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**ANTI-POLLUTION TECHNOLOGIES  
FOR VEHICLES:  
CAN NON-ATTAINMENT AREAS  
REACH ATTAINMENT VIA A  
TECHNOLOGICAL “FIX?”**

**Final Report**

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16. Abstract Over the past decade significant reductions in new vehicle emissions have been attained as a result of improvements in basic automotive technology. These improvements are a result of improvements in basic engine and exhaust technology; they are not the result of the incorporation of expensive and exotic new equipment. Today, many (but of course not all) gasoline powered vehicles are capable of meeting the California LEV emissions standards. Further reductions in new vehicle emissions can be attained through further refinements of the basic technology of the gasoline engine (and exhaust system.)  Even under the most pessimistic assumptions, passenger vehicle emissions of three (hydrocarbon, nitrogen oxide, and particulate matter) out of the four major pollutants are likely to fall considerably over the next twenty-five years. Emissions of carbon monoxide are forecast to rise. While the presence of carbon monoxide is a health hazard it has not been of principal concern in the Phoenix area. This is because our summer ozone problem is caused by hydrocarbon and nitrogen oxide emissions and our winter "brown cloud" problem is attributed to particulate matter. Thus, Phoenix's two major air pollution problems are likely to be mitigated substantially by the Federal Tier 2 standards. However, the increases in carbon monoxide emissions may lead to new problems for the Phoenix area.					
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## METRIC (SI\*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>					<b>LENGTH</b>				
in	inches	2.54	centimeters	cm	mm	millimeters	0.039	inches	in
ft	feet	0.3048	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	yd	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
<b>AREA</b>					<b>AREA</b>				
in <sup>2</sup>	square inches	6.452	centimeters squared	cm <sup>2</sup>	mm <sup>2</sup>	millimeters squared	0.0016	square inches	in <sup>2</sup>
ft <sup>2</sup>	square feet	0.0929	meters squared	m <sup>2</sup>	m <sup>2</sup>	meters squared	10.764	square feet	ft <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	meters squared	m <sup>2</sup>	yd <sup>2</sup>	kilometers squared	0.39	square miles	mi <sup>2</sup>
mi <sup>2</sup>	square miles	2.59	kilometers squared	km <sup>2</sup>	ha	hectares (10,000 m <sup>2</sup> )	2.53	acres	ac
ac	acres	0.396	hectares	ha					
<b>MASS (weight)</b>					<b>MASS (weight)</b>				
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams (1000 kg)	1.103	short tons	T
<b>VOLUME</b>					<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft <sup>3</sup>	cubic feet	0.0328	meters cubed	m <sup>3</sup>	m <sup>3</sup>	meters cubed	35.315	cubic feet	ft <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	meters cubed	m <sup>3</sup>	m <sup>3</sup>	meters cubed	1.308	cubic yards	yd <sup>3</sup>
Note: Volumes greater than 1000 L shall be shown in m <sup>3</sup> .									
<b>TEMPERATURE (exact)</b>					<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements									

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# I. Introduction

## 1) History

Policy makers have struggled with the problem of environmentally hazardous vehicle emissions for hundreds of years. At the beginning of the Twentieth Century it was estimated that each day horses deposited 2.5 million pounds of manure and 60,000 gallons of urine on the streets of New York City. [1] This situation was typical of large cities worldwide at that time and its negative impacts on the urban environment are obvious. Thus, in its early days the automobile was looked at as a *solution* to a significant environmental problem. Fifty years later the automobile's emissions problem became evident. By some estimates, smog in Los Angeles on some days in 1955 was worse than it is in Mexico City Today. [2] By the late 1950s it had become clear that automobile emissions were a significant contributor to air quality problems nation wide.

Congress reacted to the problem of automobile emissions with the Clean Air Act Amendments of 1970 which imposed performance based, technology-forcing emission standards. The standards required emissions reductions that the technology of the early 1970s could not attain. Thus, manufactures were forced to develop new technologies in order to meet the new emissions standards. The law only required compliance with the new emissions standards. The auto manufactures were not required to use any specific technologies; they were free to develop whatever technologies they felt could attain the new emissions standards in the most cost-effective manner.

The 1970 Clean Air Act Amendments required a more than 90% reduction in Hydrocarbon (HC) and Carbon Monoxide (CO) over uncontrolled levels by the 1975 model year, and an approximately 90% reduction in Nitrogen Oxides (NO<sub>x</sub>, NO, NO<sub>2</sub>) by the 1976 model year. The original deadlines were postponed several times and the nitrogen oxide requirements were modified. In 1977, Congress set more stringent emissions standards to be met by 1983 model year autos. In 1990, Congress tightened the standards further beginning with the 1994 model year. These 1994 standards are referred to as the Tier 1 standards. Currently, the Environmental Protection Agency (EPA) is moving ahead with its Tier 2 standards which would require significant emission reductions starting in the 2004 model year.<sup>1</sup> [3] Significantly, the Tier 2 standards will apply uniformly to cars and light trucks (i.e., pick-ups and sport utility vehicles). Prior standards allowed higher emissions levels for light trucks since these vehicles were thought to be used primarily in rural areas. This differential treatment is difficult to justify given the current boom in sport utility vehicle sales in urban regions.

Table 1.1 summarizes the achieved emissions standards through 1994 and the EPA's target for 2004 along with the EPA's estimated 1960 pre-control average. [2], [4]

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<sup>1</sup>The 1990 Clean Air Act Amendments allow the EPA to implement these standards through its own rule making procedures.

**Table I-1, Auto Emission Standards, Grams of Emissions Produced per Mile Traveled<sup>2</sup>**

<b>Year</b>	<b>Hydrocarbons</b>	<b>Carbon Monoxide</b>	<b>Nitrogen Oxide</b>
1960	10.600	84.000	4.100
1970	4.100	34.000	5.000
1975	1.500	15.000	3.100
1980	0.410	7.000	2.000
1981	0.410	3.400	1.000
1983	0.410	3.400	1.000
1994 (Tier 1)	0.310	4.200	0.600
2004 (Tier 2)	0.125	4.200	0.200

In addition to the requirements of the Clean Air Act listed above, in 1998 the National Low Emission Vehicle (NLEV) program was established. The NLEV program is an agreement between the EPA, 23 auto manufactures, and most of the states that establishes voluntary emission standards more stringent than the federal Tier 1 standards. The NLEV standards apply in the Northeast only for the 1999 and 2000 model year. Starting with model year 2001 the NLEV standards will apply nation wide. The main incentive for manufacturers to participate in the NLEV program is it allows them to produce a single fleet of vehicles for sale nationwide rather than having to produce a separate fleet to meet stricter requirements that only a few states have implemented.

The NLEV program is voluntary, but it arose out of attempts by numerous states and the EPA to mandate stricter standards in the Northeast and as a result of litigation challenging their authority to do so. [5]

The state of California enforces its own emissions standards on auto manufactures known as the California Low Emission Vehicle Regulations (California LEV).<sup>3</sup> The California standards are more stringent than the Tier 1, and NLEV standards discussed above. The California LEV standards were originally adopted in a 1990-1991 rulemaking of the California Air Resources Board (CARB), and generally became applicable in the 1994 model year. The California LEV program also includes requirements for the introduction of zero-emission vehicles (ZEVs). In November of 1999 the CARB adopted the California “LEV II” regulations, which generally become applicable with the 2004 model year. The LEV II rulemaking also included the adoption of Compliance Assurance Program “CAP 2000” amendments which establish new motor vehicle certification and in-use test requirements — developed jointly with the U.S. Environmental Protection Agency — applicable to 2001 and subsequent model motor vehicles. [6]

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<sup>2</sup> 1970-1994 Standards are for cars only. The 2004 standard applies to cars and light trucks. The actual regulations are more complex than the table implies in that they allow trade-offs between the various types of pollutants. See section 86.1911-04 of the Code of Federal Regulations for more detail. The tier 1 and tier 2 standards must be attainable through the full life of the vehicle, specifically new vehicles must be able to attain the standards after 100,000 operating miles. More stringent standards must be met at 50,000 operating miles. The numbers for 1960 represent the EPA’s estimated 1960 pre control average.

<sup>3</sup> Section 209(b) of the federal Clean Air Act allows states to establish their own emissions standards as long as they are more stringent than the federal standards.



## 2) Emission types and causes

The four types of vehicle emissions that are of the most concern to policy makers are: carbon monoxide (CO), hydro-carbons (HC), nitrogen oxides (NO<sub>x</sub>), and Particulate Matter (PM). Other harmful emissions such as lead and sulfur dioxide are of minimal concern because they occur at very low levels. All of these emissions are caused by inefficiencies in the combustion process. An engine operating at 100% efficiency (i.e., 100% of the fuel injected into the engine is completely oxidized) would emit only carbon dioxide.

Carbon monoxide (CO) is an invisible gas that reduces the amount of oxygen carried by the blood. This effect can be fatal in enclosed areas. carbon monoxide emissions into the ambient atmosphere has been implicated in negative health effects such as the aggravation of angina and asthma. [7] The principal cause of carbon monoxide emissions from vehicles is incomplete combustion. [8] That is, the fuel injected into the vehicle's engine is not completely oxidized, leaving a residue of gases to be emitted through the exhaust system.

Hydro-carbons (HC) are organic compounds that are not necessarily harmful on their own. However, when hydrocarbon interacts with sunlight ozone is formed. Atmospheric ozone has been implicated in lung damage and decreased lung function. [7] Ozone formation in the lower atmosphere is dependent on the presence of hydrocarbons and on sunlight. Thus, ozone is more of a concern during the summer months. hydrocarbon is also referred to as volatile organic compounds (VOC) and non-methane organic gas (NMOG). Like carbon monoxide, the principal cause of hydrocarbon emissions is incomplete combustion. hydrocarbon is also formed when vehicle lubricants are inadvertently combusted, i.e., when a vehicle burns oil. [8]

Nitrogen oxides (NO<sub>x</sub>) are brown gases that have been linked to lung irritation and increased rates of lung diseases. [7] nitrogen oxide has also been linked to lower resistance to respiratory infections such as influenza. [4] The presence of nitrogen oxide also leads to ozone formation. [4] nitrogen oxide is also the principal cause of acid rain, which is not a concern in Arizona because of low rainfall and high soil and water alkalinity. Atmospheric nitrogen oxide has also been implicated in harmful algae blooms along the East and Gulf Coasts. [4] The principal cause of nitrogen oxide emissions is high combustion temperatures. [8] When fuel is oxidized at excessively high temperatures nitrogen in the air combines with oxygen forming nitrogen oxides.

The amount of ozone produced in the lower atmosphere depends on many factors. The chemical reactions that create ozone are not only dependant on the total amount of hydrocarbon and nitrogen oxide in a given area but by their relative amounts. Also, when temperatures remain high and the air stagnant for several days ozone, hydrocarbon, and nitrogen oxide can build up and produce more ozone than would occur on a typical high temperature day. [4]

Particulate Matter (PM) refers to non-gaseous emissions. That is, particulate matter is tiny bits of solid matter. particulate matter that is less than ten microns in diameter (PM<sub>10</sub>) is responsible for the aggravation of many diseases and is implicated in premature mortality. [7] In addition to these negative health impacts particulate matter that is less than 2.5 microns in diameter (PM<sub>2.5</sub>) is the principal cause of visible smog. [7] As with carbon monoxide and

hydrocarbon, particulate matter is created by vehicles when fuel is not completely combusted. particulate matter can also be created by gaseous hydrocarbon and nitrogen oxide. [4]

### **3) Vehicle Emission Reduction Technologies**

Vehicle emissions can be reduced through four basic methods: using catalysts to “clean” tailpipe emissions, increasing the efficiency of combustion, switching to cleaner fuels, and switching to engines that do not require combustion (e.g., electric motors).

Catalysts are commonly known as catalytic converters. Catalysts have been remarkably successful. Improvements to catalyst technologies are largely responsible for the achieved emissions reductions outlined in table I-1. [2], [8] Refinements in the basic catalyst technology are expected to continue to allow emissions reductions. [8]

Vehicle manufacturers have utilized several methods to increase combustion efficiency. These refinements have the added benefits of increasing fuel efficiency and engine performance.

The use of cleaner fuels can have dramatic effects on emissions. Reducing the sulfur content of gasoline and diesel fuel can dramatically boost the effectiveness of catalysts. [4], [9], [10] Also, fuel additives, such as MTBE or ethanol, can allow for more complete combustion. [11] Also, vehicles that operate on natural gas, methane, or hydrogen can have lower emissions than similar gasoline or diesel powered vehicles.

Electric motors do not require the combustion of any fuel and they produce zero emissions. Electric motors offer other benefits compared to conventional combustion engines: they are much simpler, lighter, and quieter. However, the limitations of battery technology seriously limit the range and horsepower of electric vehicles. Batteries could potentially be replaced with fuel cells (devices that chemically combine ambient oxygen and hydrogen, producing water and electricity.) Fuel cells have been used successfully as large fixed generators, but affordable vehicle-sized fuel cells are not yet available. Hybrid vehicles which use small gasoline engines and electric motors can run extremely clean. Hybrids’ emissions are very low and their fuel efficiency is very high. Hybrids appear to have overcome the principal drawbacks of “pure” electric vehicles.

## II. Reducing Emissions From Gasoline Engines

Over the past decade significant reductions in new vehicle emissions have been attained as a result of improvements in basic automotive technology. They are not the result of the incorporation of expensive and exotic new equipment. Today, many (but of course, not all) gasoline powered vehicles are capable of meeting the California LEV emissions standards. Further reductions in new vehicle emissions can be attained through further refinements of the basic technology of the gasoline engine (and exhaust system.)

The most significant technological improvements have been to traditional catalysts and to fuel control systems. However, many other improvements have been made or show potential. Table 2.1 shows the EPA's estimate of emissions reductions from Tier 1 levels that various technologies will allow: [4]

**Table II-1 Feasible Technologies for Emission Reductions (from Tier 1 levels)**

<b>Technology</b>	<b>Hydrocarbon</b>	<b>Carbon Monoxide</b>
Modifications to combustion chamber	3-10%	3-10%
Multiple valves with variable valve timing	30%	3-10%
Increased exhaust gas recirculation (including electronic control)	0%	>10%
Improved A/F control	10%	20%
Universal exhaust gas oxygen	5%	23-35%
Air/fuel control in individual cylinders	22%	3%
Air assisted fuel injectors	3-10%	0%
Basic catalyst improvements (washcoats & cell densities)	10%	10%
Increased catalyst loading and volume	10%	20%
Advanced Catalyst design (tri-metal, multi-layered)	20-37%	30-57%
Close-coupled catalysts	50-70%	0-10%
Electrically heated catalyst	>10%	5-10%
Hydrocarbon absorbers	>10%	0%

**Note:** These percentages cannot be simply summed to achieve a total emission reduction when more than one emission control technology is being used.

What follows is a description of the latest technologies capable of reducing exhaust emissions of hydrocarbon, carbon monoxide, and nitrogen oxide from conventional gasoline powered vehicles. The technologies are divided into five categories: Improvements to exhaust after-treatment systems, base engine improvements, improved fuel control, improved fuel atomization, and improved engine calibration.

### 1) Improvements to Exhaust After-treatment Systems

The 1990s have seen tremendous advancements in exhaust after-treatment systems. Improvements to exhaust after-treatment systems are probably the single most important area of emission control development.

## A. Catalysts

Catalysts are commonly referred to as catalytic converters. The concept behind a catalytic converter is that it causes a chemical reaction to occur without being changed or consumed. Therefore, with proper maintenance, use, and fueling<sup>4</sup> a catalyst can continue to operate for the life of the vehicle. [12]

Automotive catalysts consist of a cylindrical shaped ceramic or metal substrate made up of hundreds of very small, but long cells configured in a honeycomb like shape. The substrate is coated with a substance containing precious metals, rare earth metals, and base-metal oxides. This coating is known as the catalyst washcoat. The precious metals (typically platinum and Rhodium) reduce pollutants through oxidation.<sup>5</sup> The base metal oxides, such as alumina, provide the surface area for support for the precious metals to adhere to. The rare earth metals or base components such as lanthanum, ceria, and zirconia, act as promoters and stabilizers while encouraging storage and reduction of oxygen. Conventional catalysts have a single layer of washcoat and precious metals applied to the catalyst substrate. More advanced catalysts use multi-layered washcoats consisting of different combinations of precious metals. This allows precious metals that have adverse reactions together to be separated. Use of multiple precious metals in this fashion significantly improves the catalyst's emission reduction performance and durability.

Conventional catalysts typically have cell densities of 400 cells per square inch (cpsi). With a greater number of cells there is more surface area for the washcoat components to adhere to, which results in more oxidation and a reduction in emissions. Manufacturers have been developing catalysts with substrates, which utilize thinner walls in order to attain higher cell densities. Catalysts with cell densities of 600 cells per square inch have already been commercialized and research on 900 cells per square inch catalysts is progressing. [8] Advanced high cell density catalysts have been shown to allow 1997 and 1999 model year vehicles meet the tier 2 standards. [19]

Another method of increasing the surface area of the substrate is to simply increase the size of the catalyst. Current automobiles that meet California's Low Emission Vehicle (LEV) standard have relatively large catalysts. The ratio of catalyst volume to engine displacement on these cars is between 0.7 to over 1.0. Many of today's higher emitting vehicles (such as trucks) have catalyst volume to engine displacement ratios of 0.6 or less. While increasing the size of the catalyst allows for greater substrate surface area and thus lower emissions, increased size may not be necessary to achieve these lower emissions if greater cell densities can be attained within catalysts of the traditional size. [8]

Another aspect of catalyst design is the "loading" of the catalyst. Loading refers to the amount of precious metals contained in the washcoat. Current cars that meet California's LEV standard typically have loadings that range from 50 grams per cubic foot (g/cu ft) to 300 g/cu ft.

