DIESEL ENGINES VS. SPARK IGNITION GASOLINE ENGINES - WHICH IS "GREENER"?

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Most of us have been behind heavy duty diesel powered trucks accelerating in traffic and emitting large clouds of black smoke. This exhaust smoke looks bad and intuitively it must have an adverse effect on health. However, the heavy particles comprising the black smoke quickly deposit on the ground or on the sides of buildings. Spark ignition (SI) gasoline engine powered automobiles equipped with catalytic converters appear to have clean exhausts. But then so do diesel trucks and buses built since 1994 as the human eye cannot detect smoke or carbon particles exhausted by these vehicles. It is emissions we can't see that are a concern from the human health perspective.

The fuels currently used for highway vehicles or that are viable candidates have some Cx Hy molecular structure. If we apply a carbon balance to the engine, carbon will be in the exhaust gas as either particulates (PM), hydrocarbons (HC), carbon monoxide (CO), or carbon dioxide (CO_2), the primary man made "greenhouse gas." We can either eliminate carbon and use pure hydrogen as a fuel or we can use highly efficient engines to minimize carbon in the exhaust.

Hydrogen as a fuel has widespread availability if produced from water. Unfortunately, this is a very expensive conversion. Roughly 90 percent of hydrogen used today is obtained from natural gas and used in petroleum refineries. Hydrogen is not an energy source and it will take more energy for its production than will be recovered in its use. Hydrogen costs $6 to $9 per million BTU's made from natural gas and roughly $20 to $25 per million BTU's made by electrolysis of water. About 7 gallons of diesel fuel and 8 gallons of gasoline provide a million BTU's at pre-taxed costs of about $4.20 and $4.80 per million BTU's respectively. Emissions related to hydrogen production could be substantial and so would the cost of the fuel and the supporting infrastructure. Safety concerns with hydrogen include hydrogen embrittlement which is a concern if existing pipelines are used. Leakage of hydrogen can be expected to be a factor of 3 greater than natural gas systems leakage. The energy density of hydrogen is about 1/3 that of methane, so the total energy release would be about the same. However, hydrogen leakage in a confined space will reach explosive proportions approximately 4 times faster than natural gas. Outdoors it would be safer than natural gas (1).

If hydrogen were available as an economically competitive fuel, reciprocating engines would challenge fuel cells on the basis of efficiency, cost, durability and existing field support, and manufacturing infrastructure.

What would the cost be to train `Mr. Goodwrench" to support fuel cell powered vehicles nationwide? If H is extracted from gasoline onboard the vehicle, where is the carbon going? And how much energy is consumed by this extraction? Fuel cell advocates talk about high efficiency conversion of fuel to electricity but tend to gloss over the losses in extracting H from fuel, electric power conditioning, and motor losses. Fuel cell technology will undoubtedly improve, but in 1997 on a fuel to drive train basis, fuel cells are roughly equivalent in efficiency to production gasoline cars with very low emissions and roughly 6 times the cost of a comparable SI gasoline powered automobile.

The consensus of the fuels and engine communities is that gasoline and diesel fuel will be primary fuels well into the 21st century. Reformulations of both fuels to further improve emissions are highly probable. Engine efficiency is the best way of reducing carbon emissions based on a carbon balance. As an example, the diesel engines being developed to replace spark ignition gasoline engines for light truck applications will reduce both fuel consumption and CO_2 emissions by about 50 percent! Diesel engines have a relatively flat fuel·use characteristic from idle to full power whereas gasoline engines and gas turbines have relatively high fuel use at low power and idle. Thus, the greater the extent of urban driving, the greater the advantage for diesel engine powered vehicles.

Virtually all Class 7-8 trucks worldwide are diesel engine powered. In Europe, diesel engine power is dominant thru all classes of trucks and constitutes about 30 percent of car sales. Light vehicles and cars are predominantly gasoline powered in the U.S. A meaningful comparson of diesel vs gasoline powered cars and light vehicles should include some of the European experience. VM Motori, a division of the Detroit Diesel Corporation, advertises that its diesel engine is better than the best gasoline engine with catalytic converter for the five primary emissions which are oxides of ntrogen (NO_x), particulate (PM), hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2). Let's consider these emissions:

Oxides of Nitrogen (NO_x)

SI gasoline engine powered cars are now equipped with a 3-way catalyst that reduces NO_x as long as the operating témperature is achieved and combustion is stoichiometric. Cars are equipped with as many as 4 oxygen sensors which are used in controlling the fuel/air mixture to stoichiometric conditions. Catalytic converters degrade with use and take increasingly longer to lift off. Consider the life of an automobile, which now averages about 130,000 miles. Over the last 110,000 miles, or 85 percent of the life of the car, the NO_x + HC emissions from gasoline powered cars are more than that from the diesel engine car. At the end of life there are 2.3 times the NO_x + HC out of the gasoline car as compared with the diesel engine as shown in Figure 1. Thus, NO_x emissions from the gasoline engine cars are higher than diesel engine cars over 85 percent of the life of the vehicle.

