane and cellulosic ethanol offer 2-3 times the benefit of corn ethanol. However, cellulosic ethanol is still in developmental stages and is not being commercially produced. It should be noted that biofuels only offer GHG emissions benefits if no agricultural land conversion is required to produce the fuel.

Relative to diesel fuel, natural gas reduces emissions of PM, NOx, and HC by 50%, and CO2 by 25%. However, it is necessary to invest in a private fueling storage and distribution system. It is a good alternative fuel for fleets that return to their point of origin on a daily basis (e.g. intracity buses and delivery trucks). Natural gas vehicles can cost twice as much as their diesel equivalent, but there are an increasing number of subsidies available to help offset this cost. Fischer-Tropsch (or Gas-to-Liquid diesel) is diesel fuel typically derived from natural gas. California has been mixing Fischer-Tropsch diesel with petroleum diesel to reduce PM emissions. Table X shows the costs and savings (both capital costs and emissions) associated with heavy-duty vehicle alternative fuel and engine choices.

Table 32: Costs and Savings of Alternative Engines and Fuels

Engine/Fuel Type	Target Market	PM	NOx	CO	HC	CO2	FE	Cost
Electric Hybrid	Buses, Short-haul	H				M	M	MH
Hydraulic Hybrid	Buses, Short-haul	H			M	M	M	L
ULSDiesel	All diesel vehicles	L						L
Emulsified Diesel	Buses, Non-attainment areas	M	L				L	L
Biodiesel (B20)	All diesel vehicles	L	L	L	L	H[1]		L
Ethanol (E85)	All gasoline vehicles					H[2]	L	L
Liquefied Petroleum Gas	All		L	L		L	L	
Natural Gas	All	M	M		M	L		H
Gas-to-Liquid Diesel	All diesel vehicles	M	L	M	L	L[3]		L

L	Low Cost (0-30%)
M	Medium Cost (31-60%)
H	High Cost (60+ %)
L	Low Savings (0-30%)
M	Medium Savings (31-60%)
H	High Savings (60+ %)

Notes: 1) Net GHGs could actually increase if land conversion is necessary; negligible GHG savings when considering only tailpipe emissions. 2) CO2 savings varies greatly by feed stock used to produce fuel; net GHGs could actually increase if land conversion is necessary. 3) May increase or decrease GHGs depending on production method used.

To meet EPA's 2007 and 2010 emissions standards for PM, most, if not all, trucks will utilize diesel particulate filters. When used with ultra-low sulfur diesel, PM emissions can be reduced by 90%. There are a few options to reduce NOx emissions. Most manufacturers will be using selective catalytic reduction (SCR) to meet 2010 NOx standards. Navistar is the exception, and they plan to rely on exhaust gas recirculation. NOx adsorbers are a newer technology that reduces NOx emissions by 90%, but will probably not be fully developed early enough for the

2010 model year. In addition to these technologies, methods of optimizing engine and exhaust temperature can decrease NOx and PM emissions caused by cold starts. Improved fuel injection can also further improve NOx emissions.

Truck idling wastes approximately 1 gallon of fuel per hour and can cost approximately $2000 per truck depending on fuel prices. In addition to the fuel waste, excess emissions are being released into the atmosphere. Auxiliary power units, automated engine idle systems, and direct-fire heaters are all on-board devices aimed at eliminating the need for a truck to idle during extended rest periods. These can reduce fuel use by 3-10% and cost between 2 and 8 thousand dollars. Auxiliary power units cost more, but also save more fuel and have a shorter payback time. Electrified truck stops are a method of reducing engine idling without an on-board device. These stops either provide climate control for the cabin or provide the truck with electricity from which to run its own climate control system and other accessories. For this to be cost effective, it is necessary for the per-gallon price of fuel to be more than the hourly rate of the stop. Driver training and idle restriction policies can be an effective method of reducing fuel consumption and emissions from idling at pick up and drop off locations and in congested traffic.

Aerodynamic drag has decreased by 40% in the last 30 years, and the add-on devices available today can offer further reduction of 25%. Unfortunately, many of these devices infringe on the operational performance of the vehicle, making them undesirable. Low-resistance tires and super single tires are designed to reduce the rolling resistance between vehicle tires and the road surface, and can improve fuel economy by 3%. Low rolling resistance tires can be used on any truck, but require high pressure and frequent monitoring. Super singles are lower maintenance, but can only be used on newer model trucks.

The operating factors that affect heavy-vehicle emissions can be classified into roadway characteristics, traffic characteristics, driver characteristics and vehicle characteristics. As many of these factors act in tandem, it is very difficult to isolate the individual effect of each operating factors. In general, emissions increase with increase in grades, increase in congestion, aggressive driving, powerful acceleration/deceleration and stop and go traffic. These factors are important in developing and evaluating vehicle emissions models. These emission estimation models can be classified as either static emission factor based models or dynamic instantaneous emission models. Static emission factor based models calculate emission based on average traffic conditions such as average speed. There are fewer data requirements for these models, but they cannot be used to evaluate the impact of various traffic management strategies. Dynamic emission models can capture the impact of acceleration and deceleration and can be used to evaluate the impact of various traffic management strategies. However they have high data requirements such as detailed vehicle trajectory data.

Various levels of the U.S. and European heavy vehicle emissions standards are used in much of the world and are based on emissions per unit of energy expended. Japan has its own standards based on emissions per unit of distance traveled. Japan has also implemented the world's first heavy-duty vehicle fuel economy standards in 2006. In the U.S., emissions standards for PM and NOx are becoming more stringent with EPA's 2007 and 2010 heavy-duty vehicle standards.

The test cycles used to enforce these emissions standards are somewhat inadequate because engines can be designed to pass the test, yet frequently exceed the standards in real driving conditions (and is referred to as cycle beating). As a result, vehicle emissions may not be decreasing at the rate implied by the standards. To prevent test cycle beating, supplemental test cycles that are less predictable, and could potentially test a larger portion of an engine's operating range, are now being used.

It is only recently that greenhouse gases have been regulated. In 1997, several countries agreed to adhere to the maximum GHG emissions level that applied to them according to the Kyoto Protocol, and since then the United Kingdom and the European Union have implemented GHG cap and trade schemes to meet these targets. The U.S. has yet to set national GHG emissions targets, but several states have done so. Groups of states are planning future regional emissions trading schemes. At the federal level, several plans to control greenhouse gas emissions have been proposed that include targets, cap-and-trade, and carbon taxing to various degrees.

Future transportation policies related to vehicle emissions include cap and trade, carbon taxing, and road user charging. Despite numerous legislations, cap and trade and carbon taxes have not been implemented in the transportation sector, and road user charging is currently the most widespread of the three policy types. In the United States, high-occupancy toll (HOT) lanes are being implemented in multiple states, and truck only toll (TOT) lanes are also being considered in several corridors. Europe has three main types of emission related tolling strategies: (i) distance based truck tolling which vary depending on truck emission classes (ii) low emission zones where trucks have to pay a daily rate for entering based on emission class (iii) eurovignette tolls. It has been shown that HOT lanes are effective in reducing fuel consumption and GHG emissions at a corridor level. Though very few studies to date have investigated impacts for TOT lanes, it is reasonable to expect similar results. However, it is expected that much greater savings can be achieved with vehicle-centered strategies (e.g. FE standards, retrofits) than operational strategies. In addition, tolling structure can impact travel choices in such a way that may actually increase overall emissions. Distance-based charges may encourage fewer trips with heavier vehicles, while weight-based charges may encourage more trips with lighter vehicles.

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