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<sup>4</sup> Catalysts require unleaded gasoline.

<sup>5</sup> When heated to a temperature of 500 degrees Celsius platinum causes carbon monoxide (CO) particles to fuse with free oxygen (O<sub>2</sub>) to form carbon dioxide (CO<sub>2</sub>). At this temperature rhodium causes nitric oxide (NO) molecules to swap nitrogen and oxygen atoms forming oxygen gas (O<sub>2</sub>) and harmless nitrogen gas. [13]

[8] That is, their washcoats contain between 50 and 300 grams of precious metals per cubic foot of substrate material. The loading of a catalyst directly and significantly affects its cost since the cost of the precious metals used in the catalyst are a large proportion of the total cost of the catalyst.

Manufacturers are working to reduce the loading necessary to attain a given emissions reduction, a process referred to as thrifting. One of the most common thrifting techniques is matching the attributes of the catalyst to the attributes of the vehicle. By working in unison, vehicle manufacturers and catalyst suppliers can optimize the vehicle fuel control strategy, exhaust mass flow rate, and exhaust temperature with various catalyst parameters, such as catalyst location, substrate design, cell density, oxygen storage capability, and precious and base metal dispersion. Thus, catalysts that are designed with the attributes of a specific vehicle in mind can achieve the same emissions reduction as “off the shelf” catalysts that have higher precious metal loadings. [8] Another thrifting method is to improve washcoat formulations such that precious metals better adhere to the substrate surface. Finally, improvements to the washcoat application process can improve catalyst performance while allowing thrifting of precious metals. Improvements to the application process typically allow for greater dispersion of precious metals throughout the washcoat. [8] That is, instead of relatively large clumps of precious metals relatively unevenly dispersed throughout the catalyst surface, many smaller precious metal sites are dispersed uniformly throughout the catalyst surface. This increases the chances of pollutants coming into contact with the precious metals and reacting into harmless emissions. As thrifting techniques improve it may be possible for catalyst loadings to decrease while attaining emission reductions.

Catalysts work best at high temperatures. Thus, emissions tend to be high during “cold start” conditions. This is especially true for hydrocarbon emissions since cold start operations usually imply an overly rich air-fuel mixture as well as an inefficient catalyst. One of the most effective methods of reducing cold start hydrocarbon emissions is to reduce the time it takes for the catalyst to attain its optimal operating temperature. Moving the catalyst closer to the exhaust manifold is one method of doing this. Retarding the spark timing and increasing the idle speed are other methods of quickly heating the catalyst.

Using an electrically heated catalyst (EHC) is another method of quickly bringing the catalyst up to optimum temperature. The EHC is a small catalyst equipped with an electric heater that is placed directly in front of the conventional catalyst. The EHC is powered by the car's battery and/or alternator. An EHC is capable of heating up almost immediately, assisting the conventional catalyst in achieving its optimal temperature more quickly. Manufacturers indicate that EHCs may only be necessary for larger displacement engines (such as V-8s) since cold start emissions are especially difficult to control for these engines. [8]

## **B. Absorbers and Traps**

hydrocarbon absorbers and traps are exhaust after-treatment systems that are designed to be used in conjunction with catalysts. Absorbers trap hydrocarbon with an absorption material when the catalyst is cold and thus unable to sufficiently convert hydrocarbons. The absorption material releases the hydrocarbon once the catalyst is warmed up. The hydrocarbon then enters

the fully functional catalyst where it is converted to harmless emissions. [8] There are three principal methods for incorporating absorbers into the exhaust system. The first is to directly coat the catalyst substrate with the absorber material. This has the advantage that there are no additions to the exhaust system necessary. However the release of hydrocarbon can not be easily controlled in such a system and may occur before the catalyst has reached its optimum temperature. The second method locates the absorber in another exhaust pipe parallel to the main exhaust pipe and in front of the catalyst. A system of valves routes the exhaust through the absorber during cold start operations and through the main exhaust (and catalyst) thereafter. Such a system requires a system to purge the absorber. The third method is similar to the second except that the parallel absorber is located behind the catalyst. This avoids the problem of absorber over heating, but requires a system to purge the contents of the absorber back through the catalyst.

### **C. Secondary Air Injection**

Injection of air into exhaust ports during cold start operation when the air-fuel mixture is rich, coupled with spark retard, can promote combustion of unburned hydrocarbon in the exhaust manifold and increase the warm up rate of the catalyst. [8] Secondary air injection systems use an electric pump to inject outside air into the exhaust system as close to the exhaust valve as possible. The combination of outside oxygen with the hot exhaust components leads to additional combustion and allows the exhaust gases (and thus the catalyst) to heat up more quickly. The effectiveness of secondary air injection systems depends heavily on how well they are integrated into the design of specific power-trains. The development of secondary air injection systems poses a significant engineering problem.

### **D. Insulated or Dual Wall Exhaust Systems**

Exhaust systems can be effectively insulated through the use of laminated thin-wall exhaust pipes. This allows for less heat to be lost in the exhaust system and thus leads to a reduction in the time it takes for the catalyst to reach its optimum temperature. [8] Advanced thermally insulated exhaust components used in conjunction with advanced catalysts have been shown to allow 1999 and 1997 model year cars to meet the federal tier 2 standards. [19]

## **2) Base Engine Improvements**

Base engine improvements are most effective for reducing emissions of hydrocarbons and nitrogen oxide. hydrocarbon emissions are caused by unburned fuel (and the combustion of lubricating oil) which can be reduced through improvements in combustion chamber design, valve and valve timing design, and leak free exhaust systems. nitrogen oxide emissions are caused by high combustion temperatures which can be remedied through improvements in combustion chamber design, valve and valve timing design, and improvements in exhaust gas recirculation design.

## **A. Combustion Chamber Design**

Unburned fuel can result from fuel being momentarily trapped in crevice volumes (i.e., the space between the piston and cylinder wall.) Thus reducing crevice volumes leads to reduced hydrocarbon emissions. This is especially relevant for large displacement engines that typically have higher hydrocarbon emissions than lower displacement engines.

The combustion of lubricating oil (and thus the emissions of hydrocarbons) can be reduced by tightening the tolerances of and improving the surface finishes of cylinders and pistons, improving piston ring design and material, and improving exhaust valve stem seals. [8]

Reducing combustion temperatures will reduce the amounts of nitrogen oxide emitted by gasoline engines. Combustion temperatures can be reduced by the combination of increasing the rate of combustion, reducing spark advance, and diluting the air-fuel mixture, typically through exhaust gas recirculation (EGR). The rate of combustion is increased by introducing turbulence (or swirl) into the combustion chamber, which increases the surface area of the “flame front.” Locating the spark plug at the center of the combustion chamber reduces Spark advance. [8]

## **B. Improved Exhaust Gas Recirculation Design**

Exhaust gas recirculation is a very effective method of reducing combustion temperatures, which leads to reduced nitrogen oxide emissions. The recirculation of spent exhaust gas into the combustion chamber causes the overall air-fuel mixture to be diluted, which lowers peak combustion temperatures. The use of high turbulence combustion chambers can allow the amount of exhaust gas recirculation to increase from current levels of 15 to 17% to levels as high as 20 to 25% which would result in 15 to 20% reductions in nitrogen oxide emissions. Most current exhaust gas recirculation systems are mechanical, relying on vacuum from the intake manifold to regulate exhaust gas recirculation flow. Manufactures are starting to use electronically controlled exhaust gas recirculation systems, which perform significantly better than mechanically controlled systems during heavy throttle operation. [8]

While most manufactures agree that exhaust gas recirculation systems do reduce nitrogen oxide emissions, many have been able to attain similar reductions through other methods and shun exhaust gas recirculation systems. Exhaust gas recirculation systems have been sited as negatively impacting the ability to control fuel-air mixtures. [8]

## **C. Multiple Valves and Variable Valve Timing**

Conventional engines have two valves per cylinder (one for the intake of the fuel-air mixture and one for the exhaust of combusted fuel) that operate at a constant speed and lift regardless of engine speed. Doubling the number of valves per cylinder reduces the aerodynamic resistance to pumping air, which increases useful power output per unit of fuel burned. Also, a four valve design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) and allows for greater mixing of air and fuel. Greater mixing of air and fuel increases combustion efficiency, which lowers hydrocarbon emissions.

The constant speed and lift distances of conventional valves are typically set at levels that are a compromise between low speed torque and high-speed horsepower. Through variable valve timing the speed and lift of the valves can be set for maximum combustion efficiency at various engine speeds, thus increasing overall engine efficiency.

Multi-valve engines are becoming common and their use is expected to increase in the foreseeable future.

#### **D. Leak Free Exhaust System**

Because of the pressure difference created by flowing gas inside the exhaust pipe, leaks in the exhaust system typically suck in ambient air. The air that is sucked in is unmeasured and, thus, unaccounted for in the fuel systems closed-loop feedback control. The excess air in the exhaust causes the fuel control computer to increase the fuel-to-air ratio above efficient levels. Also, exhaust leaks lead to conditions that are detrimental to the effectiveness of catalysts. Various methods for reducing or eliminating exhaust leaks are being used or developed. Leak-free exhaust systems are expected to continue to be one of the principal tools manufacturers use to reduce emissions. [8]

### **3) Improved Air-Fuel Ratio Control**

Modern catalysts minimize emissions of hydrocarbon, carbon monoxide, and nitrogen oxide when the air-fuel mixture is as close to stoichiometry (the amount of air and fuel just sufficient for nearly complete combustion) as possible. Stoichiometry (or very close to it) is maintained in modern vehicles through the use of closed-loop feedback fuel control systems. The most important part of these systems is the heated exhaust gas oxygen (HEGO) sensor. Generally HEGO sensors work well under normal operating conditions, but their accuracy is challenged during episodes of rapidly changing throttle control (e.g. acceleration). Also, the accuracy of HEGO sensors deteriorates with age.

#### **A. Dual Oxygen Sensors**

Placing an additional HEGO sensor downstream of the catalyst is one method for improving the performance of closed-loop feedback fuel control systems. The downstream sensor monitors the effectiveness of the catalyst and monitors the primary sensor's performance. If the primary sensor exhibits slow response or drift from the calibration point, the downstream sensor can modify the fuel system controls to compensate. The downstream sensor is less susceptible to the effects of aging since the exhaust gas it is monitoring is significantly cooler than the exhaust gas that the primary sensor monitors. Currently, all vehicle manufacturers use a dual oxygen sensor system to monitor the catalyst. A growing number of manufacturers use dual sensors to increase the accuracy of fuel system controls. [8]

#### **B. Universal Oxygen Sensors**

Universal exhaust gas oxygen (UEGO) sensors may replace HEGO sensors. Current HEGO sensors only determine that the air-fuel mixture is richer or leaner than stoichiometry.



universal exhaust gas oxygen sensors determine both the direction and magnitude of deviations from stoichiometry, which facilitates faster response to the fuel control system and tighter control of the air-fuel mixture. Although some manufactures do use universal exhaust gas oxygen sensors most claim that their benefits do not justify their high costs. Improvements in the basic design of HEGO sensors may make universal exhaust gas oxygen sensors irrelevant. [8]

### **C. Individual Cylinder Air-Fuel Control**

Current fuel control systems control the air-fuel mixture for the entire engine (or an entire bank of cylinders) without accounting for the variations in the air-fuel ratio among the cylinders. Fuel control systems that adjust the air-fuel mixture for each cylinder individually are possible and would lead to increased engine performance and lower emissions. Such systems would require the use of universal exhaust gas oxygen sensors and engine control computers that have significantly faster processing speeds than those currently available. [8]

### **D. Adaptive Fuel Control Systems**

The fuel control systems of almost all current vehicles use a feature know as “adaptive memory” or adaptive block learn” that adjusts the amount of fuel delivered to compensate for varying environmental conditions, component wear, varying fuel compositions, etc. However, current adaptive fuel control systems are only effective during steady state operating conditions (i.e., constant or slowly changing throttle). More accurate fuel control during transient (i.e., rapidly changing throttle) conditions would lead to significant emissions reductions, especially nitrogen oxide. [8] Designing adaptive fuel control systems that improve the accuracy of fuel delivery during transient conditions is a current engineering challenge.

### **E. Electronic Throttle Control Systems**

The time delay between the air mass measurement and the calculated fuel delivery is one of the primary difficulties of accurately maintaining fuel delivery during transient conditions. This problem can be significantly mitigated by replacing the conventional mechanical throttle system with an electronic throttle control system, known as “drive by wire.” Drive by wire systems are expensive, but are currently used on several high-priced vehicles. [8] Because of their high cost, it is not likely that drive by wire systems will become commonplace in the near future.

## **4) Improvements in Fuel Atomization**

In addition to maintaining stoichiometry, it is important that a homogeneous air-fuel mixture is delivered at the proper time and that the mixture is finely atomized to provide the optimal combustion characteristics. When combustion conditions are less than optimal, combustion is not complete; thus, excessive unburned hydrocarbon is emitted. This problem presents itself primarily during cold start conditions and during the warm-up phase of the engine. With better fuel atomization, combustion is more complete, fuel economy is higher, and emissions are lower.

## **A. Sequential Multi-Point Fuel Injectors**

Sequential multi-point fuel injectors are common in today's vehicle fleet and are expected to be ubiquitous soon. [8] Sequential multi-point fuel injectors are superior to older multi-point fuel injectors because they inject fuel into each cylinder independently. This ensures that the precise amount of fuel needed by each cylinder can be delivered precisely when it is needed. Older multi-point fuel injectors fire fuel into several cylinders simultaneously. Since only one cylinder is ready for fuel at any given moment, the other cylinders get either too much or too little fuel. This obviously inhibits complete combustion.

## **B. Air-Assisted Fuel Injectors**

Air-assisted fuel injectors inject high-pressure air in the injector and, thus, the fuel spray. This leads directly to greater atomization of the fuel spray. Air-assisted fuel injectors are especially effective at reducing emissions at low engine speeds when airflow into the engine is low. [8]

## **5) Improvements in Engine Calibration Techniques**

Engine calibration techniques are the software algorithms used in vehicles' power-train control modules. Advancements in software can have significant impacts on engine emissions. As computer technology advances so does the ability of engineers to use calibration techniques to optimize emission control systems. Faster computer processors allow for quicker response times for controlling engine parameters while increased memory allows for more sophisticated algorithms.

Manufacturers have indicated that tighter air-fuel ratio control through the use of advanced calibration techniques may be the single best method of controlling nitrogen oxide emissions. [8] Thus, significant reductions in nitrogen oxide may be feasible without the use of advanced technologies such as universal exhaust gas oxygen sensors. Improved calibration techniques have been used to meet federal cold carbon monoxide requirements as well as California's LEV standard without the use of advanced hardware such as EHCs or absorbers.

For competitive reasons, manufacturers are typically very secretive about their work on calibration techniques. Thus, it is difficult to predict what forms of calibration improvements will occur. However, it is clear that improvements in calibration techniques are viable and will play a significant part in future emission control systems. [8]

## **6) Particulate Matter Emissions from Gasoline Engines**

Particulate matter emissions from gasoline engines are composed of both carbon- and sulfur-containing compounds. Carbon-based particulate matter is produced from the incomplete burning of gasoline fuel and the inadvertent burning of lubricating oil. Technologies that reduce gaseous hydrocarbon emissions also tend to reduce carbon-based particulate matter. Sulfuric acid (commonly referred to as sulfate) is the predominate form of sulfur-containing particulate matter. Sulfate is produced in both the engine and the exhaust system through the oxidation of sulfur

dioxide contained in gasoline. The primary technique of reducing sulfate emissions is the reduction of sulfur levels in gasoline. [4]

### III. Reducing Emissions from Diesel Engines

The control of emissions from heavy-duty vehicles (which are primarily diesel fueled) has lagged behind control of other sources of emissions such as passenger cars. This lack of emissions control is compounded by the durability of diesel engines. For example, estimates from registration data in the Northeast indicate that 40% of trucks in the region are pre-1989 model year, and thus are uncontrolled for particulate matter. In the case of non-road engines, the disparity is even greater, given that all pre-1996 engines are uncontrolled. Due to this disparity in emissions between heavy-duty vehicles and other sources, heavy-duty engines contribute disproportionately to the emissions inventory for nitrogen oxide and particulate matter. [14]

Heavy duty diesel engines tend to emit slightly more hydrocarbon than gasoline powered passenger vehicles. They tend to produce slightly less carbon monoxide than gasoline powered passenger vehicles. However, heavy duty diesel vehicles tend to emit much more nitrogen oxide and particulate matter than gasoline powered passenger vehicles. Table III-1 illustrates actual estimated vehicle emissions in the Phoenix area for the winter of 1996:

**Table III-1 1996 Actual Emissions Estimates: Grams per mile [15]**

	Hydrocarbon	Carbon Monoxide	Nitrogen Oxide	PM10
Passenger Vehicles	2.76	11.96	1.67	0.07
Heavy duty Diesel vehicles	3.06	7.22	6.97	1.65
Ratio of diesel to passenger emissions	1.10	0.60	4.17	23.57

Diesel engines run on a very lean air-fuel mixture. That is, relative to a gasoline engine, there is more air and less fuel in the mixture. This results in low emissions of hydrocarbon and carbon monoxide, but it results in high emissions of nitrogen oxide. Also, lean air-fuel mixtures make the use of catalyts significantly more difficult. [28]

Recent studies of air quality indicate that up to 15% of the particulate matter emitted in the Phoenix area can be attributed to diesel engines. [7] According to the EPA heavy-duty diesel engines produce 25% of all vehicle generated nitrogen oxide. [23]

Given the long life of diesel engines and the lack of significant controls on their emissions until relatively recently, retrofitting older heavy-duty vehicles with emission control devices can be a viable policy option. This will be further discussed in Chapter VIII Policy Conclusions.