The catalytic converters currently used in cars have made a considerable contribution to cleaning up the air. Their use was stimulated by efforts of the California Air Resources Board (CARB) in 1974. These 3-way catalysts reduce levels of CO, HC, and NO_x. They typically use platinum, rhodium, or palladium deposited on ceramic or metallic substrates. The catalytic converters require stoichiometric combustion for NO_x reduction. If the engine runs rich (I. e., excess fuel) the CO and HC emissions will increase. If the engine runs lean, (i.e., excess air) then there is very little NO_x reduction. This restriction of the fuel/air ratio to 1, i.e., stoichiometric combustion, prevents achieving several points in efficiency that could be obtained with lean burn engines. Also, the oxygen sensors degrade with time (they are typically warranted for 2 years or 24,000 miles.)

Catalytic converters do not function until they reach their operational temperature. A car with a catalytic converter must be driven for about 7 miles in an urban area for the catalytic converter to reach operational temperature. In Great Britain, about 40 percent of the car trips are less than 3 miles. So the catalytic converter never lights off in these vehicles. In testing done in Great Britain on comparable cars, the gasoline powered car with 3-way catalyst over the first kilometer produced 83.9 grams of pollution (72.9 g/km of CO, 10.0 g/km of volatile organic compounds [VOC's], and 1.0 g/km of NO_x) while the diesel car produced 9.0 gms of pollution (5.3 g/km of CO, 1.9 g/km of VOC and 1.8 g/kmNO_x)

The new U. S. diesel engine fuel systems using microprocessor control, high fuel injection pressures, rate shaping, and pilot injection plus cooled EGR (exhaust gas recirculation) will dramatically reduce NO_x even lower. The NO_x and HC levels for the light vehicle (i.e., Sport Utility Vehicles (SUVs) vans, pickup trucks) diesel engines being developed at Cummins, Caterpillar, and DDC are projected to be equivalent or lower than those from new gasoline powered vehicles. NO_x levels from these diesel engines in development would not deteriorate as they do with catalytic converters. Nonthermal plasmas could further reduce NO_x and PM to near zero levels! Non-thermal plasma devices replacing 3-way catalysts in S.I. gasoline engines would eliminate the cold start engine and allow lean burn operation with consequent improved efficiency without the degradation of the catalytic converter and oxygen sensors. Early work suggests non-thermal plasmas are self-cleaning.

Carbon Monoxide

Spark ignition (SI) gasoline engines with functioning catalytic converters emit at least 10 times as much CO as comparable diesel engines. CO is a product of incomplete combustion of a carbon containing fuel. Catalytic converter operation requires the stoichiometric ratio wherein there is just enough air oxygen to completely burn all the gasoline. As the mixture of fuel/air becomes richer, i.e., more fuel than air, the concentration of CO increases rapidly. This happens during vehicle operation. However, in the diesel engine with its very lean fuel/air mixture, the excess oxygen introduced into the combustion chamber fully oxidizes the carbon to carbon dioxide (CO_2) with only a small amount of CO. The level of CO emitted from gasoline engine powered cars is very high during cold start, i.e., before the catalytic converter lights off, and during acceleration enrichment.

CO emissions may become an increasing concern. In a recent study at Stanford University, CO levels 2 to 14 times greater were measured inside cars than in the air 150 feet away from the highway. Low CO levels induce drowsiness and headaches. These low CO levels are also dangerous to pregnant women and those with heart disease. High levels of CO can cause death. There are 2,850 deaths annually attributed to exhaust from gasoline engine cars. This is not the case with a diesel engine powered vehicle.

Another source of CO emissions is the programmed fuel/air enrichment during hard acceleration. During this hard acceleration excess fuel is introduced to prevent thermal damage to emission control parts as well as in-cylinder components under warranty. General Motors Research tested a 1989 3.8L V-6 gasoline powered car for 350 miles in Los Angeles with aggressive driving but with the fuel/air mixture maintained near stoichiometric most of the time. Compared with the Urban Dynamometer Driving Schedule there were 2,500 times more CO and 40 times more HC emissions measured. This test was considered representative of three-way catalyst equipped SI gasoline engines.

The only production cars that have eliminated acceleration enrichment are the Mercedes Benz C Class cars. This is achieved in these cars by using larger catalysts relative to engine displacement, an electric air pump to oxygenate exhaust manifolds, and electrically heated elements in the cylinder head. These technologies are costly. Acceleration enrichment cannot be achieved by reprogramming engine control components (3)

Particulate Matter (PM)

Particulates that are respirable by people are at the environmental center stage in mid-1997. Particulates that have an aerodynamic diameter of 10 microns or less are respirable. Most of the PM which are under 10 microns but over 2.5 microns are comprised of tire and brake wear debris, soil, and other crustal material. The PM 2.5 microns and below that typically result from combustion of fossil fuels in transportation, manufacturing and power generation, are referred to as fine particles. Ultra-fine PM are below 0.10 microns. The smaller the particle size, the greater the probability is that it will deposit in the lung.

The Harvard Six Cities Study, which involved 8,111 adults in 6 U.S. cities covering a 14 to 16 year period, showed a nearly linear relationship between the level of fine-particle pollution and mortality (4). A followup study with a larger cohort but shorter time period produced similar results.