#### 1) Light-Duty Vehicles

Light-duty vehicles powered by diesel engines have emissions characteristics similar to heavy-duty vehicles: They emit relatively low amounts of hydrocarbon and carbon monoxide and relatively high amounts of nitrogen oxide and particulate matter. The EPA indicates that such vehicles will have no problem meeting the tier 2 standards for hydrocarbon and carbon monoxide. However, it may be a challenge for these vehicles to meet the tier 2 nitrogen oxide and particulate matter standards. The EPA also indicates that these vehicles will not be able to

meet the tier 2 standards through engine modifications; they will require significant exhaust after-treatment.<sup>6</sup> [8]

The EPA identifies the following exhaust after-treatment devices that may significantly reduce diesel emissions from light duty vehicles: [8]

- lean nitrogen oxide catalysts
- selective catalytic reduction
- nitrogen oxide absorbers
- oxidation catalysts
- traps and particulate matter filters

## 2) Heavy Duty Vehicles<sup>7</sup>

While light-duty diesel vehicles will be required to meet the same tier 1 and 2 standards as gasoline powered passenger vehicles, heavy-duty diesel vehicles have their own sets of emissions standards. Table III-2 illustrates the current and proposed future federal emissions standards for heavy-duty vehicles. Standards for heavy duty vehicles are expressed in terms of grams emitted per brake horsepower hour (g/bhp-hr) since the varying conditions under which they are operated (e.g., loaded or unloaded trucks) do not allow for meaningful grams per mile traveled comparisons.

**Table III-2 Current and Proposed Future Standards For Heavy-Duty Vehicles g/bhp-hr<sup>8</sup>**  
[16] [17]

<b>Model Year</b>	<b>hydrocarbon</b>	<b>carbon monoxide</b>	<b>nitrogen oxide</b>	<b>particulate matter</b>
1990	1.3	15.5	6.0	0.60
1998-2006	1.3	15.5	4.0	0.10
2007	1.3	15.5	0.5	0.01

Note: 2007 numbers are proposed.

Table III-2 demonstrates that emissions of nitrogen oxide and particulate matter from new diesel trucks have been substantially reduced during the 1990s. The EPA's proposed standards for 2007 call for reductions of 87.5% and 90% for nitrogen oxide and particulate matter respectively. [16] [17] It is unclear whether the EPA will implement the above proposed standards.

Current exhaust after-treatment technologies that will most likely allow heavy-duty vehicles to meet the proposed standards include: [18] [28]

- oxidation catalysts
- particulate filters or traps

<sup>6</sup> It should be noted that similar projections were made concerning particulate matter emissions a decade ago. However, manufactures were able to significantly reduce particulate matter emissions from diesel engines without the use of after-treatment devices. [8]

<sup>7</sup> Vehicles are considered to be heavy-duty by the EPA if they weigh 8,500 pounds or more.

<sup>8</sup> Current allowable particulate matter emissions for urban buses are slightly lower than those for trucks illustrated in table III-2.

- Selective catalytic reduction
- Fuel born catalysts in combination with filters and oxidation catalysts
- Exhaust Gas Recirculation in combination with the above technologies

In addition to the above technologies, the following technologies are under development and show potential: [28]

- Lean nitrogen oxide catalysts (also referred to as denitrogen oxide catalysts)
- nitrogen oxide absorbers or nitrogen oxide traps
- non thermal plasma devices

Testing of the above technologies on 1999 model year heavy-duty diesel engines indicates that a particulate matter standard of 0.05 g/bhp-hr is attainable. [18] However, this result was only attained with the use of low sulfur fuel. Results were less impressive with the higher sulfur diesel fuel which is currently the standard. [18] Research indicates that dramatic reductions in diesel fuel sulfur levels will be necessary for a truly “clean” diesel engine. [28]

Also, the above technologies were tested on engines that were not specifically tuned to work with them. Designing versions of these technologies for specific engines could result in greater emissions reductions. [18]

In addition to the above exhaust after-treatment technologies, improvements to basic engine design can achieve significant reductions in emissions from heavy-duty vehicles. Incorporating electronic superchargers with traditional turbochargers is one example that has proven effective. [21]

### 3) Description of Technologies

**Lean-nitrogen oxide catalysts or denitrogen oxide catalysts** solve the lean air-fuel mixture problem by injecting a small amount of diesel fuel (or other on board source of hydrocarbon) into the exhaust system ahead of the catalyst. These systems can result in a loss of fuel efficiency of 3%, but afford a reduction in nitrogen oxide emissions of 30%. More advanced Lean-nitrogen oxide catalysts are being developed that are expected to reduce nitrogen oxide emissions by between 50 and 70%. [28]

Lean-nitrogen oxide catalysts are used in Europe on some passenger cars. However, the sulfur level in European diesel fuel limits their effectiveness to a 15% nitrogen oxide reduction. Research indicates that current levels of sulfur will limit Lean-nitrogen oxide catalysts to nitrogen oxide reductions of 15 or 20%. This is far below their potential if cleaner fuel were used. [28] [29]

While lean nitrogen oxide catalysts are capable of reducing nitrogen oxide emissions by 15-20% in actual applications, much greater reductions in nitrogen oxide will be required to meet the tier 2 standards. The EPA indicates that it is unlikely that lean nitrogen oxide catalysts will be widely used in the near future. [8]

**Selective Catalytic Reduction (SCR)** has been demonstrated commercially on stationary diesel engines for at least 15 years. It was found to reduce nitrogen oxide emissions by 80-90%. Selective catalytic reduction has a significant drawback however, it requires the injection of the chemical urea into the exhaust before the catalyst. Thus, vehicle owners would have to periodically refuel their vehicles with urea. Selective catalytic reduction has also had problems with ammonia emissions which have an objectionable odor. [8]

Recently selective catalytic reduction has been evaluated on mobile sources. Using urea as a reductant, it has been demonstrated to reduce nitrogen oxide emissions by 90%. With an optimized engine/selective catalytic reduction system in-use reductions of nitrogen oxide of 70% have been demonstrated in Europe. [28]

Selective catalytic reduction technology in current stationary applications is sulfur tolerant. However, vehicle exhaust typically has a much wider range of temperatures than do stationary applications. In order to cover the broad range of temperatures typical of diesel exhaust and still maintain high nitrogen oxide reductions, selective catalytic reduction systems will have to be effective at temperatures below 250 degrees Celsius. The effectiveness of these systems is inhibited by high sulfur contents in diesel fuel. [28] [29]

**Nitrogen oxide absorbers or nitrogen oxide Traps** have been demonstrated to reduce nitrogen oxide emissions by 90% in the laboratory. [8] [28] However, sulfur contained in diesel fuel quickly poisons these absorbers. Sulfur levels in commercially available diesel fuel would have to be substantially reduced for widespread deployment of these devices to be feasible. [8]

**Nitrogen oxide absorbers** could achieve nitrogen oxide actual reductions of 50 to 90%. [28] nitrogen oxide traps first catalytically oxidize nitrogen oxide into nitrate which is stored in a chemical trapping site adjacent to the catalyst. This stored nitrate is then purged in a process that involves injecting diesel fuel into the exhaust. Use of nitrogen oxide traps would result in a 3% reduction in fuel economy, however if the 90% reduction in nitrogen oxide is achieved engines could be calibrated to make up for this loss. [28]

Laboratory tests indicate that 90% nitrogen oxide reductions are attainable from nitrogen oxide traps if low sulfur fuel is used. The effectiveness of nitrogen oxide converters declines sharply with the sulfur content of fuel. With sulfur levels of 210 parts per million (which is below the current average) nitrogen oxide traps achieved only a 30% reduction of nitrogen oxide. Furthermore, the effect of sulfur on nitrogen oxide traps increases with their age and is irreversible. [28] [29]

**Diesel oxidation catalysts** are very similar to the three-way catalysts used on gasoline powered vehicles. These devices convert hydrocarbon compounds in the exhaust to water and carbon dioxide. They can reduce hydrocarbon emissions by up to 90%. Typically, particulate matter emitted from diesel emissions is comprised of 30% hydrocarbons.<sup>9</sup> Thus, diesel oxidation catalysts can reduce particulate matter emissions by 15-27%. This would not be sufficient to bring light-duty diesel engines into compliance with tier 2 standards on its own. [8] The

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<sup>9</sup> Gaseous hydrocarbon emissions are referred to as HC in this report. Hydrocarbon emissions that are in their solid state are included with particulate matter.

hydrocarbon fraction of particulate matter is important because it contains many chemicals that are health hazards. Oxidation catalysts also reduces visible diesel smoke and eliminates the pungent diesel exhaust odor. [28]

Theoretically, oxidation catalysts should work well in conjunction with nitrogen oxide absorbers, denitrogen oxide catalysts or selective catalytic reduction systems. Oxidation catalysts have been used successful on a variety of on and off road applications for a several years and have proven very durable. [28]

While oxidation catalysts are effective even with current fuel sulfur levels, their effectiveness would increase if lower sulfur fuel were to be used. Through a complex process sulfur in exhaust gases is converted into sulfuric acid and emitted as particulate matter when oxidation catalysts are used. **Oxidation catalysts must be carefully calibrated to minimize this effect since it could potentially result in exhaust particulate matter emission levels higher than engine-out particulate matter emission levels.** Laboratory results indicate that oxidation catalysts are much more effective when lower sulfur fuel is used. [28]

**Particulate Traps and Filters** are a promising emission reduction technology for diesel engines. They can reduce particulate matter emissions by up to 90%. Traps filter carbon based particulate matter from the exhaust. This collected material must be burned off periodically. Otherwise the trap would fill up and inhibit proper engine function. Traps are currently being used successfully on buses in several U.S. cities. The operating temperatures of buses and other heavy-duty vehicles allows traps to regenerate (i.e., burn off) frequently enough for proper functioning. Light-duty vehicles may not have operating temperatures high enough to allow for proper regeneration. Regeneration can be enhanced at lower exhaust temperatures through the use of more active catalysts on the surface of the trap. However, such catalysts would require diesel fuel with almost no sulfur. [8]

Diesel Particulate Filters consists of a filter material in the exhaust designed to collect solid and liquid particulate emissions while allowing exhaust gases to pass through the system. Eventually, such a filter will “fill up” and plug the exhaust system, thus the collected particulate must be removed. This is accomplished by oxidizing the particulate to carbon dioxide, i.e. the particulate is burned off. This burning off is often refereed to as regeneration. [28]

A number of filter materials have been evaluated, including ceramic monoliths, woven silica fiber coils, ceramic foam, wire mesh, and sintered metal filters. Most of these filters are designed to achieve an 80% reduction in particulate matter emissions. [28] A recent study indicated that an advanced experimental filter technology virtually eliminated the very fine particulate matter that is of most concern for health reasons. Very fine particulate matter (particles that are less than 100 nanometers<sup>10</sup> across) can be carried deep into the lungs and thus cause respiratory problems. [28]

Diesel exhaust temperatures are not always sufficient to initiate regeneration of particulate filters. To address this problem a number of regeneration techniques have been

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<sup>10</sup> There are one million nanometers in a meter.



developed. In-line fuel burners and electrical heaters can be used to raise the exhaust temperature. [28]

Instead of raising exhaust temperatures, catalysts can be used to lower the temperature necessary for regeneration. This can be done by applying a catalyst directly on the filter material. This type of technology is referred to as a catalytic particulate filter. Fuel borne catalysts can also be used. A catalyst placed in front of the filter that oxidizes NO into NO<sub>2</sub> (a strong oxidant) can also be effective. The NO<sub>2</sub> will absorb into the collected particulate and cause combustion. This technology is referred to as “continuously regenerating” diesel particulate filters. [28]

Particulate filters have been used on trucks and buses successfully in Europe. In use systems are achieving particulate matter reductions of 90% while demonstrating excellent durability. Further, catalytic particulate filters have long been used successfully on mining equipment. [28]

The effect of sulfur on particulate filters is similar to its effect on oxidation catalysts. Also, the high fuel sulfur levels increase the temperature that is needed for regeneration. This is important because higher regeneration temperatures imply higher exhaust backpressure. Higher backpressure results in decreased fuel economy and other problems. Also, lower sulfur fuel would allow expanding the use of particulate filters to engines with low exhaust temperatures. [28] [29]

High sulfur levels inhibit the performance of continuously regenerating particulate filters. High sulfur levels inhibit the conversion of NO into NO<sub>2</sub>. Thus, regeneration occurs less frequently and exhaust back pressure increases. Continuously regenerating particulate filters have been demonstrated excellent particulate control when low sulfur fuel is used, even after several hundred thousand miles of operation. [28]

**Pulsed-power after-treatment devices** may become an effective way to reduce nitrogen oxide emissions from diesel engines. These devices consist of a chamber incorporated into the exhaust system which contains an electronic switch that produces thousands of short electric pulses per second. Energetic electrons from these high voltage sparks are injected into the exhaust stream, similar to an electron beam in a fluorescent light bulb. The electrons strike air and water vapor molecules in the exhaust which creates an ion plasma which in turn reacts with nitrogen oxide and particulate hydrocarbons to produce carbon dioxide, free nitrogen, and water vapor. [23] While pulsed-power after-treatment devices are still experimental, they may become a common emission control technology.

**Non-Thermal Plasma** assisted catalysts have been demonstrated to reduce nitrogen oxide emissions by 80% in laboratory conditions. Non-thermal plasma systems work as follows: a high voltage is applied to two plates positioned in the exhaust ahead of a selective nitrogen oxide catalyst. The voltage ionizes molecules that pass through the plates converting nitrogen oxide to NO<sub>2</sub>. NO<sub>2</sub> is more easily removed by the catalyst. The effect of sulfur on these systems is not documented, but, since catalysts are employed, they are likely to be significant and negative. [28]

In addition to exhaust after-treatment technologies, manufactures are working to develop emissions reductions from basic engine improvements. Electronic superchargers are one technology that shows promise. **Electronic superchargers** can make up for the deficiencies of the turbo chargers that many diesel engines employ

Turbochargers are common on heavy-duty diesel engines. Turbo chargers use the energy of the exhaust gas to inject compressed air into the intake manifold. The advantage of compressing the air is that it lets the engine stuff more air in a cylinder. More air means that more fuel can be stuffed in too. Therefore more power is generated from each explosion in each cylinder. Turbochargers allow for substantial increases in horsepower, torque, and acceleration. One problem with turbochargers is “turbo lag.” At low revolutions per minute turbochargers do not function, thus there is a lag in acceleration, torque, and horsepower when vehicles are accelerating from a stationary position. Since the fuel injection system is tuned for use with the turbocharger, the air-fuel mixture will be extremely rich during the lag period. Thus, exhaust emissions during the lag period are relatively high. The plumes of black smoke emitted from diesel vehicles as they accelerate from a stand still are a result of this phenomena.

Electronic superchargers are devices that inject compressed air into the intake manifold during the turbo lag period. They are powered by the vehicle’s battery and/or alternator. Since these devices only operate during the relatively short turbo lag period the drain on the vehicle’s electrical system is negligible. Electronic superchargers provide the triple benefits of increased performance, increased fuel economy, and reduced emissions. While the concept of electronic superchargers is fairly simple they were not feasible until the last decade because they rely on advanced electronic components. [20]

Retrofitting older heavy-duty diesel vehicles with electronic superchargers has been demonstrated to produce substantial emissions reductions. The emissions reductions are most dramatic for vehicles that operate under conditions that require frequent starts and stops such as city buses and garbage trucks. The Turbodyne corporation manufactures an electronic supercharger, the Turbopack, which has demonstrated substantial emissions reductions under real operating conditions. [21] The average cost to install a Turbopack system is \$3,000. [21] Both the EPA and the California Air Resources Board have certified the Turbopack as meeting the requirements of their Urban Bus Retrofit/Rebuild Programs (discussed further in Chapter VIII) when used in conjunction with an advanced catalyst. Tests indicate that the Turbopack when used in conjunction with an advanced catalyst reduces particulate matter emissions by 52% and carbon monoxide emissions by 80%; however, the effect on nitrogen oxide emissions was negligible. [22]

## **IV. Cleaner Gasoline and Diesel Fuel and Fuel Additives**

The introduction of unleaded fuel during the 1970s made substantial emissions reductions possible. In addition to its direct effect on public health, lead in gasoline completely and permanently destroys catalyst activity. [26] Thus the substantial emissions reductions that catalysts have allowed since the 1970s would not have been possible without a dramatic change in gasoline formulation. [2] The EPA's Tier 2 requirements contain a similarly sweeping requirement: a ninety percent reduction in the sulfur content of gasoline. [3] As discussed in previous chapters, sulfur has a detrimental impact on catalyst performance. Reductions in gasoline sulfur levels will result in increased performance by existing catalysts and allow for the development of more advanced catalysts. The EPA has also been considering requiring the reduction of the sulfur content of diesel fuel. [24] Recently the EPA announced that it will impose a 15 parts per million sulfur standard for on-road diesel fuel by 2006. [57]

Fuel additives that improve oxidation were first used extensively in the 1970s. These additives, known as oxygenates, were initially added to gasoline to boost its octane. Octane boosts were necessary because unleaded gasoline has a significantly lower octane than leaded gasoline. Oxygenated gasoline can have positive impacts on emissions; carbon monoxide and hydrocarbons emissions decline as a result of oxygenates, but nitrogen oxide emissions increase. Colorado was the first state to use oxygenates as an emission control strategy when it mandated their winter time use in 1988. In 1990, amendments to the federal Clean Air Act required states to implement programs to require the use of oxygenates in areas that exceed federal carbon monoxide standards. The amendments also required the use of reformulated gasoline (RFG) in areas with serious ozone pollution. [25]

### **1) Reducing Fuel Sulfur Content**

Gasoline and diesel fuel contain sulfur because it naturally occurs in crude oil. Current processes for refining crude oil into fuels does not remove all of the sulfur. [8] Currently gasoline sold in the U.S. has a sulfur content that ranges between 30 and 1,000 parts per million (PPM) with an average of 300 parts per million plus or minus 50 parts per million. This level of gasoline sulfur has remained constant since the 1970s. [26]

While federal control of gasoline sulfur levels has been lenient until very recently, California implemented sulfur controls in 1996. California's Phase 2 reformulated gasoline requirements specify an average gasoline sulfur content of 30 parts per million and a maximum sulfur content of 80 parts per million. [26] California refineries manage to produce low sulfur fuel despite their use of California and Alaskan crude oil which is of very low quality. [8] Japan also imposes a low sulfur requirement. Gasoline in Japan averages about 20 parts per million. [8]

The California Air Resources Board estimates that cleaner gasoline costs between 5 and 15 cents more per gallon to refine than conventional gasoline. This translates into a 5 to 8 cent increase in the retail price of a gallon of gasoline.<sup>11</sup> [27]

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<sup>11</sup> These cost estimates include the cost of adding oxygenates and reducing levels of benzene and other chemicals in addition to the cost of removing sulfur.