Heavy duty diesel engines manufactured before 1994 powering trucks and buses. characteristically belch large plumes of black smoke during acceleration. The human eye can't detect smoke from a post-1994 diesel engine powered heavy vehicle. The problem is that the Environmental Protection Agency (EPA) specified the mass levels of particulates in emission standards not particle size and distribution. Human health concerns suggest particle size and distribution as well as attached chemicals.

PM exhausted from spark ignition gasoline engine powered automobiles is typically smaller in diameter and lower in quantity than that from diesel engines. However, driving patterns strongly influence PM emissions. Cold start PM can be 2 orders of magnitude greater than PM emitted driving at engine operating temperatures. Rapid acceleration also produces significant PM which is not detected in current EPA tests for spark ignition (SI) gasoline powered automobiles.

Results of testing in the United Kingdom (UK) of comparable SI gasoline powered cars with 3-way catalysts compared with turbocharged diesel engine powered cars are shown in Figures 2 and 3. Note that the quantity of PM from the diesel car is larger with a distribution peak about 0.10 microns while the quantity from the SI gasoline auto is considerably smaller but the peak of the distribution is 0.030 microns, or 1/3 the diameter of the peak of the diesel car distribution. Figure 4, published by the Harvard School of Public Health, shows the relative deposition in the human pulmonary track of PM as a function of size. The peaks of the UK data are superimposed on this chart showing that the PM from the gasoline car has about twice the deposition factor of that from the diesel car.

Carbon Dioxide (CO_2)

If one does a carbon balance with a heat engine fueled with a hydrocarbon fuel, the exhaust gas will have the carbon as either particulates (PM), hydrocarbons (HC), carbon monoxide (CO), or carbon dioxide (CO_2). Since the particulates resulting from the combustion of hydrocarbon fuel are typically less than 2.5 microns in diameter, the least harmful to human health of carbon in exhaust is CO_2. While CO_2 is not a pollutant, it is a "greenhouse gas." Every breathing creature emits CO_2 which plants absorb then release oxygen into the atmosphere. Only about 4 percent of CO_2 in the atmosphere is manmade, essentially from the combustion of hydrocarbon fuels. Improving engine efficiency is the best near term technical answer to man-made CO_2 reduction. The new DOE light vehicle diesel engine will use 50 percent less fuel for combined city/-highway driving than the current gasoline engines; this also reduces CO_2 by 50 percent for each gasoline engine replaced with a diesel engine in these vehicles. This could be a meaningful contribution to the US commitment to the Global Warming issue.

Onhighway Emission Measurements

Emissions from primarily gasoline powered vehicles are being measured during regular on-highway use by portable remote sensing systems. Infrared beams are used to measure CO and HC and an ultraviolet beam is used for NO_x Calibrations are done with CO_2 absorption. Over two million cars in several countries have been tested this way. In California testing, a consistent pattern emerged. Emissions levels have gone down steadily as new and better emission control technology is introduced. However, for every vehicle model year, 10 percent of the vehicles contribute half of the total fleet's CO and HC emissions. These high emitters are found in all model year vehicles(5). It is not just the older vehicles that are the high emitters.

Evaporative Emissions From Gasoline

The levels of HC evaporation from automobiles is comparable to HC in the exhaust. Evaporation of HC from the vehicle fuel system can be classified into 3 categories: diurnal emissions, hotsoak emissions, and running losses. Diurnal emissions refer to those that occur in a parked vehicle as it draws in air at night as it cools down and expels air and gasoline vapor as it heats up during the day. This "diurnal breathing" of the fuel tank can produce evaporative HC emissions of about 50 g/day. Hot soak emissions occur after the engine is shut off and the residual thermal energy heats the fuel system. Running losses occur as gasoline vapors are expelled from the fuel system when the car is driven and the fuel becomes hot. In addition, gasoline vapors can escape from the fuel system during fueling at the gas station. Regulations have required evaporative controls for over 20 years. However, these systems have been very ineffective in service. (5) These evaporative emissions contribute to photochemical ozone. Diesel powered vehicles have insignificant evaporative emissions.

The relative volatility of diesel fuel and gasoline has another human safety aspect. During a question and answer session at the SAE 1995 meeting in Detroit, Cayot of Lucas, responded to a human health related question by saying that in France, where 40-50 percent of new car sales since 1989 have been diesel engine powered cars, there have been about 5,000 people burned to death in collisions involving gasoline engine powered cars. However, there were no deaths reported in collisions involving diesel engine cars caused by burning. This is due to the high volatility of gasoline and low volatility of diesel fuel.

Benzene

Benzene is defined by the World Health Organization as a known human carcinogen. It is a proven cause of leukemia. The recommended limit of benzene in the atmosphere is currently 5 ppb, which will soon be reduced to 1 ppb. There is a minimal amount of benzene in diesel fuel (0.05%) because it reduces the cetane number. However, it is added to gasoline (about 1.0%) to increase the octane rating. Thus, there is more than 1 pint of benzene, a known carcinogen, in a 14 gallon tank of gasoline. EPA's National Air Pollution trends in October 1996 indicated that 97 percent of the benzene in the atmosphere came from gasoline engines and 3 percent from diesel engines in a highway study (7). Curiously benzene from gasoline has not been a candidate for Proposition 65 in California but has been identified as a toxic substance in diesel exhaust (8).

MTBE Gasoline Oxygenate

Methyl tertiary butyl (MTBE) is by far the most extensively used of the gasoline oxygenate required by the US Environmental Protection Agency (EPA). Gasline with 1 percent MTBE reduces CO by 20 percent, H_2 by 6 percent, and NO_x by 8 percent, but increases aldehydes, which are a precursor of ozone. MTBE is a potential carcinogen. The big problem with MTBE is that it mixes thoroughly with water, travels great distances through water, and is very difficult to remove from water. A significant number of wells in the Santa Monica area are contaminated with MTBE. The water is described as having a bad taste and odor. Water contamination with MTBE has been reported by the U. S. Geological Survey nationwide. Sources of MTBE are gasoline spills, leaks from underground tanks, and motorboat gasoline engines. Water contamination by MTBE as a result of a gasoline spill in North Carolina has resulted in a judgement against the oil company involved. The investment by the oil companies in MTBE is large. It is roughly a ten billion dollar a year business. Additional legal suits by residents encountering MTBE in their water should be anticipated. MTBE is not a diesel fuel additive (6).

Nitrous Oxide (N_2O) - Greenhouse Gas

Nitrous oxide (N_2O) is a greenhouse gas that is more commonly known as "laughing gas" as used by dentists. N_2O has about 300 times the infrared absorbing capability of CO_2. It is this infrared absorption along with, reflection and radiation back to earth by water vapor, CO_2, , and methane that provide the greenhouse effect. Solar energy, which is primarily the ultraviolet and visible part of the spectrum, is fairly well transmitted through the earths's atmosphere to the earth's surface. However some solar energy is reflected back to space by the atmosphere. The earth's surface absorbs incident solar energy and radiates some of it to deep space as thermal energy in the infrared wavelength. The transparent shield of tropospheric greenhouse gases absorbs some of this infrared radiation and radiates it back to earth, resulting in increased warming. With these greenhouse gases the average temperature of the earth is 59°F; without the greenhouse gases the average temperature of the earth would be -4° F. The source of N_2O from highway vhicles is primarily the catalytic converter. EPA reports 99 percent of the on-road vehicle emissions of N_2O come from SI gasoline engine powered cars (7). N_2O emissions are not regulated. About 200,000 tons of NO are emitted worldwide per year. On a CO equivalent basis, N_2O contributes only a few percent to the global warming potential. Conversion of NO_x to N_2O by non-thermal plasma or lean NO_x catalyst should be (and can be) avoided. Early work with lean NO_x catalysis suggests considerable N_2O generation.

Greener Engines

Technology is emerging at the laboratory scale that suggests diesel and gasoline engine emissions can be further reduced to very low levels. Extensive engineering development is necessary to bring this technology into production. The question is becoming how low do we want to reduce onhighway emissions and how much are we willing to pay to do it?

SI gasoline engines are limited in efficiency by the necessity of stoichiometric air/fuel combustion to enable NO_x reduction by the catalytic converters. Stoichiometric combustion is maintained by using as many as 4 oxygen sensors controlling combustion. The problem is that both the catalytic converters and oxygen sensors degrade with use requiring replacement and the older cars typically wind up with drivers with low income levels. Many low income people are not in a position to pay $100 per oxygen sensor and several hundred more for a replacement catalytic converter. The State of California is considering paying the cost of oxygen sensor and catalytic converter replacement for California's low income vehicle owners up to some cap. This is probably a better approach than the earlier CARB sponsored cash for "clunkers" to get the older cars off the road. Public transportation is inadequate in Southern California and cars are a necessity for most residents. The other states will probably watch how well this works in California.

Non-thermal plasma devices are still in the development stage but early testing suggests 70 percent simultaneous NO_x and PM reduction stages; they will be self cleaning, will allow lean burn combustion with its attendant increase in efficiency and since they operate essentially independent of temperature, the cold start problem with gasoline engine powered cars could be eliminated. Non-thermal plasma device cost and power requirements are main concerns. There are several approaches which could minimize the electrical power requirement. Device costs are projected to be under $500. PM reduction can be improved with soot catalytic traps that are now available or microwave regenerated particulate traps that should be available within 2 years. Reformulated fuels should provide further PM emission reductions as sulfur and aromatics are further reduced.

Diesel engine emission reduction for the Class 7 & 8 trucks since 1978 has seen NO_x reduced by 73 percent and PM by 93 percent as shown in Figure 4. The EPA-required transient tests for heavy duty truck diesel emissions measurements while the Europeans and Japanese require much easier 13 step steady state testing. This chart presents difficulties for those involved with the human health aspects of diesel engine emissions. Evaluation of human exposure over the years involves emissions from a domestic truck fleet that is becoming dramatically cleaner over the years. For example, detailed health studies of people exposed to diesel exhaust from 1960-1980 would be questionable contrasted to those exposed to diesel exhaust say from 1997-2017.