It is well known that actual vehicle emissions do not correspond to emissions levels achieved during the certification process used to prove that vehicles meet emissions standards. This is because the gasoline used for the U.S. Federal Test Procedure for certifying vehicles typically has a sulfur content below 50 parts per million while commercially available gasoline could have a sulfur content as high as 1,000 parts per million. The wide range of sulfur content in commercially available gasoline (30-1,000 parts per million) results in a wide range of emissions levels. [26]

When combusted gasoline sulfur forms sulfur dioxide (SO<sub>2</sub>), a known inhibitor of catalyst performance. [26] Unlike lead which completely and permanently destroys catalysts, sulfur dioxide acts as an inhibitor which competes with the exhaust pollutants for space on the catalyst surface. [26]

Lower sulfur gasoline will result in better performance from the 125 million three-way catalysts that are already in use. [26] Thus, reduced sulfur levels will have an immediate impact on emissions. The long term implications of low sulfur gasoline are even more important. Lower sulfur gasoline is critical to achieving the very low emissions levels required for meeting Tier 2 and lower emission standards. [26]

The negative effects of high sulfur gasoline are greater on vehicles calibrated to meet the California LEV and Tier 2 standards. This is because the materials used in advanced catalysts are especially sensitive to sulfur inhibition. Studies conducted by the EPA indicate that sulfur inhibition increases the emissions level of a California LEV certified vehicles to that of Tier 0 vehicles. [26] Also, EPA studies concluded that switching from gasoline with 40 parts per million to gasoline with 1,000 parts per million of sulfur resulted in increases of emissions of 60% for hydrocarbons, 65% for carbon monoxide, and 180% for nitrogen oxide. [26]

Vehicles certified as California LEVs that switch to low sulfur fuel after extended operation with high sulfur fuel will experience improved catalyst performance. However, the catalyst will never perform as effectively as if low sulfur fuel was used throughout its life. [26]

Sulfur levels in diesel fuel used by on-road vehicles are as high as 500 parts per million with an average of 300 parts per million. Diesel fuel used for off-road vehicles can have sulfur contents twice that level. [28] These sulfur levels preclude the use of several advanced nitrogen oxide controls such as nitrogen oxide absorbers and lean nitrogen oxide catalysts. Effective and commercially available particulate matter filter technologies that use a nitrogen oxide catalyst-assisted oxidation process to regenerate are also precluded by these sulfur levels. particulate matter controls that are compatible with current sulfur levels, such as diesel oxidation catalysts and particulate filters, would achieve significant improvements if operated with low sulfur diesel fuel. [28]

Sulfur levels below 30 parts per million will be necessary to achieve a truly “clean” diesel engine. [28] [29] The specifics of sulfurs negative effects on diesel exhaust after-treatment technologies are discussed in Chapter III.

## 2) Oxygenates

The 1990 amendments to the federal Clean Air Act required the states to implement programs to require gasoline to contain 2.7% by weight of oxygen during winter months in areas that exceed the federal carbon monoxide standards. Thirty-nine areas were identified as exceeding the federal carbon monoxide standards including the Phoenix and Tucson areas.

There are several oxygenates that can be added to gasoline, methyl tertiary butyl ether (MTBE) and ethanol are used most frequently. Other oxygenates such as tertiary amyl methyl ether (TAME) and ethyl tertiary butyl ether (ETBE) are used in much smaller quantities. In 1996, over 95% of California's gasoline was blended with MTBE. The remainder was blended with ethanol, TAME, or ETBE. [25]

Studies of ambient carbon monoxide levels in cities with winter oxidized gasoline programs find reductions in ambient carbon monoxide of about 10%. [30] Vehicle emissions show a consistent reduction in carbon monoxide when oxygenates are used and temperatures are above 50 degrees F. At temperatures below 50 the magnitude of the reduction is decreased and highly uncertain. [30] The effect of oxygenates is more pronounced on older vehicles than on newer vehicles. This is because both the total amount of carbon monoxide emissions are less on newer vehicles and the percentage reductions in carbon monoxide attributable to oxygenates is less for new vehicles. [30] New vehicles use sensors to monitor the balance of fuel and oxygen. If the fuel has oxygenates in it these sensors decrease the air intake and increase the fuel proportion. The net result is that the emission levels of carbon monoxide stay the same, but more fuel is consumed.

Oxygenates also effect hydrocarbon emissions. Some forms of hydrocarbon (for example, benzene and butadiene) are decreased when oxygenates are used. While other forms of hydrocarbon (for example, acetaldehyde from the use of ethanol and ETBE and formaldehyde from the use of MTBE) increase when oxygenates are used. [30] Nitrogen oxide emission levels are not affected by oxygenate levels that are less than 2% by weight of gasoline. Gasoline with higher oxygenate levels would result in higher nitrogen oxide emissions. [30] Consequently, regulations requiring 2.7% oxygen reduce carbon monoxide and hydrocarbon emissions while increasing nitrogen oxide emissions.

MTBE has been used so frequently because it offers several advantages over other oxygenates. It is cheaper and easier to combine with gasoline than other oxygenates. [25] Specifically, MTBE can be blended with gasoline at the refinery, while ethanol must be blended at individual terminals. This is because ethanol has a high affinity for water. If gasoline containing ethanol were to come into contact with water (which is common in gasoline pipelines) the ethanol would combine with the water and "fall out" of the gasoline. [25] ETBE and TAME are similar to MTBE in many respects, but it is more difficult for refiners to add them to gasoline. [25]

Recently, the use of MTBE has become a problem. MTBE has been found in ground water in several states, including Arizona, California, and Maryland. [31] [32] [33] MTBE can enter water supplies through seepage from underground gasoline storage tanks or from

inefficient boat engines. [31] This is a concern because MTBE has been shown to cause cancer in animals and the EPA recognizes it as a potential human carcinogen. [31] California's governor has issued an executive order banning the use of MTBE by 2003. However, California may need to obtain a waiver from the EPA's fuel oxygenate requirement if it is to ban MTBE. [31]

## V. Electric Vehicles, Fuel Cells, and Hybrids

Electric motors have several inherent advantages over gasoline engines:

- They produce zero emissions
- They do not require an exhaust system
- They do not require a transmission
- They do not require fuel injectors or carburetors
- They have fewer moving parts.

In short, electric motors are vastly more simple than gasoline engines. However, electric vehicles suffer from a debilitating drawback: they rely on batteries for power. Batteries are expensive, heavy, short lived, and store very little energy relative to their weight. [34] [35]

In the early days of the automobile electric cars were common, approximately 50,000 of them were in use in the United States in 1912. [34] However, electric vehicles were quickly displaced by gasoline and diesel powered vehicles when they became readily available. This was because the battery technology of the time placed severe limitations on electric vehicle range and performance. Although much progress has been made in battery technology, batteries are still the Achilles heel of electric vehicles.

Fortunately, there are alternatives to batteries. Fuel cells are devices that chemically combine ambient oxygen and hydrogen, producing water and electricity. Vehicles powered by fuel cells would have all of the emissions reductions of conventional electric cars<sup>12</sup> without the limitations of batteries. While fuel cell powered vehicles are not currently viable, they have the potential to power many of the future's cars. Hybrid vehicles are another potential "solution" to the battery problem. Hybrid vehicles use small gasoline engines in conjunction with electric motors. Hybrids' emissions are very low and their fuel efficiency is very high. Hybrids appear to have overcome the principal drawbacks of "pure" electric vehicles. The advantages and disadvantages of the three types of electric vehicles (battery powered, fuel cell powered, and hybrid vehicles) will be discussed in detail below.

### 1) "Conventional" Battery Powered Electric Vehicles

At least nine manufactures are selling battery powered electric vehicles in California. [36] The range of the vehicles with fully charged batteries varies from as low as 43 miles to as high as 152 miles. [36] These cars are available in only small numbers and information concerning many of them is difficult to obtain. Also, many manufactures only make their electric vehicles available through leases, with no option to buy.

The General Motors EV-1 is a good example of an electric vehicle. The EV-1 is a small two-seat vehicle. It has decent acceleration, achieving 0 to 60 miles per hour in less than 9 seconds. This, combined with the EV-1's 80 mph (governed) top speed, allows the car to

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<sup>12</sup> Actually, fuel cell powered vehicles could produce substantially less emissions than conventional electric vehicles since they would not place any demands on the electric power grid.

function competently in everyday driving conditions. The car also comes equipped with many amenities such as power windows, power locks, and air conditioning. The EV-1 is available with a lead-acid battery pack with a range of 55 to 95 miles per charge or a nickel-metal hydride battery pack with a range of 75 to 130 miles. The range per charge will vary depending on driving conditions and the degree to which accessories, such as air conditioning and heat, are used. The lead-acid battery requires 5.5 to 6 hours to charge and the nickel-metal hydride requires 6 to 8 hours to charge. [37]

The EV-1 is available only for lease, there is no option to buy this vehicle. However, GM has recently announced that they will sell returned 1997 model EV-1s. EV-1s are available through a limited number of Saturn dealers in California and Arizona. The EV-1 is an expensive car. Lead-acid battery powered EV-1s lease for \$574 a month in Arizona. In California lease prices for lead-acid battery powered EV-1s range between \$424 and \$574 a month depending on the level of subsidy provided by the state. These lease rates are based on a manufacturer's suggested retail price (MSRP) of \$33,995. EV-1s equipped with the longer-range nickel-hydride battery pack are available only in California. In areas of California with the highest government incentives they lease for \$499 per month, in other areas they are more expensive. These lease rates are based on a MSRP of \$43,995. [37]

The EV-1's specifications illustrate the principal drawbacks of electric vehicles: high cost and limited range. The EV-1's size and performance is comparable to that of conventional entry-level cars that sell for much less than \$33,000 to \$43,000. The range of a fully charged EV-1 is less than the range of a conventional car with a full tank of gasoline. Furthermore, a conventional car can be refueled in a matter of minutes while the EV-1 takes several hours to recharge.

Electric vehicles would be much more practical if recharging stations were widely available. Currently, electric vehicle users recharge their vehicles at their home over night. If recharging stations were available at work and shopping places the problems associated with limited range would be mitigated. Since recharging stations use standard electronic components, developing such an infrastructure should not be prohibitively expensive.

Ford has recently announced the largest order for electric vehicles in history. The U.S. Postal Service ordered 500 electric Ford Rangers and has an option to order 6,000 more. The bulk of the electric postal vehicles will be used for mail delivery in California, with the remainder going to the Washington, D.C. area. Affordability was an issue to the Postal Service. Incentive dollars from New York, the Washington, D.C. area, California, the federal government and various utilities made the order palatable to the Postal Service. [48]

Despite their disadvantages electric cars are attractive because they produce zero emissions. No other emission reduction technology can make that claim. Wide spread deployment of electric vehicles would result in dramatic reductions in emissions. However, the electricity used to charge electric car batteries must be generated somewhere. The increased demand put on the electrical grid by electric vehicles could result in greater emissions from electric power plants. However, emissions from fixed sources, such as power plants, are generally easier to control than mobile source emissions. Also, power plants can be located away from urban areas where air pollution is a significant problem.



## 2) Fuel Cells

Fuel cells are devices that use a chemical reaction to generate electricity. Using a catalyst (typically platinum) fuel cells combine hydrogen and oxygen to form water. This chemical reaction results in significant levels of electrical energy. Fuel cells produce up to 800 times the amount of energy of conventional batteries of the same size and weight. Also, fuel cells do not wear out, as long as hydrogen and oxygen are available they will continue to generate electricity. [38] [39]

Fuel cells were first demonstrated in 1839, but their technical difficulties kept them from being used until the 1960s when NASA employed small and very expensive fuel cells on its spacecraft. [38] In addition to NASA's use of fuel cells, these devices have recently been used successfully as large stationary generators. [40]

Currently, most major auto manufactures have programs for developing fuel cell powered vehicles. DaimlerChrysler and General Motors both claim they will make some passenger cars for the mass market by 2004. [41] Ford has demonstrated fuel cell vehicles that use methanol to manufacture hydrogen onboard. [42] Honda claims it will be selling fuel cell based vehicles by 2003. [43]

Widespread deployment of fuel cells is inhibited by two principal technical problems: the expense of materials (e.g. platinum) and obtaining a practical delivery system for hydrogen. These problems are exacerbated when designing fuel cells that are small, light, and inexpensive enough for use in automobiles.

Vehicle fuel cells can employ various chemicals as an electrolyte, the material that electrically connects the electrodes inside the cell. To reduce electrical resistance fuel cells employ electrolytes that are highly alkaline or highly acidic. Alkaline fuel cells were first used to power a prototype vehicle in 1959. However, alkaline fuel cells were considered impractical since they require pure hydrogen. Most fuel cell vehicle concepts involve creating hydrogen onboard the vehicle from a source such as natural gas. This process creates hydrogen mixed with carbon dioxide, which will contaminate alkaline-based fuel cells. [41]

Acidic electrolytes are insensitive to carbon dioxide, but have their own problems. Most acids require liquid water to conduct hydrogen ions, so cells must operate at temperatures below the boiling point of water. Operating at such low temperatures dramatically reduces the efficiency of fuel cells. This problem was overcome through the use of phosphoric acid that can operate effectively at high temperatures. Fuel cells that use phosphoric acid have been in use powering hospitals and hotels since the early 1990s. They have also been used to power city buses, but since they require several hours to warm up before use their applications in consumer vehicles are limited. [41]

The proton-exchange membrane fuel cell is now seen as the most practical form of fuel cell for vehicular use. These fuel cells employ synthetic acids as electrolytes and require the use

of platinum as a catalyst. The high cost of platinum is the principal constraint on the deployment of these devices. [41]

The amount of platinum needed for these devices has fallen sharply since the 1980s. In 1986 proton-exchange fuel cells required 16 grams of platinum for each kilowatt of power produced (a kilowatt is roughly equivalent to 1.3 horsepower.) At current prices 16 grams of platinum would cost \$180. Since 1986 researchers have reduced the necessary amount of platinum by 30 times. Modern proton-exchange fuel cells require about \$6 to \$8 worth of platinum per kilowatt produced. Researchers expect to be able to halve that amount, but do not expect to be able to reduce it any further than that. [41]

In order for fuel cells to ever be widely used in vehicles, improvements will have to be made in the onboard systems for either storing or manufacturing hydrogen. If hydrogen gas were to be delivered to vehicles in its pure form an entirely new network of hydrogen refueling stations would have to be developed. Hydrogen with an energy equivalent of a gallon of gasoline could be produced for less than \$1.50. Since fuel cell vehicles would be more than twice as efficient as gasoline powered vehicles the per mile vehicle fuel cost would be extremely low. The challenge is to design a system that would allow cars to carry the requisite amount of hydrogen. Although hydrogen is quite light it is very voluminous. The hydrogen necessary to drive a car 250 miles would weigh only about six pounds, but would take up the space of several normal sized cars. Manufactures, such as Ford, are working on pressurized systems that may reduce the volume requirements substantially. Recent experimental results indicate that carbon nanofibers may be used to store sufficient amounts of hydrogen gas in a relatively small volume. [41]

Instead of delivering pure hydrogen to the vehicle, many manufactures are developing systems to manufacture hydrogen onboard. Methanol or gasoline could be converted into hydrogen on board vehicles with little difficulty. Such systems would result in ultra low emission vehicles, not zero emission vehicles, because the onboard processing of the fuel will create some pollutants. [41]

DaimlerChrysler and General Motors agree that a methanol based system is the best alternative to pure hydrogen. However, a methanol based system would require an extensive delivery infrastructure. Methanol systems would work best with phosphoric acid based fuel cells. Manufactures are also developing systems to convert gasoline into hydrogen on board vehicles. Such systems would require gasoline that is free of sulfur. [41]

Even though fuel cells are highly efficient, when the energy expended to convert methanol or gasoline into hydrogen is taken into consideration the overall efficiency of fuel cell vehicles is less than the efficiency of hybrid gasoline-electric vehicles. [41]

Hybrid fuel cell vehicles are also being considered. Such vehicles would employ batteries and fuel cells. This would allow for the use of regenerative braking systems (see below) and the battery could provide power at startup if the fuel cell requires a warm up period. [41] However, no manufactures currently have plans to produce such a vehicle.

### 3) Hybrid Vehicles

Hybrid vehicles use both an electric motor and a gasoline engine. To understand the advantage of such a system consider a car traveling down a level highway at a constant speed. In this case the car's engine is doing three things: it is overcoming rolling resistance in the drive train, it is overcoming air resistance, and it is powering accessories like the alternator and air conditioner. The engine could handle this load with only 10 to 20 horsepower. Cars generally have engines rated at between 100 and 200 horsepower because additional power is needed for acceleration from a standing stop, passing, and hill climbing. The maximum horsepower is typically used for only 1% of driving time. [44] The rest of the time cars must carry the weight of the larger engine, which wastes energy.

The traditional hybrid vehicle concept was a complete electric car with an electric motor that provides *all* of the power to the wheels. Batteries are needed to supply the motor with electricity. The car also has a completely separate gasoline engine *powering a generator*. The engine is very small - perhaps 10 to 20 horsepower - and it is designed to run at just one speed for maximum efficiency. The purpose of this small, efficient engine is to provide enough power for the electric motor at cruising speed. During acceleration, the batteries provide the extra power necessary. When the car is decelerating or standing still, the batteries recharge. The problem with this concept is weight. The car has to carry the weight of the electric motor, the generator, the gasoline engine and the batteries. This can cut back significantly on the efficiency of the vehicle. [44]

Hybrid cars that are currently in production attempt to strike a compromise between weight and engine efficiency. Honda's Insight, for example, uses a larger gasoline engine that is connected directly to the drive train along with a small electric motor attached to the engine. The gasoline engine provides most of the car's power, with the electric motor adding extra power when needed for acceleration. Because the electric motor can double as a generator during braking and only has to run part of the time, it is extremely light. The disadvantage of this approach is that the gasoline engine must run at varying speeds, which reduces its efficiency. [44] [45]

The Honda Insight is the first hybrid vehicle to go on sale in the U.S. This vehicle went on sale in December of 1999 and Honda plans to sell 4000 of them in the U.S. annually. With an MSRP close to \$20,000 the Insight is affordable. However, it is highly likely that these vehicles are being sold at a loss. [45] The Insight is a small two-seat vehicle and it is the most fuel-efficient gas powered production vehicle in the world with estimated miles per gallon of 61 for city streets and 70 for highways. The Insight's batteries never need to be recharged; the vehicle only needs to be refueled with gasoline. Although the Insight is not a zero emission vehicle it does meet California's Ultra Low Emission Vehicle standard. [46]

The Insight is a comfortable car that performs as well as most comparable gasoline powered cars. [45] The Insight employs many innovative features such as regenerative braking. When the vehicle is coasting in gear or the brakes are applied, the electric motor acts as a generator, capturing mechanical energy otherwise lost in engine or brake heat. This energy is

used to recharge the battery. [45] For added efficiency the Insight also employs an “idle stop” feature that shuts the gas engine off whenever the car comes to a stop. The engine is restarted instantly when the accelerator is pushed (essentially the electric motor acts as a giant starter.) [45]

Because the Insight employs a very lean air-fuel mixture an nitrogen oxide *adsorptive* catalyst is used. [45] As discussed in Chapter 2 nitrogen oxide absorbers collect nitrogen oxide molecules during lean-mix running and then releases them during rich-mix cycles to mingle with hydrocarbons and carbon monoxide, forming water, carbon dioxide, and nitrogen.

Later this year, Toyota plans to introduce a hybrid vehicle, the Prius, to the U.S. The Prius is already available in Japan. The Prius is expected to be larger than the Insight, with room for four passengers, but it is also expected to display poorer acceleration. [45] The Prius should have the same emissions characteristics as the Insight.

Ford, GM, and DaimlerChrysler all have conducted research on Hybrid vehicles and may produce them over the next several years. Ford claims that its hybrid vehicle is superior in many ways to those discussed above, but no production date is set. [47]

Hybrid vehicles represent a compromise between the emission benefits of pure electric vehicles and the practicality of traditional gasoline powered vehicles. Hybrid vehicles could potentially offer substantial emissions benefits. However, it has not been demonstrated that hybrid vehicles can be sold at a profit. Therefore, their future is uncertain.

## VI. Natural Gas and Other Alternative Fuels

Using alternative fuels, such as natural gas to fuel vehicles, has commonly been thought of as an effective means of reducing emissions. Many municipal and other governments use alternatively fueled vehicles for their fleets and for public transit. They have justified the additional cost of these vehicles by citing their emissions benefits. While it is true that alternatively fueled vehicles have had more favorable emissions characteristics than gasoline powered vehicles, that may be changing. As Chapter 2 detailed, the emissions of gasoline powered vehicles are likely to decrease dramatically over the next several years. Of the thirty model year 2000 vehicles that the California Air Resources Board (CARB) certified as Ultra Low Emissions Vehicles only two are powered by an alternative fuel (compressed natural gas), one is Honda's electric/gasoline hybrid, and the other 27 are gasoline powered. Five of the seven model year 2000 vehicles that the CARB certified as Super Ultra Low Emissions Vehicles are powered by compressed natural gas. The other two are gasoline powered. [46] So while alternative fuels do have emissions benefits, gasoline can run just as clean. As more gasoline powered vehicles begin to operate with extremely low emissions levels, the need for alternatively fueled vehicles will decrease.

### 1) Natural Gas

Natural gas is a mixture of hydrocarbons—mainly methane (CH<sub>4</sub>)—and is produced either from gas wells or in conjunction with crude oil production. Natural gas is consumed in the residential, commercial, industrial, and utility markets. The interest for natural gas as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end-users. Because of the gaseous nature of this fuel, it must be stored onboard a vehicle in either a compressed gaseous state (CNG) or in a liquefied state (LNG). [49]

Most natural gas consumed in the United States is domestically produced. Gas streams produced from reservoirs contain natural gas liquids and other materials. Processing is required to separate the gas from petroleum liquids and to remove contaminants. First, the gas is separated from free liquids such as crude oil, hydrocarbon condensate, water, and entrained solids. The separated gas is further processed to meet specified requirements. For example, natural gas for transmission companies must generally meet certain pipeline quality specifications with respect to water content, hydrocarbon dewpoint, heating value, and hydrogen-sulfide content. A dehydration plant controls water content; a gas processing plant removes certain hydrocarbon components to hydrocarbon dewpoint specifications; and a gas sweetening plant removes hydrogen sulfide and other sulfur compounds (when present). [49]

Natural gas is distributed throughout the United States in extensive pipeline systems that extend from the well-head to the end user. Every continental state has access to natural gas through pipelines. The pipeline system consists of long-distance transmission systems, followed by local distribution systems. Some underground storage is also used to help supply seasonal peak needs. [49]

According to the California Energy Commission, costs for a "slow fill" system or "quick fill" system to handle public or private fleets can cost \$250,000 or as much as \$3 million for a bus fleet. A compressor station typically costs \$2,000 to \$4,000 per vehicle served. Refueling can be done easily by trained drivers. Costs for a compressor for use with a single vehicle in private homes averages about \$3,500. Individual home compressors use a slow-fill system for overnight refueling. The small compressor would usually be located in a home's garage area and would be connected directly to the natural gas supply in the house. [49]

Exhaust emissions from natural gas vehicles (NGVs) are much lower than those from *conventional* gasoline-powered vehicles. The Natural Gas Vehicle Coalition claims that natural gas vehicle emissions of carbon monoxide are approximately 70% lower, non-methane organic gas emissions are 89% lower, and oxides of nitrogen emissions are 87% lower than those of gasoline powered vehicles. Compared to diesel engines, natural gas vehicles produce only tiny amounts of particulate matter. In addition to these reductions in pollutants, natural gas vehicles also emit significantly lower amounts of greenhouse gases and toxins than do gasoline vehicles. [50]

Dedicated natural gas vehicles produce little or no evaporative emissions during fueling and use. For gasoline vehicles, evaporative and fueling emissions account for at least 50% of a vehicle's total hydrocarbon emissions. Dedicated natural gas vehicles also can reduce carbon dioxide exhaust emissions by almost 20%. [50]

About 80,000 natural gas vehicles are operating in the United States today, dwarfed by more than 200 million gasoline and diesel vehicles. Most natural gas vehicles are fueled at some 1,225 compressed natural gas stations throughout the United States, a number that has increased four-fold since 1991. Natural gas vehicles are the most commercially advanced of the alternatively fueled vehicles (which, in addition to natural gas vehicles, includes those powered by methanol, ethanol, propane and electricity). [51]

Fleet vehicles in areas with air quality concerns offer the most promise. The benefits of natural gas vehicles are most pronounced in congested urban areas that have air quality concerns, and federal, state and local organizations have recognized the potential benefits of natural gas vehicles in these areas. Promotional federal initiatives include the Clean Air Act, the Clean Cities Program, the Congestion Mitigation Air Quality Program, the Energy Policy Act and the Advanced Natural Gas Vehicle Program. A number of factors make fleet vehicles — buses, taxis, delivery vehicles — the prime target for natural gas. Because natural gas generally costs less than gasoline, these high-mileage vehicles can realize large savings in fuel costs. Also, fleet vehicles tend to be centrally located. Thus, fleets can locate near refueling stations, or they can install their own facility. [51]

In addition to their emissions benefits, natural gas vehicles reduce the nation's extreme dependence on imported oil, and the fuel cost is generally less than the cost of gasoline or diesel fuel. Despite these benefits and the fact that a survey of fleet operators by the Natural Gas Vehicle Coalition showed that natural gas vehicles are their favorite type of alternatively fueled vehicle, market growth for these vehicles has not been dramatic. The primary obstacle is that vehicle production levels are limited, making the purchase price of a natural gas vehicle higher

than the price of a comparable conventionally fueled vehicle. Even for high-mileage vehicles, it is difficult to offset the extra thousands of dollars on a natural gas vehicle's price tag with the savings in fuel costs of 10 to 20 cents per gallon. Once the demand for natural gas vehicles reaches a level that can sustain full production, prices will fall. Currently, the natural gas fueling infrastructure also is limited, but the fueling infrastructure will expand as natural gas vehicles gain in popularity. [51]

## **2) Biodiesel**

Biodiesel (mono alkyl esters) is a cleaner-burning diesel fuel made from natural, renewable sources such as vegetable oils. Just like petroleum diesel, biodiesel operates in combustion-ignition engines. Essentially no engine modifications are required, and biodiesel maintains the payload capacity and range of diesel. [49]

The use of biodiesel in a conventional diesel engine results in substantial reduction of unburned hydrocarbons, carbon monoxide, and particulate matter. Emissions of nitrogen oxides are either slightly reduced or slightly increased depending on the duty cycle and testing methods. The use of biodiesel decreases the solid carbon fraction of particulate matter (since the oxygen in biodiesel enables more complete combustion to CARBON DIOXIDE), eliminates the sulfate fraction (as there is no sulfur in the fuel), while the soluble, or hydrocarbon, fraction stays the same or is increased. Therefore, biodiesel works well with new technologies such as catalysts (which reduces the soluble fraction of diesel particulate, but not the solid carbon fraction), particulate traps, and exhaust gas recirculation (potentially longer engine life due to less carbon). [49]

Biodiesel fuel can be made from new or used vegetable oils and animal fats. It is biodegradable, requires minimal engine modification when used either as a blending component or as is, and is potentially cleaner burning than the diesel it replaces. Vegetable oils can be chemically reacted with an alcohol (methanol is the usual choice) to produce chemical compounds known as esters. Biodiesel is the name given to these esters when they are intended for use as fuel. Glycerol (used in pharmaceuticals and cosmetics, among other markets) is produced as a co-product. [49]

Much of the current interest in biodiesel production comes from soybean producers faced with an excess of production capacity, product surpluses, and declining prices. Methyl soyate, or SoyDiesel, made by reacting methanol with soybean oil, is the main form of biodiesel in the United States. [49]

Waste animal fats and used frying oil (known as 'Fellow grease') are also potential feedstocks. These are cheaper than soybean oil and are being considered as a way to reduce feedstock costs. Peanuts, cottonseed, sunflower seeds, and canola (a variant of rapeseed) are other candidate oil sources. Esters made from any of these sources can be used successfully in diesel engines, although they may differ slightly in terms of energy content, cetane number (analogous to gasoline's octane rating in terms of engine performance), or other physical properties. [49]

Biodiesel is relatively unknown and faces several barriers to gaining widespread commercial use. Biodiesel must overcome a number of regulatory obstacles, and its price must become more competitive, before it will make any significant market penetration. According to the American Biofuels Association, with Government incentives comparable to those provided for ethanol, biodiesel production from seed oils could reach about 2 billion gallons per year, or about 8% of highway diesel consumption early in the twentyfirst century. At this level of market penetration, biodiesel would probably be used as a fuel mostly in bus fleets and heavy-duty trucks (primarily in blends with fossil diesel at the 20% level). [49]

Methyl soyate currently costs over \$2 per gallon and seeks to compete with diesel which costs 65 to 70 cents per gallon. Feedstock costs account for over 90% of direct production costs, including cost of capital and return on capital. It takes about 7.3 pounds of soybean oil, for example, costing about 20 cents per pound, to produce a gallon. Feedstock costs alone, therefore, are at least \$1.50 per gallon of methyl soyate, not counting marketing and overhead expenses and profit. Efforts are ongoing to try to reduce feedstock costs by developing soybean hybrids with higher oil content. Soybeans, for example, contain about 20% oil, whereas some other oil seeds contain as much as 50% oil. The rapeseed used in Europe has an oil content of about 40%. [49]

The use of biodiesel in a conventional diesel engine results in substantial reduction of unburned hydrocarbons, carbon monoxide, and particulate matter. Emissions of nitrogen oxides are either slightly reduced or slightly increased depending on the duty cycle and testing methods. Particulate emissions from conventional diesel engines can be divided into three components. Each component is present in varying degrees depending on fuel properties, engine design and operating parameters. [52]

The first component, and the one most closely related to the visible smoke often associated with diesel exhaust, is the carbonaceous material. This material is in the form of sub-micron sized carbon particles which are formed during the diesel combustion process and is especially prevalent under conditions when the fuel-air ratio is overly rich. This can occur as a result of insufficient combustion air, overfueling or poor in-cylinder fuel-air mixing. The second component is hydrocarbon material which is absorbed on the carbon particles, commonly referred to as the soluble fraction. A portion of this material is the result of incomplete combustion of the fuel, and the remainder is derived from the engine lube oil. Finally, the third particulate component is comprised of sulfates and bound water. The amount of this material is directly related to the fuel sulfur content. [52]

The use of biodiesel decreases the solid carbon fraction of particulate matter (since the oxygen in biodiesel enables more complete combustion to CARBON DIOXIDE), eliminates the sulfate fraction (as there is no sulfur in the fuel), while the soluble, or hydrocarbon, fraction stays the same or is increased. Therefore, biodiesel works well with new technologies such as catalysts (which reduces the soluble fraction of diesel particulate, but not the solid carbon fraction), particulate traps, and exhaust gas recirculation (potentially longer engine life due to less carbon). [52]



### **3) Hydrogen**

Hydrogen gas (H<sub>2</sub>) is being explored for use in combustion engines and fuel-cell electric vehicles. It is a gas at normal temperatures and pressures, which presents greater transportation and storage hurdles than exist for the liquid fuels. Storage systems being developed include compressed hydrogen, liquid hydrogen, and chemical bonding between hydrogen and a storage material (for example, metal hydrides). While no transportation distribution system currently exists for hydrogen transportation use, the ability to create the fuel from a variety of resources and its clean-burning properties make it a desirable alternative fuel. [49]

Two methods are generally used to produce hydrogen: (1) electrolysis and (2) synthesis gas production from steam reforming or partial oxidation. Electrolysis uses electrical energy to split water molecules into hydrogen and oxygen. The electrical energy can come from any electricity production sources including renewable fuels. It is unlikely that electrolysis will become the predominant method for large quantities of hydrogen production in the future. The predominant method for producing synthesis gas is steam reforming of natural gas, although other hydrocarbons can be used as feedstocks. For example, biomass and coal can be gasified and used in a steam reforming process to create hydrogen. [49]

A distribution system for hydrogen as a transportation fuel does not exist. While pipeline transportation is generally the most economic means of transporting gaseous fuels, a pipeline system is currently not in place. Transportation of hydrogen is typically in canisters and tanker trucks. [49]

### **4) Liquefied Petroleum Gas (LPG)**

Liquefied petroleum gas (LPG) consists mainly of propane, propylene, butane, and butylene in various mixtures. However, for all fuels in the United States, the mixture is mainly propane. It is produced as a by-product of natural gas processing and petroleum refining. The components of LPG are gases at normal temperatures and pressures. LPG, like natural gas and unlike gasoline, is a simple mixture of hydrocarbons, mainly propane/propylene (C<sub>3</sub>S) and butane/butylene (C<sub>4</sub>S). [49]