Environmentalists

"Watchdog" environmentalists can and do make worthwhile contributions. They are certainly attacking diesel engine exhaust as a toxic air contaminant. The California Environmental Protection Agency is in the process of identifying diesel exhaust as a toxic air contaminant with its legal ramification. A cornerstone of this approach are the rat studies of exposure to diesel exhaust greater than 2.5 mg/m3 for 24 month's exposure. This diesel exhaust produced cancer. However, the group that conducted this testing says it was a unique rat reaction not duplicated in other animals and not extrapolative to humans. This test was reproduced in Germany with road dust that produced similar cancers. Even after the author of this work wrote to the people preparing this report, the diesel exhaust causal effect of cancer in rats is still in the report. Why isn't gasoline engine exhaust with its high level of benzene (97% to 3% from diesels), high NO_x, PM, and CO levels causing concern for impartial environmentalists? (the World Health Organization has identified benzene as a known carcinogen). There are also problems in diesel exhaust for health concerns. There are significant concerns for automobile gasoline engine exhaust that the environmental community for the most part ignores. Accurate technical identification of human health concerns will generally cause more attention to be focused on the problem.

Summary/Conclusions

Criteria emissions, i.e.; NO_x, PM, CO, CO_2, and H_2, from recently manufactured automobiles, compared on the basis of what actually comes out of the engines, the diesel engine is "greener" than spark ignition gasoline engines and this advantage for the diesel engine increases with time. SI gasoline engines tend to get out of tune more than diesel engines and 3-way catalytic converters and oxygen sensors degrade with use. Highway measurements of NO_2, H_2, and CO revealed that for each model year, 10 percent of the vehicles produce 50 percent of the emissions and older model years emit more than recent model year vehicles. Since 1974, cars with SI gasoline engines have uncontrolled emission until the 3-way catalytic converter reaches operating temperature, which occurs after roughly 7 miles of driving. Honda reports a system to be introduced in 1998 that will alleviate this cold start problem by storing the emissions then sending them through the catalytic converter after it reaches operating temperature. Acceleration enrichment, wherein considerable excess fuel is introduced to keep temperatures down of SI gasoline engine in-cylinder components and catalytic converters so these parts meet warranty, results in 2,500 times more CO and 40 times more H_2 being emitted. One cannot kill oneself, accidentally or otherwise, with CO from a diesel engine vehicle in a confined space. There are 2,850 deaths per year attributable to CO from SI gasoline engine cars.

Diesel fuel has advantages compared with gasoline. Refinery emissions are lower as catalytic cracking isn't necessary. The low volatility of diesel fuel results in a much lower probability of fires. Emissions could be improved by further reducing sulfur and aromatics and/or fuel additives. "Reformulated fuel" has become the term covering reducing the fuels contribution to emissions. Further PM reduction should be anticipated with reformulated diesel and gasoline fuels.

References

1. F.J. Edesbuty et al, "Critical Review and Assessment of Environmental and Safety Problems in Hydrogen Energy Systems", prepared for Dept. of Energy under Contract W-7405-ENE-36, Los Alamos National Laboratory, Los Alamos, New Mexico.

2. EPA AP-42, 4th Edition.

3. Ward's Engine and Vehicle Technology Update, Dec. 1993.

4. D.W. Dockney, et al, "An Association Between Air Pollution and Mortality in Six U. S. Cities," The New England Journal of Medicine, Vol. 329, No. 24, Dec. 9, 1993.

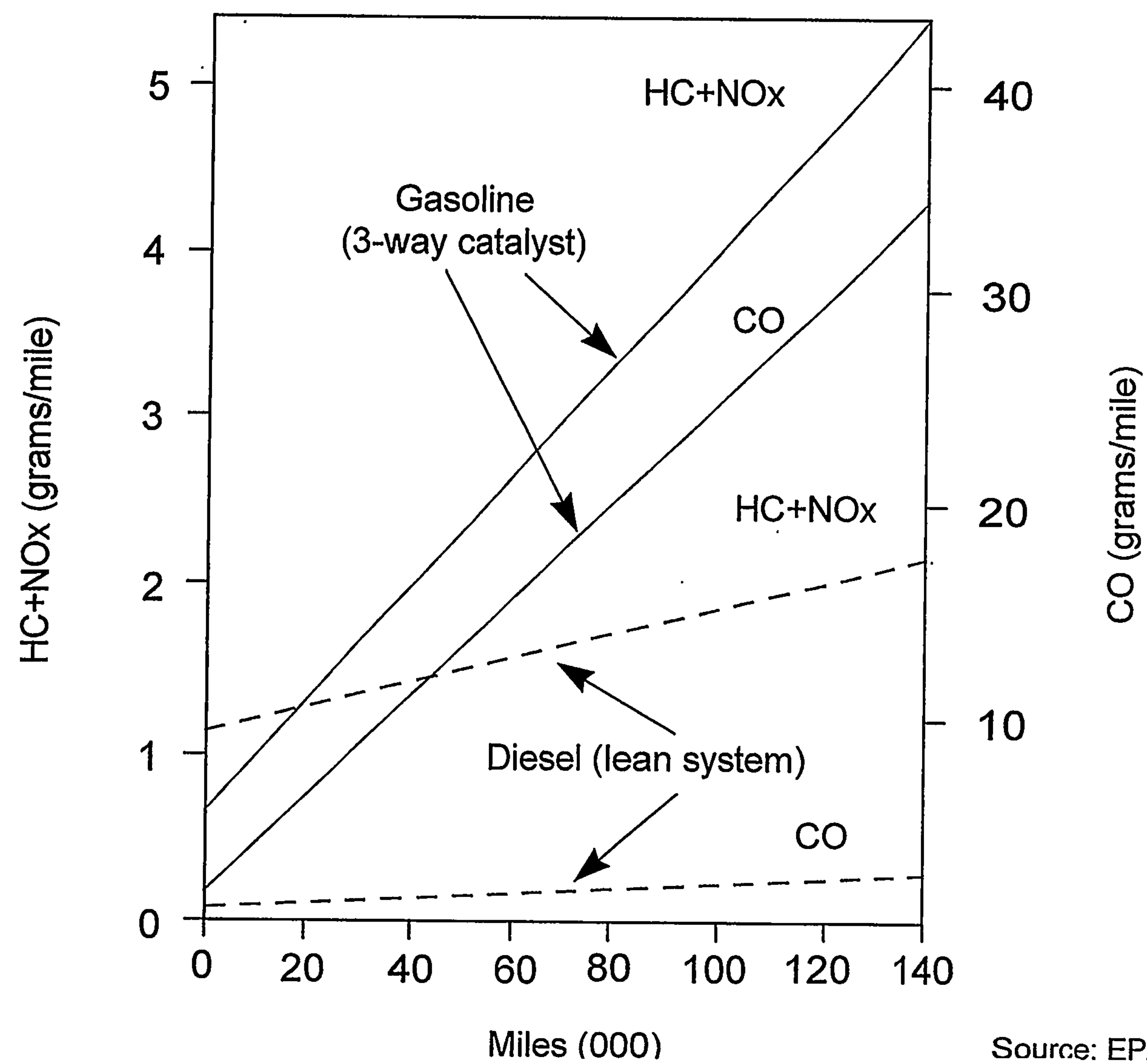
5. J.B. Haywood, "Motor Vehicle Emissions Control: Past Achievements, Future Prospects,"Combustion Engine Group Prestige Lecture presented at a Sponsored Lecture, London, 21 May 1996.

6. R. Brooks, personal communication - Ward's Engine Vehicle Technology Update contributor, August 1997.

7. National Air Pollutant Trends published by EPA, Oct. 1996.

8. Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant, Executive Summary, California Environmental Protection Agency Public comment and SRP Version, May 9, 1997.

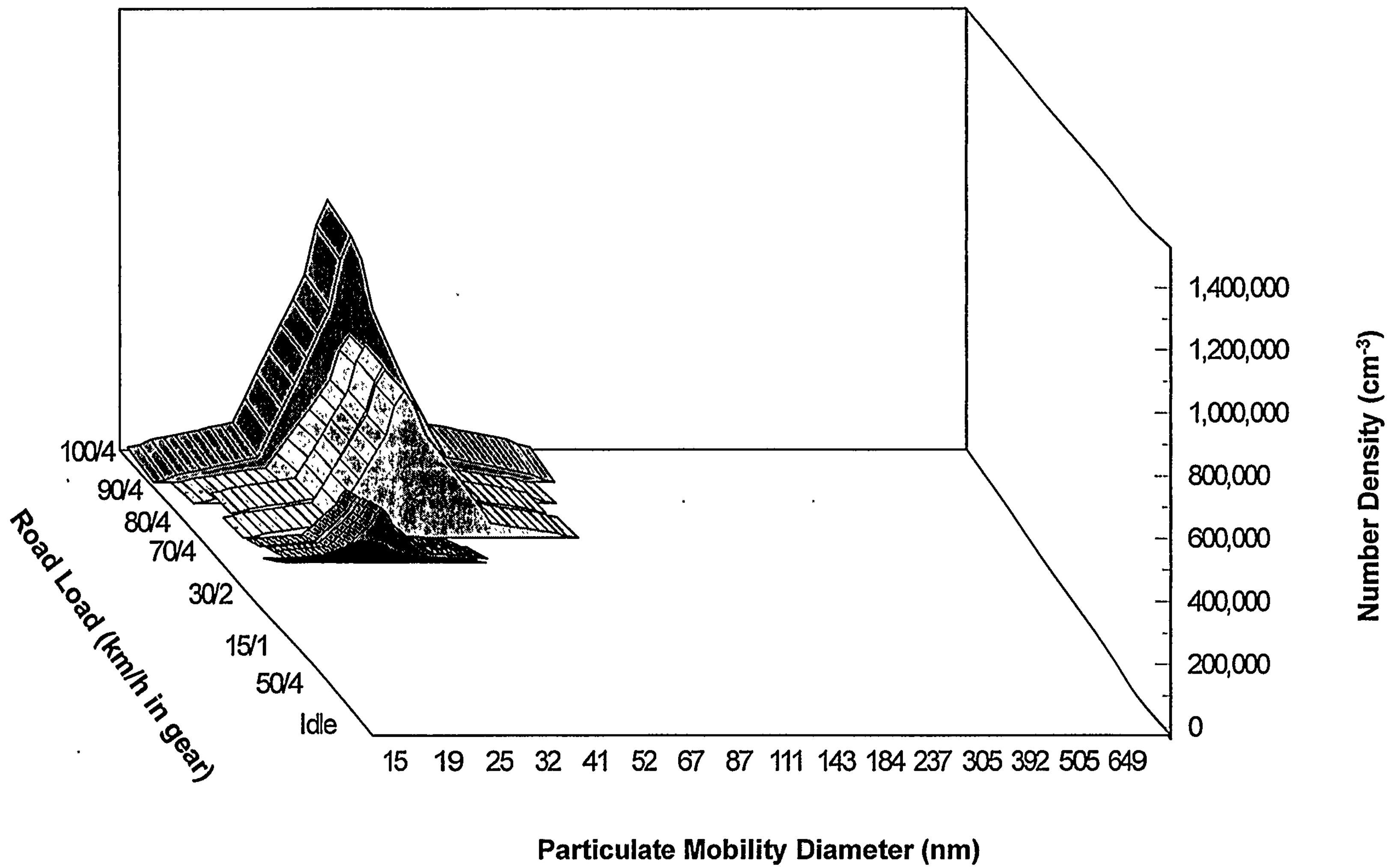
Projected Emissions of 1990 Light-Duty Vehicles