LPG is a by-product from two sources: natural gas processing and crude oil refining. Most of the LPG used in the United States is produced domestically. When natural gas is produced, it contains methane and other light hydrocarbons that are separated in a gas processing plant. The natural gas liquid components recovered during processing include ethane, propane, and butane, as well as heavier hydrocarbons. Propane and butane, along with other gases, are also produced during crude refining as a by-product of the processes that rearrange and/or break down molecular structure to obtain more desirable petroleum compounds. [49]

More than 350,000 vehicles, mostly in fleets, are traveling the nation's highways under propane power. Propane is powering taxis in Las Vegas; school buses in Kansas City and Portland, Oregon; sheriff and police cars in other communities; and in dozens of fleets around California. Propane is used in both light- and medium-duty vehicles. Estimates have placed the

number of registered vehicles in California that are powered by propane as high as 40,000. Propane has been used as a transportation fuel around the world for more than 60 years. [49]

## **5) Methanol**

Methanol (CH<sub>3</sub>OH) is an alcohol fuel. Today most of the world's methanol is produced by a process using natural gas as a feedstock. However, the ability to produce methanol from non-petroleum feedstocks such as coal or biomass is of interest for reducing petroleum imports. [49]

The alternative methanol fuel currently being used is M-85. In the future, neat methanol, or M-100, may also be used. Methanol is also made into an ether, MTBE, which is blended with gasoline to enhance octane and to create oxygenated gasoline. [49]

Methanol is predominantly produced by steam reforming of natural gas to create a synthesis gas, which is then fed into a reactor vessel in the presence of a catalyst to produce methanol and water vapor. Although a variety of feedstocks other than natural gas can and have been used, today's economics favor natural gas. Synthesis gas refers to combinations of carbon monoxide (CO) and hydrogen while a large amount of synthesis gas is used to make methanol, most synthesis gas is used to make ammonia. As a result, most methanol plants are adjacent to or are part of ammonia plants. The synthesis gas is fed into another reactor vessel under high temperatures and pressures, where carbon monoxide and hydrogen are combined in the presence of a catalyst to produce methanol. Finally, the reactor product is distilled to purify and separate the methanol from the reactor effluent. [49]

Methanol will probably be transferred from import terminals or production facilities by barge, rail, or truck to eventually reach retail outlets. While the alcohol fuel is a liquid at ambient temperatures and atmospheric pressures, they cannot be moved easily through the existing petroleum product network. [49]

The California Energy Commission forecasts the M85 price in the year 2010 will be \$1.27 for a gasoline gallon equivalent, compared to gasoline priced at \$1.48 a gallon. Diesel fuel is forecast at \$1.24 a gallon. [49]

## VII. Long Term Projections

While making long term projections is always problematic, it is possible to develop a general view of the probable future of emissions in the Phoenix area. In order to keep this presentation manageable several simplifying assumptions will be made. Assumptions will tend toward being pessimistic, so that we will likely overestimate future traffic levels and underestimate rates of adoption of advanced emission control technologies, such as electric vehicles. Thus, the forecasts here represent a worst case scenario. This section is meant as a general guide to the probable future emissions characteristics in the Phoenix area, it is not meant as a precise forecast of future emissions.

### 1) Cars and Light Duty Trucks (LDTs)

This analysis will focus on vehicle emissions only; it will not attempt to deal with actual *levels* of pollutants in the air. While there is, of course, a correlation between the two, other factors such as the weather have a large impact on the actual amount of pollutants in the air at any given time. This analysis still produces valuable information since emissions are a key variable in determining pollutant levels and they are the only variable that we can control.

Data for this section were gathered from a variety of sources. First, we established the emissions characteristics of the current fleet. Table 1-1 in Chapter 1 summarized the achieved emissions standards for passenger vehicles (cars) through 1994 and the EPA's target for 2004 along with the EPA's estimated 1960 pre-control average. [2], [4] Table I-1 is reproduced below as Table VII-1. The assumption is made that the vehicle (car and light truck) fleet will actually produce the emissions in Table VII-1.

**Table VII-1, Auto Emission Standards, Grams of Emissions Produced per Mile Traveled<sup>13</sup>**

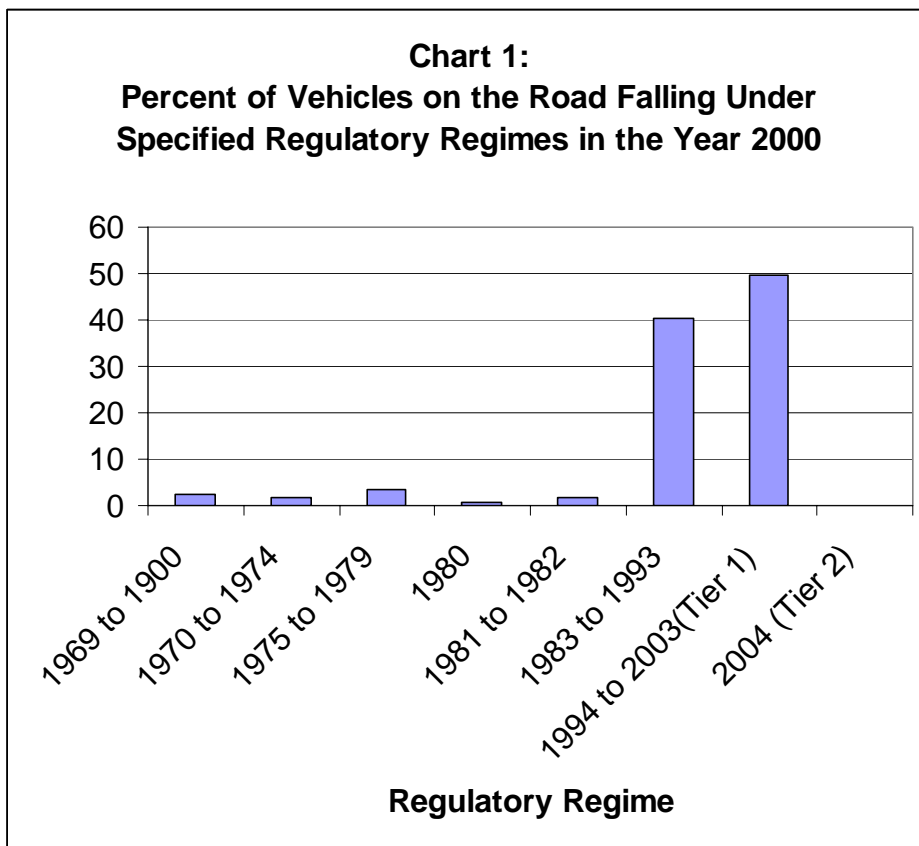
<b>Year</b>	<b>Hydrocarbons</b>	<b>Carbon Monoxide</b>	<b>Nitrogen Oxide</b>
1960	10.600	84.000	4.100
1970	4.100	34.000	5.000
1975	1.500	15.000	3.100
1980	0.410	7.000	2.000
1981	0.410	3.400	1.000
1983	0.410	3.400	1.000
1994 (Tier 1)	0.310	4.200	0.600
2004 (Tier 2)	0.125	4.200	0.200

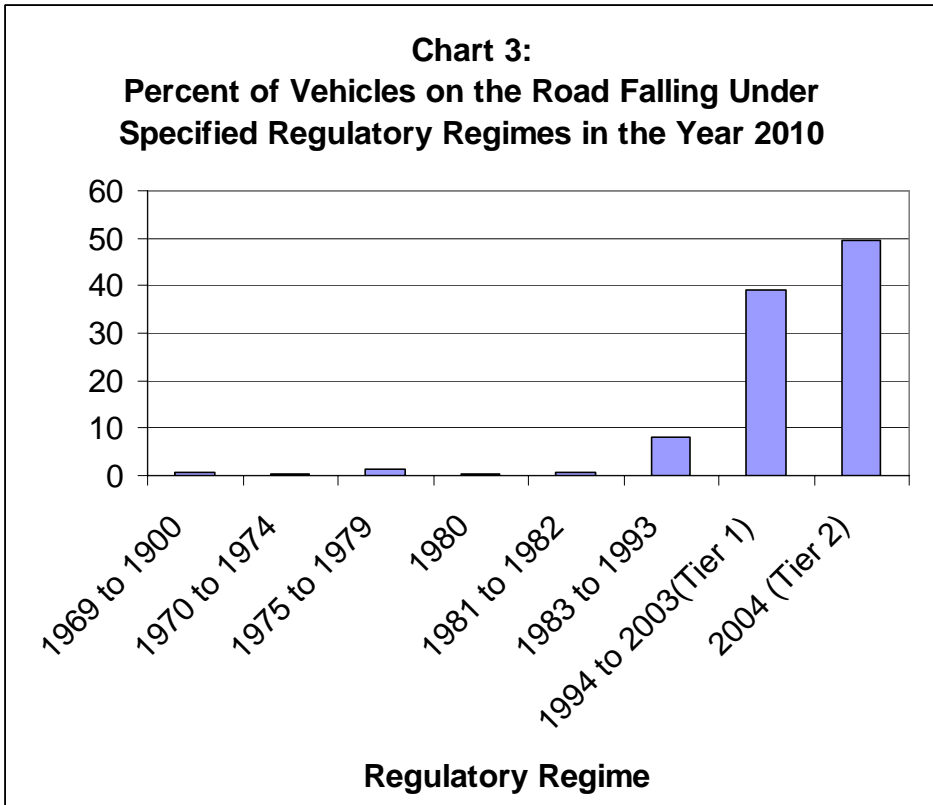
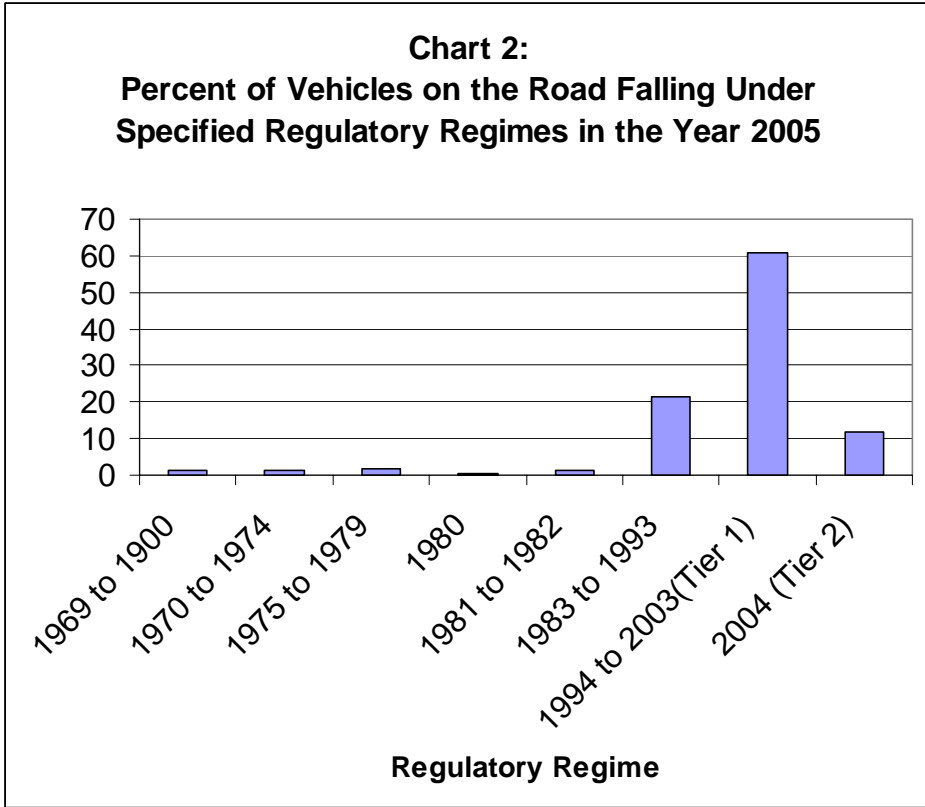
Historical information on particulate matter standards could not be obtained. Therefore we will assume that the passenger vehicle and LDT fleet for model years 2003 and earlier produces 0.07 grams of particulate matter per mile traveled. [15] Starting in 2004 the vehicle

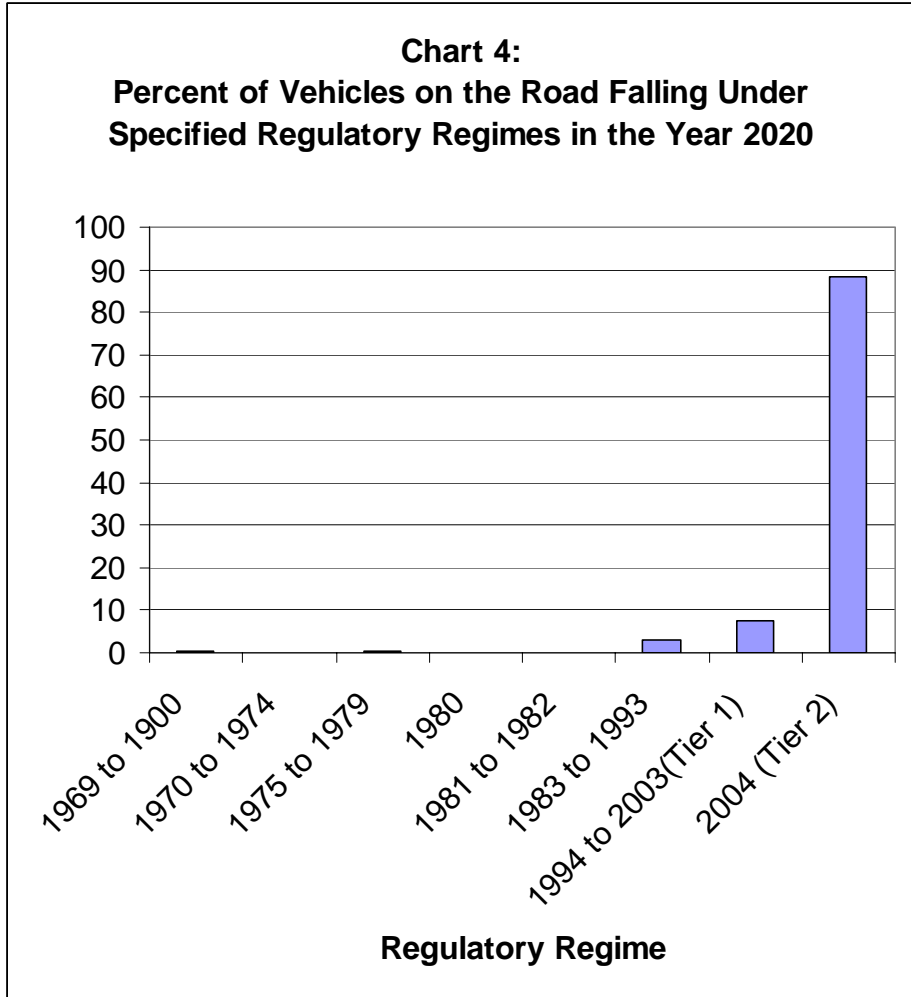
<sup>13</sup> 1970-1994 Standards are for cars only. The 2004 standard applies to cars and light trucks. The actual regulations are more complex than the table implies in that they allow trade-offs between the various types of pollutants. See section 86.1911-04 of the Code of Federal Regulations for more detail. The tier 1 and tier 2 standards must be attainable through the full life of the vehicle, specifically new vehicles must be able to attain the standards after 100,000 operating miles. More stringent standards must be met at 50,000 operating miles. The numbers for 1960 represent the EPA's estimated 1960 pre control average.

fleet must meet the Tier 2 standards of 0.01 or 0.02 grams per mile traveled. [4] We will make the pessimistic assumption that the fleet will have average particulate matter emissions of 0.015 grams per mile.

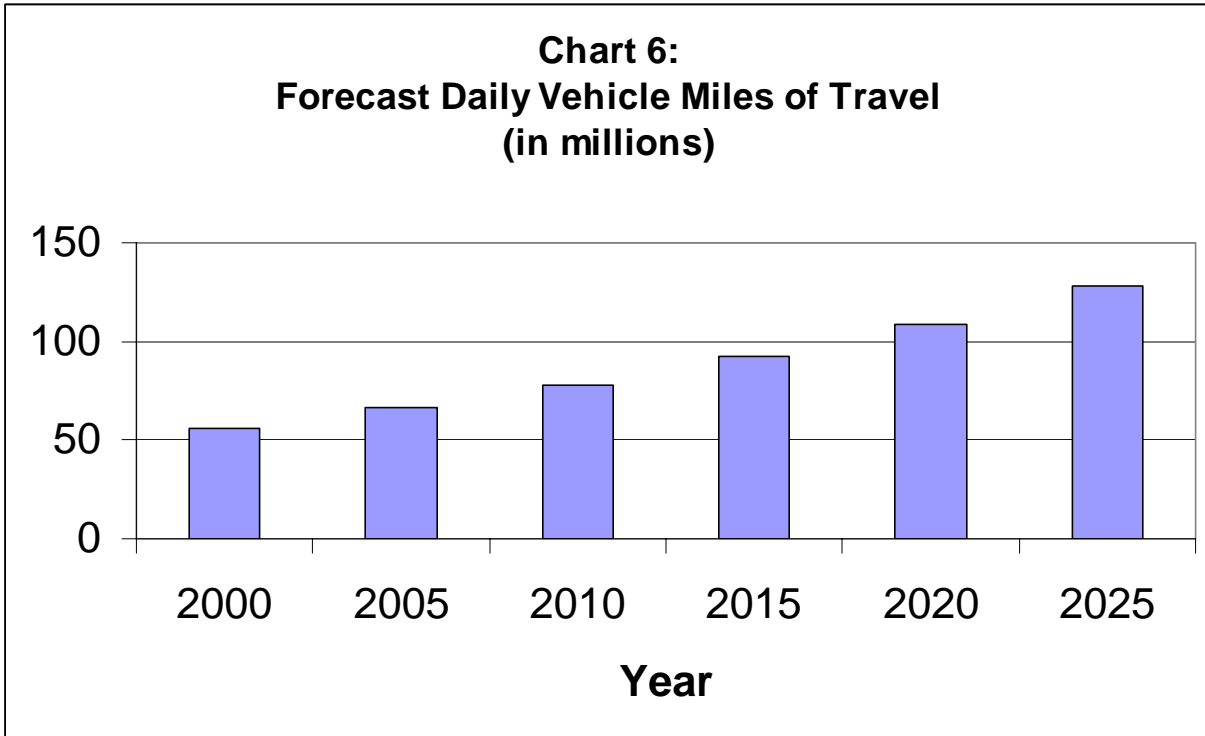
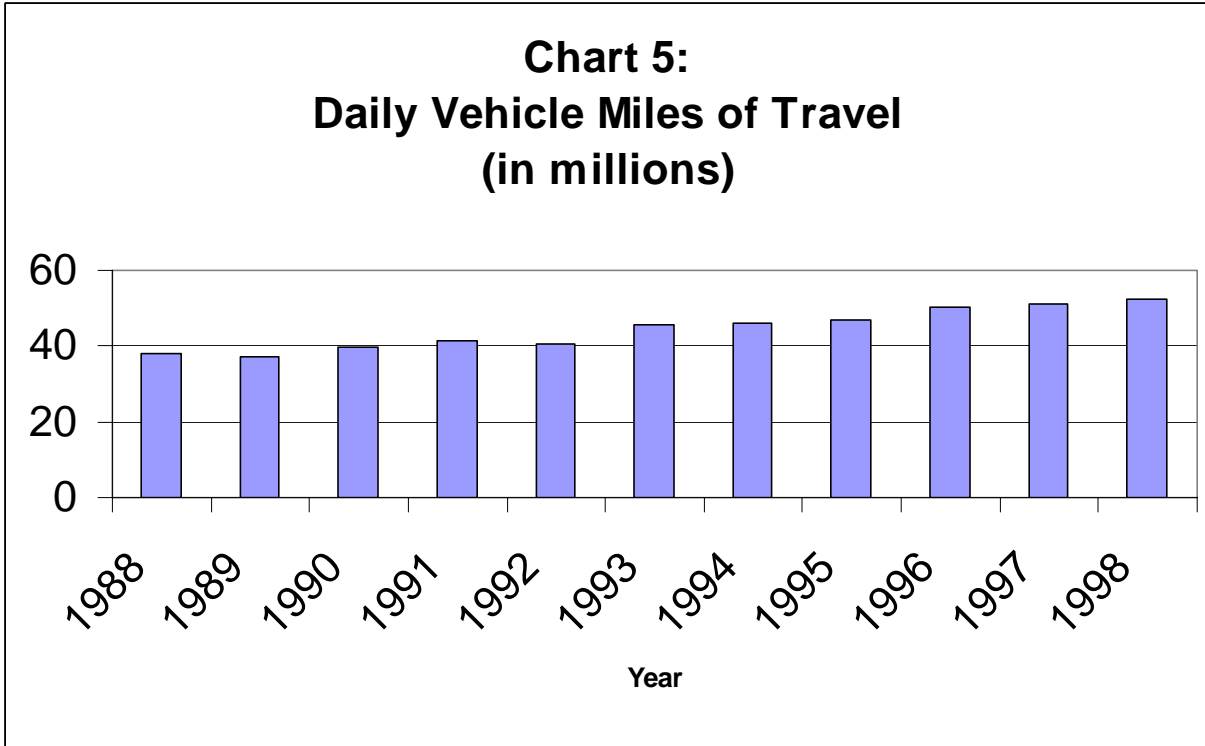
Next we needed to determine what percent of the current fleet falls into each of the model year categories in table VII-1. Vehicle counts by year are available from the ADOT Motor Vehicle Division and were used to determine the percent of the current passenger car fleet that falls within each of the model year categories. [53] Chart 1 illustrates the percent of the current fleet that falls within each of the model year categories. Assuming that the *relative* number of new and used vehicles will remain constant at the amounts illustrated in Chart 1, we can forecast the future composition of the vehicle fleet. Chart 2 (2005), Chart 3 (2010), and Chart 4 (2020) are examples of the results of these calculations.







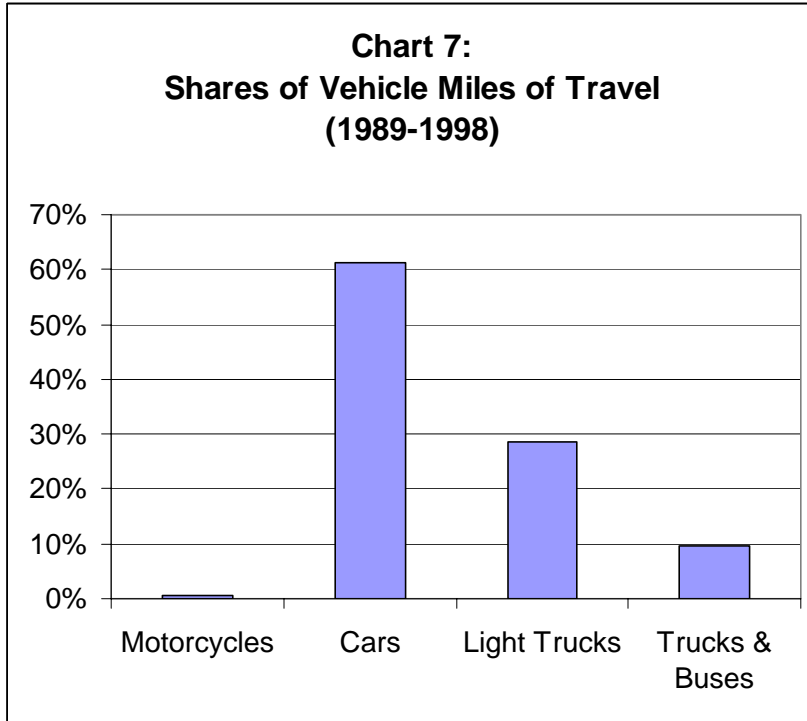
Next we needed to examine the daily vehicle miles traveled (VMTs) in the Phoenix area. Also, we needed to know how this travel is divided among the various types of vehicles. This is data that the ADOT collects. [54] Chart 5 illustrates the daily VMTs in thousands, in the Phoenix area, as calculated by the ADOT, from 1988 to 1998. Reviewing this data indicates that daily VMTs increased at an average annual rate of 3% over that ten-year period. This 3% growth rate in VMTs will be used to forecast future levels of daily VMTs. This 3% growth rate is higher than population forecasts for the Phoenix area, which tend towards 2.2% a year. [55] The assumption that VMTs will continue to grow at a 3% rate over the next twenty-five years is actually very pessimistic. It is unlikely that current growth levels can be maintained for the next twenty-five years. Chart 6 illustrates the forecast of daily VMTs in the Phoenix area based on a 3% growth rate.



The ADOT also collects data on what types of vehicles are responsible for the VMTs. [54] That data is summarized in Chart 7 and in Table VII-2.

**Table VII-2: VMTs by vehicle type (average over 1989 to 1998)**

<b>Motorcycles</b>	1%
<b>Cars</b>	61%
<b>Light Trucks</b>	29%
<b>Trucks &amp; Buses</b>	10%

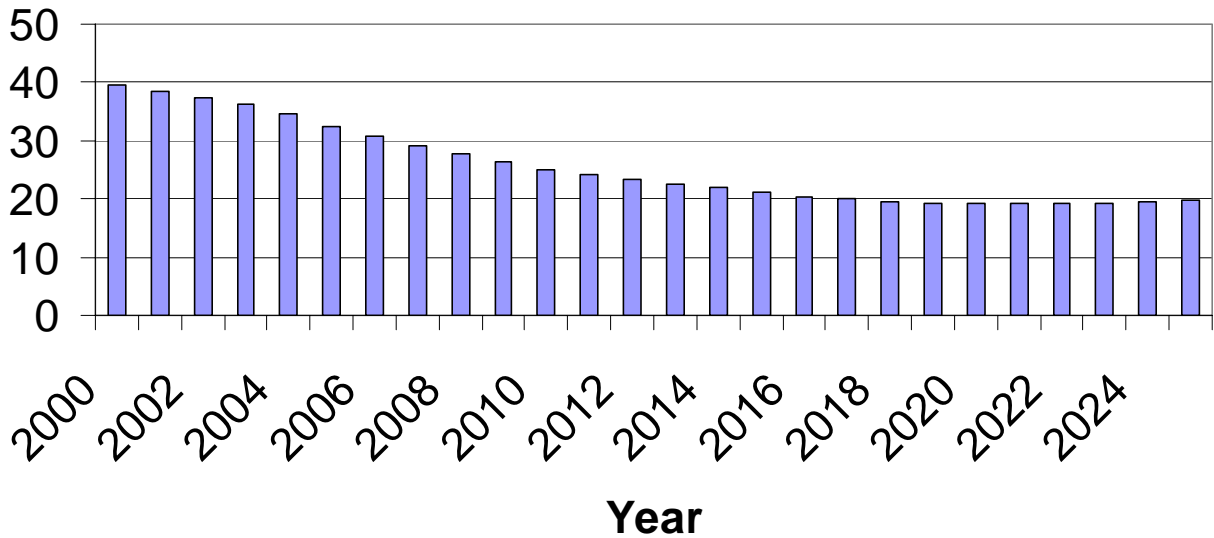


The assumption was made that cars and light trucks have the same emissions characteristics. This is not accurate for the current fleet (aside from Ford products), but starting in the 2004 model year cars and light trucks will be subject to the same emissions requirements. This assumption will understate current levels of emissions and thus understate any percentage reductions in emissions.

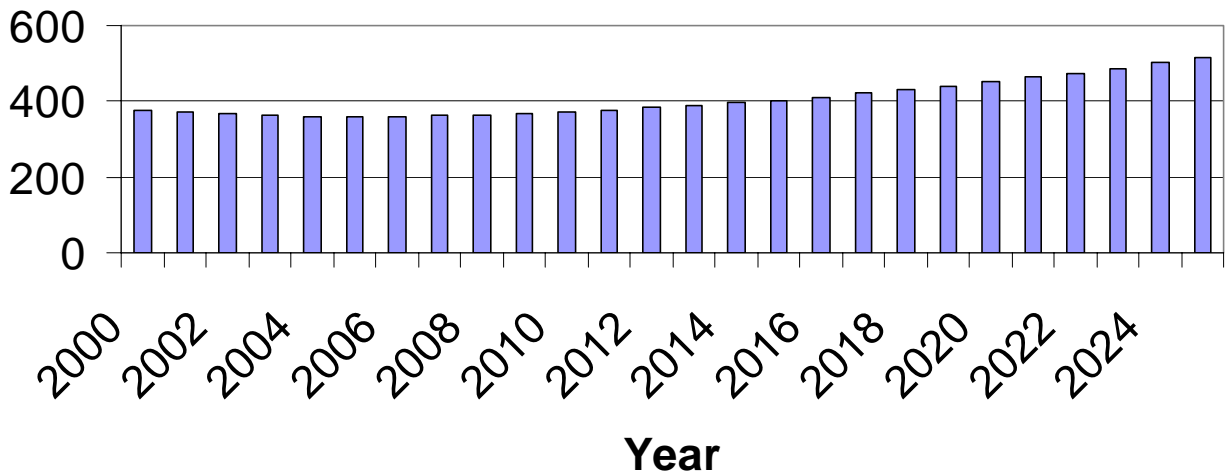
Using the emissions levels from Table VII-1, the fleet breakdowns illustrated in Charts 1 through 4, the daily VMT forecast in Chart 6, and recognizing that collectively cars and light trucks are responsible for 90% of daily VMTs future emissions levels can be forecast. Charts 8, 9, 10, and 11 illustrate the results of this analysis. This analysis clearly shows that we can expect drastic decreases in hydrocarbon, nitrogen oxide, and particulate matter emissions when the Tier 2 standards take effect. However, since the Tier 2 standards do not mandate reductions in carbon monoxide emissions, they are likely to rise considerably. However, as Chapter 2 detailed, new vehicle technologies will afford substantial reductions in carbon monoxide emissions. Thus, future strengthening of emissions standards could reduce carbon monoxide emissions considerably. Also, reduced future fuel sulfur levels would lead to substantial reductions in carbon monoxide (and the other emissions), but it is difficult to quantify this effect.



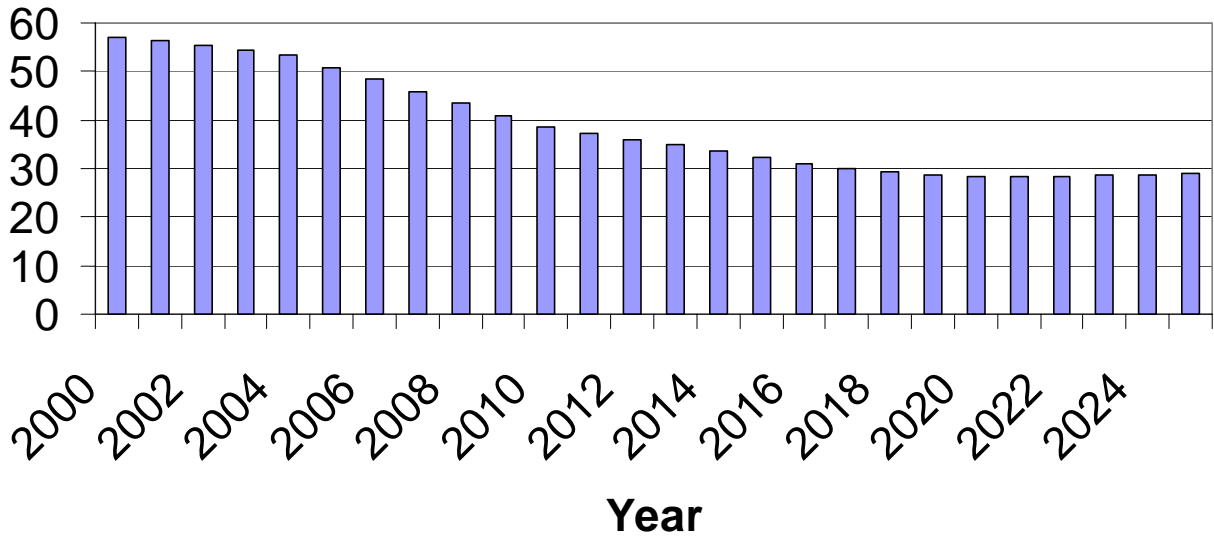
### Chart 8: Daily Tons of Hydrocarbons Emitted by Cars and Light Trucks



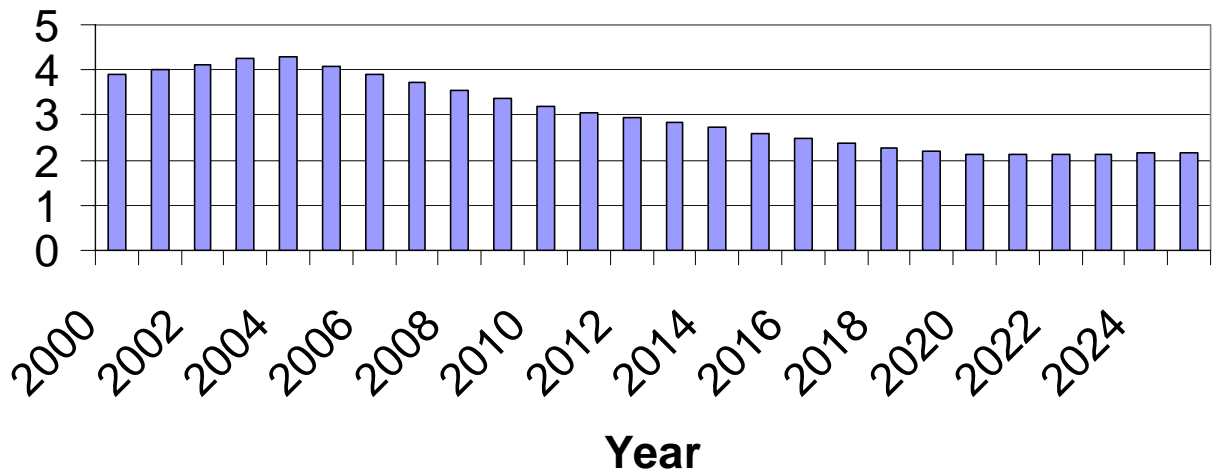
### Chart 9: Daily Tons of Carbon Monoxide Emitted by Cars and Light Trucks