Source: EPA AP-42 4th Edition

Figure 1. EPA Projected Emissions of 1990 Light-Duty Vehicles

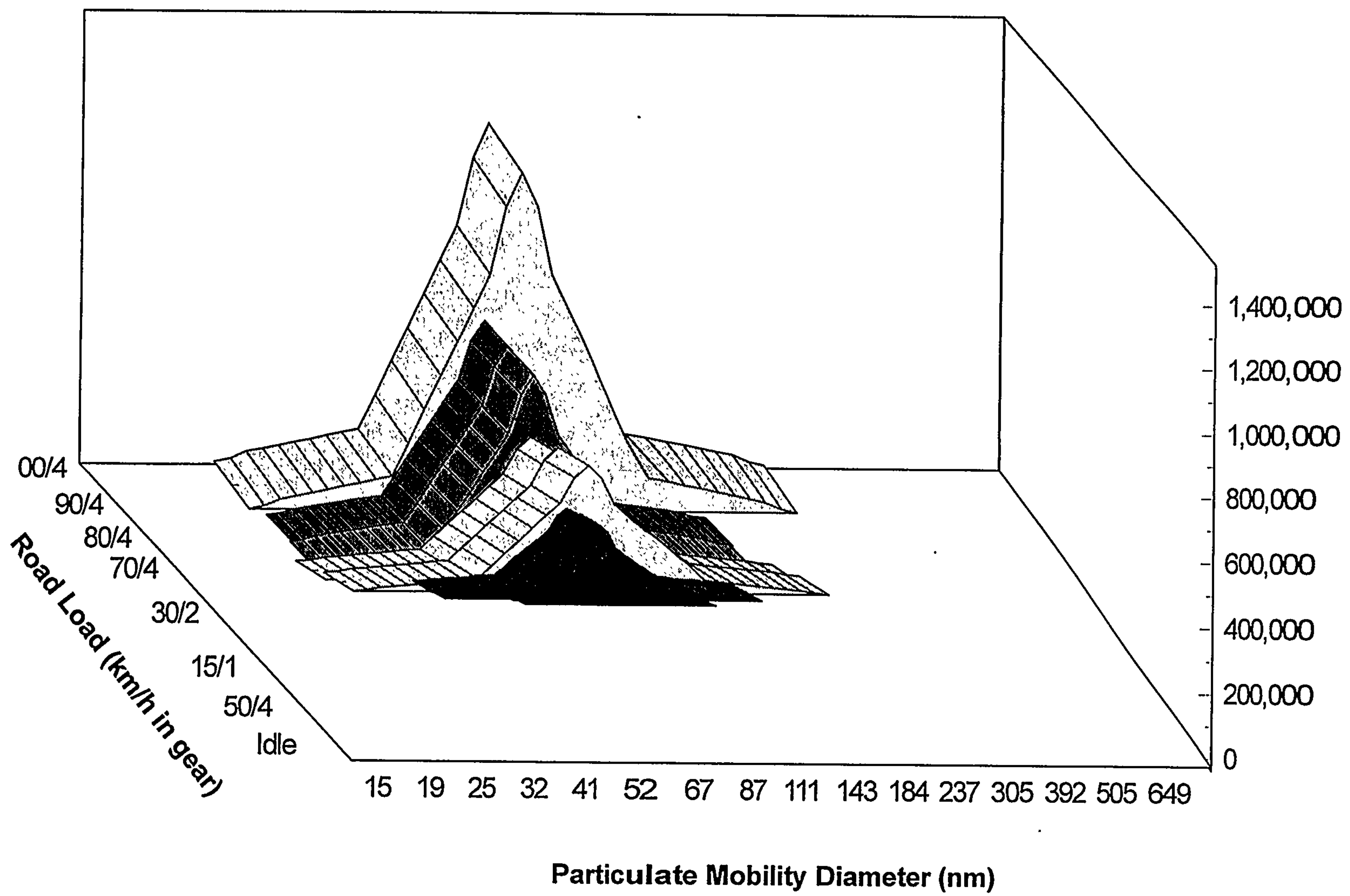
Particle Size Distribution from a 2.2 Liter Gasoline Vehicle (with Catalyst) at Constant Speeds