### Chart 10: Daily Tons of Nitrogen Oxides Emitted by Cars and Light Trucks



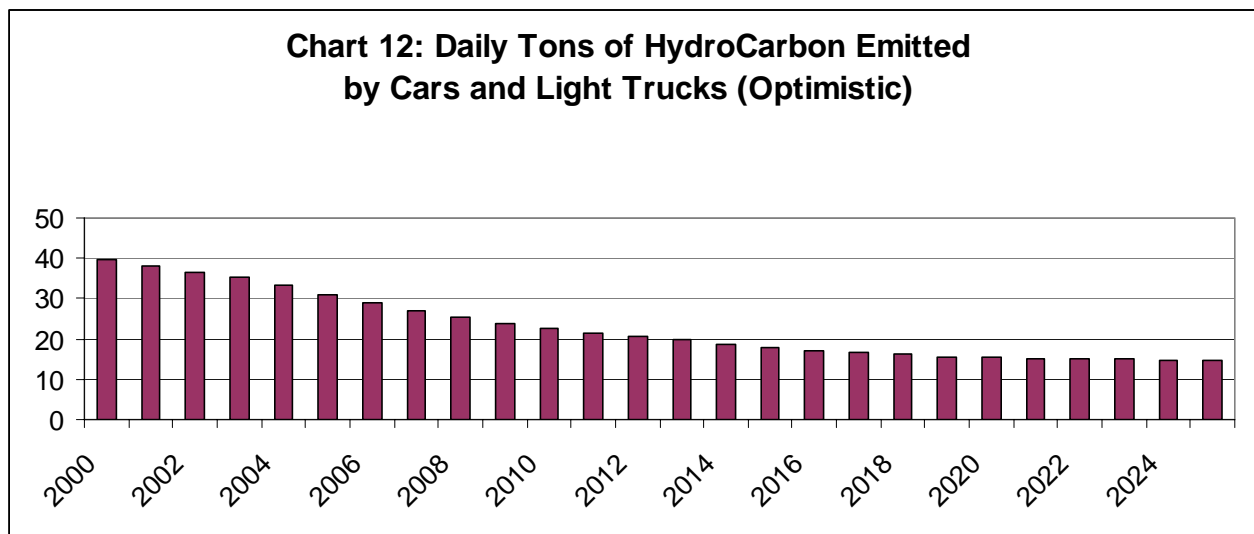
### Chart 11: Daily Tons of Particulate Matter Emitted by Cars and Light Trucks



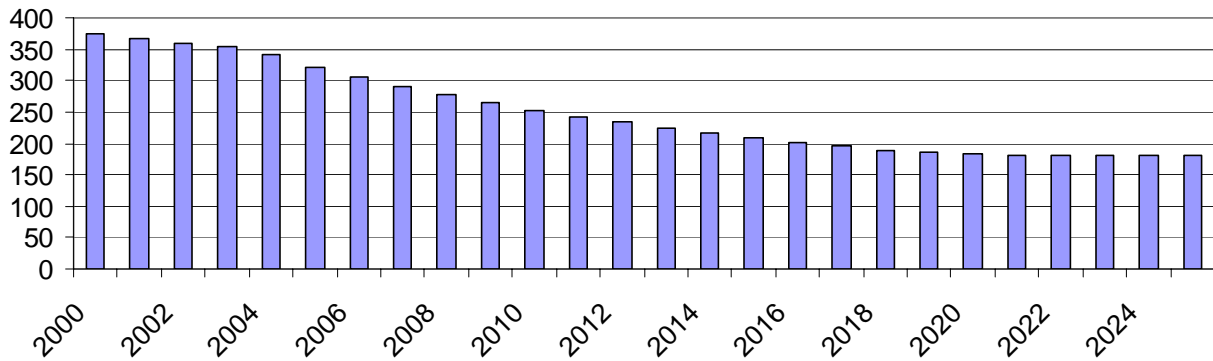
A more optimistic forecast was also calculated. This forecast was calculated in the same way as the pessimistic forecast except for two different assumptions:

- 1) The model year 2004 and later passenger vehicle fleets will obtain reductions in carbon monoxide of 60% compared to the tier 1 standard. That is, CO emissions for model year 2004 and later passenger vehicle are assumed to be 1.68. This assumption is justified by the EPA's findings outlined in Table 2.1.
- 2) It is assumed that starting in model year 2001, 1% of passenger vehicles are zero (or very close to zero) emission vehicles. This percentage is assumed to increase 1% every year thereafter. For model year 2002 2% of passenger vehicles are assumed to be zero emissions, 2003 3% etc. In 2025 25% of passenger vehicles are assumed to be zero emissions.

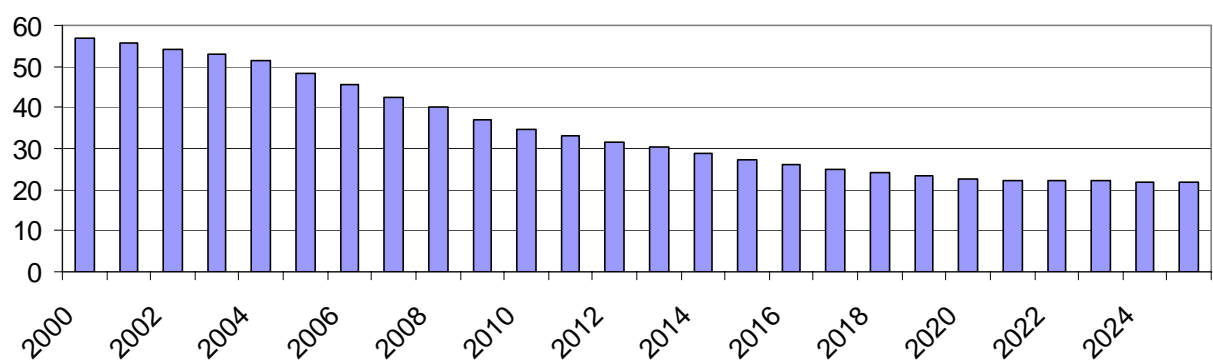
The results of the optimistic forecast are illustrated in charts 12-15. These results are actually very straightforward. The assumption concerning CO emissions results in reductions in CO emissions comparable to reductions in the other types of emissions. The assumption concerning zero emission vehicles (ZEVs) results in a linear reduction in each of the types of emissions. That is, when one percent of the fleet is assumed to be ZEVs, emissions of HC, CO, NOx, and PM are all reduced by 1% (relative to the pessimistic forecast). When ZEVs are assumed to comprise 25% of the fleet each type of emission is reduced by 25%.



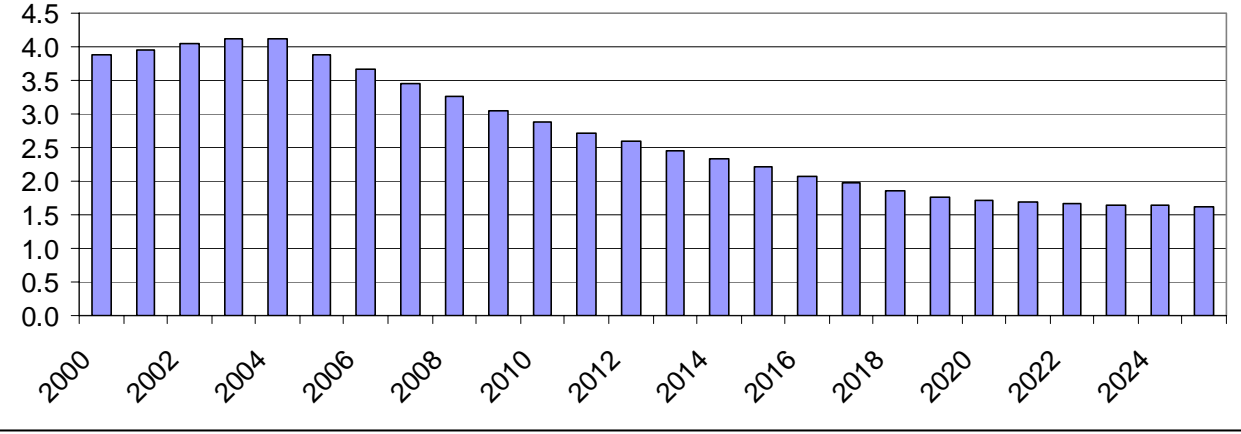
**Chart 13: Daily Tons of Carbon Monoxide Emitted  
by Cars and Light Trucks (Optimistic)**



**Chart 14: Daily Tons of Nitrous Oxide Emitted  
by Cars and Light Trucks (Optimistic)**



**Chart 15: Daily Tons of Particulate Matter Emitted  
by Cars and Light Trucks (Optimistic)**



## 2) Heavy-Duty Vehicles

Producing emissions forecasts for heavy duty vehicles in the same manner as was done for passenger vehicles above is not possible because federal emissions standards for heavy-duty vehicles are not expressed in terms of vehicle miles traveled. Also, future standards for heavy-duty vehicles are still uncertain. Table III-2 in Chapter 3 summarized current and proposed emissions standards for heavy-duty vehicles. Table III-2 is reproduced below as Table VII-3.

**Table VII-3 Current and Proposed Future Standards For heavy-duty Vehicles g/bhp-hr<sup>14</sup>**  
[16] [17]

<b>Model Year</b>	<b>hydrocarbon</b>	<b>carbon monoxide</b>	<b>nitrogen oxide</b>	<b>particulate matter</b>
1990	1.3	15.5	6.0	0.60
1998-2006	1.3	15.5	4.0	0.10
2007	1.3	15.5	0.5	0.01

Note: 2007 numbers are proposed.

Table VII-2 demonstrates that emissions of NO<sub>x</sub> and PM from new diesel trucks have been substantially reduced during the 1990s. The EPA's proposed standards for 2007 call for reductions of 87.5 percent and 90 percent for NO<sub>x</sub> and PM respectively. [16] [17] The proposed 2007 standards are likely to be unattainable without lowering the sulfur content of diesel fuel considerably. The EPA recently announced that it will impose a 15 parts per million sulfur standard for on-road diesel fuel by 2006. Further, once low sulfur diesel fuel is available the EPA will impose new standards for PM and NO<sub>x</sub>, although it is not yet clear what those standards will be. [57] As discussed in Chapters 3 and 4 dramatic reduction in PM and NO<sub>x</sub> will not be possible with dramatic reductions in diesel fuel sulfur content. The EPA's new diesel sulfur rule is not yet final, public hearings will be held, but it is likely that the new regulations will take effect. [57]

The proposed 2007 emission levels are technically obtainable once lower sulfur diesel fuel is available. If the proposed standards are attained we can expect a reduction in heavy-duty diesel emissions similar to that for gasoline engines discussed above. However, because diesel vehicles tend to last longer than gasoline vehicles, the diesel vehicle fleet will become cleaner at a slower pace.

## 3) Conclusion

Even under the most pessimistic assumptions, passenger vehicle emissions of three (hydrocarbon, nitrogen oxide, and particulate matter) out of the four major pollutants are likely to fall considerably over the next twenty-five years. Our summer ozone problem is caused by hydrocarbon and nitrogen oxide emissions and our winter "brown cloud" problem is attributed to particulate matter. Thus, two of Phoenix's major air pollution problems are likely to be mitigated substantially by the Federal Tier 2 standards.

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<sup>14</sup> Current particulate matter standards for urban buses are slightly less than those for trucks illustrated in table VII-3.

Emissions of carbon monoxide are forecast to rise over the next 20 years (in the pessimistic forecast). Phoenix has only recently come into compliance for carbon monoxide levels. Maintaining this compliance status is a major concern. So, the forecast increases in carbon monoxide emissions are a potential problem area that will require monitoring.

Significant reductions in diesel emissions are certainly technically feasible. Recently the EPA has taken significant steps towards reducing diesel emissions. A recent EPA announcement indicates diesel fuel sulfur content will be reduced significantly. If the EPA follows through, heavy-duty diesel vehicles may become significantly cleaner.

## **VIII. Policy Implications**

The preceding chapters demonstrate that dramatic reductions in vehicle emissions are possible and that those reductions can result from a variety of different technologies. Since so many different technologies can be effective and these technologies are constantly changing, policy makers should never mandate the adoption of a particular technology. Mandating a particular technology is likely to stifle research on other technologies that could have resulted in greater or more efficient emissions reduction. Any mandates that Arizona might consider should be based on emissions levels not on the promotion of particular technologies.

Policies that Arizona should consider include:

### **Incentives for ULEVs, SULEVs, and ZEVs**

In California electric vehicle users have been subsidized for some time. The amount of the subsidy depends on where the user lives. Arizona should consider adoption of a similar policy, not just for electric vehicles, but for all vehicles that meet California's standards for ultra low emission vehicles (ULEVs), super ultra low emission vehicles (SULEVs), and zero emissions vehicles (ZEVs). Such a policy will reward users of low emission vehicles without discriminating among them.

Recently, the Arizona legislature instituted a similar policy. However, the supply of ULEVs and ZEVs is so small in Arizona that many consumers simply can not utilize the subsidies. Given the dramatic reductions in emissions that ULEVs and ZEVs allow (see the differences between the optimistic and pessimistic forecasts in the previous chapter) Arizona should remain committed to encouraging their use. Perhaps tax credits that encourages dealers and manufactures to make ULEVs and ZEVs available in Arizona is appropriate. Also, Arizona's subsidy program for ULEVs and ZEVs needs to be aggressively publicized.

The success or failure of Arizona's ULEV/ZEV program will determine whether we experience the optimistic or the pessimistic forecasts from Chapter VII.

### **Retrofitting Diesel Engines**

Heavy-duty diesel vehicles contribute disproportionately to emissions of nitrogen oxide and particulate matter. Also, since diesel vehicles tend to last much longer than gasoline powered vehicles, the rate of replacement for diesel vehicles is lower than that of gasoline vehicles. Thus, introducing cleaner new diesel vehicles will not lower emissions as fast, or as economically, as is the case for gasoline powered vehicles. Older diesel vehicles can be retrofitted with emissions reducing equipment for a fraction of the cost of replacing the whole vehicle. Arizona could mandate that all older diesel vehicles operated by the state or other governments be retrofitted (if technically feasible). The State could also offer incentives, such as tax credits, for private owners of older diesel vehicles to retrofit. Private companies that operate heavy-duty diesel vehicles could be offered a variety of tax breaks in exchange for retrofitting their vehicles.



## **Diesel Sulfur Levels**

Chapters III and IV of this report indicated that truly clean heavy-duty diesel vehicles will require dramatically lower sulfur content in diesel fuel. Lower sulfur diesel fuel will not only allow for cleaner new vehicles, it will also cause existing vehicles to run cleaner. While the federal government has taken the lead on imposing standards for gasoline, it is still not clear whether federal standards for diesel fuel will be tightened. However, the EPA recently announced that it will require drastic reductions in diesel fuel sulfur content. [57] If the EPA's latest proposal falls through, Arizona should seriously consider joining California in requiring diesel fuel sold here to meet stringent sulfur content standards. According to the California Air Resources Board (CARB) diesel fuel sold in California is cleaner than that sold in any other state and the economic impact of the stricter standards has been minimal. [56] A CARB study indicates that even with the tighter sulfur content standard California diesel wholesale prices were similar to diesel wholesale prices in Arizona, Nevada, and Oregon. [56]

## Glossary of Acronyms

<b>ADOT</b>	Arizona Department of Transportation.
<b>CARB</b>	California Air Resources board.
<b>CNG</b>	Compressed Natural Gas.
<b>CO</b>	Carbon Monoxide, a toxic gas contained in auto emissions.
<b>CPSI</b>	Cells per square inch, refers to catalyst technology.
<b>EGR</b>	Exhaust gas recirculation, a method of reducing combustion temperatures, which leads to reduced nitrogen oxide emissions.
<b>EHC</b>	Electrically heated catalyst, used to mitigate the reduced performance of catalysts during “cold-start” conditions.
<b>EPA</b>	United States Environmental Protection Agency.
<b>ETBE</b>	Ethyl tertiary butyl ether, used as an oxygenate for gasoline.
<b>g/bhp-hr</b>	Grams per break horsepower hour.
<b>HC</b>	Hydro carbons, organic material contained in auto emissions. Also referred to as Volatile Organic Compounds (VOCs) and sometimes subdivided into Methane and Non-Methane Hydrocarbons (NMHC). HC is responsible for the formation of ozone.
<b>HEGO</b>	Heated exhaust gas oxygen (sensor), a type of oxygen sensor.
<b>LDT</b>	Light Duty Truck.
<b>LEV</b>	Low Emission Vehicle.
<b>MSRP</b>	Manufactures Suggested Retail Price.
<b>MTBE</b>	Methyl tertiary butyl ether, used as an oxygenate in gasoline.
<b>NGV</b>	Natural gas vehicles.
<b>NLEV</b>	National Low Emission Vehicle (NLEV) program. The NLEV program is an agreement between the EPA, 23 auto manufactures, and most of the states that establishes voluntary emission standards more stringent than the federal Tier 1 standards.

<b>NMOG</b>	Non-methane Organic Compounds, see HC.
<b>NOx</b>	Nitrous Oxide, a gas contained in auto emissions, along with HC it is responsible for the formation of ozone.
<b>PM</b>	Particulate Matter, solid particles contained in emissions.
<b>PM10</b>	Particulate Matter less than 10 microns in diameter, PM10 is recognized as a health hazard.
<b>PM2.5</b>	Particulate Matter less than 2.5 microns in diameter, PM2.5 is mainly responsible for visible smog, i.e. the “brown cloud.”
<b>RFG</b>	Reformulated Gasoline, gasoline that has been reformulated to produce less emissions, principally through the addition of oxygenates.
<b>SCR</b>	Selective Catalytic Reduction, a method of reducing NOx emissions from diesel engines.
<b>SULEV</b>	Super ultra low emission vehicles.
<b>UEGO</b>	Universal exhaust gas oxygen (UEGO) sensor, a type of oxygen sensor.
<b>ULEV</b>	Ultra low emission vehicles.
<b>VMT</b>	Vehicle Miles Traveled, a measure of traffic flow.
<b>VOC</b>	Volatile Organic Compounds, see HC.
<b>ZEV</b>	Zero Emission Vehicles.

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