Report of the UK Particulate Group (Harwell)

Figure 2. UK Test Showing PM Distribution From 2.2 Liter Gasoline Vehicle With Catalysts

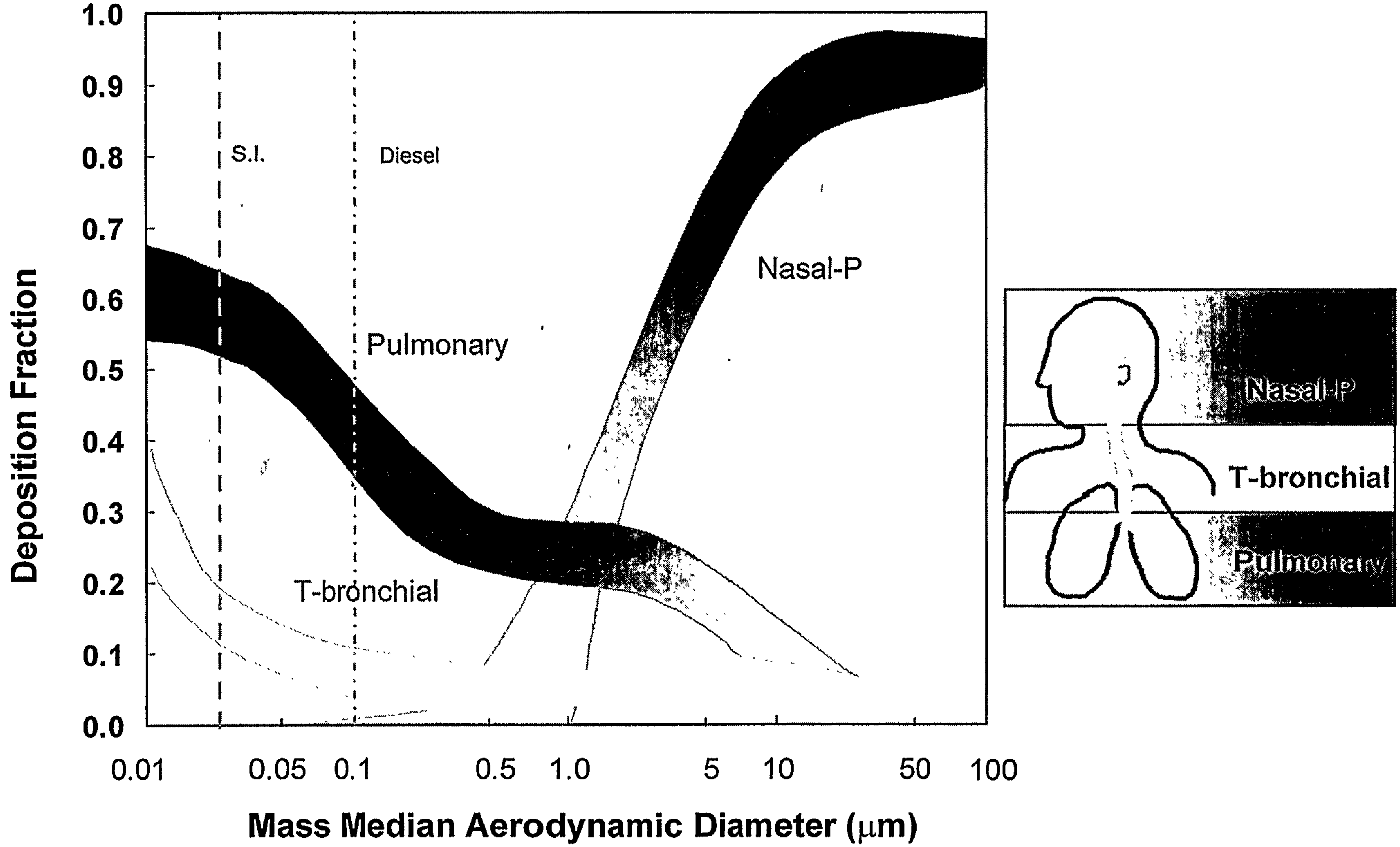
Particulate Size Distributions from a 1.9 Liter Turbocharged Diesel Vehicle at Constant Speeds



Report of the UK Particulate Group (Harwell)

Figure 3. UK Test Showing PM Distribution from a 1.9 Liter Turbocharged Vehicle

"Regional" Deposition of Particulates



Source: Particles in Our Air: Concentrations and Health Effects
1996 Harvard School of Public Health

Figure 4. Deposition of PM In The Human Respiratory Tract

Evolution of Heavy Duty Diesel Engine Emissions Control

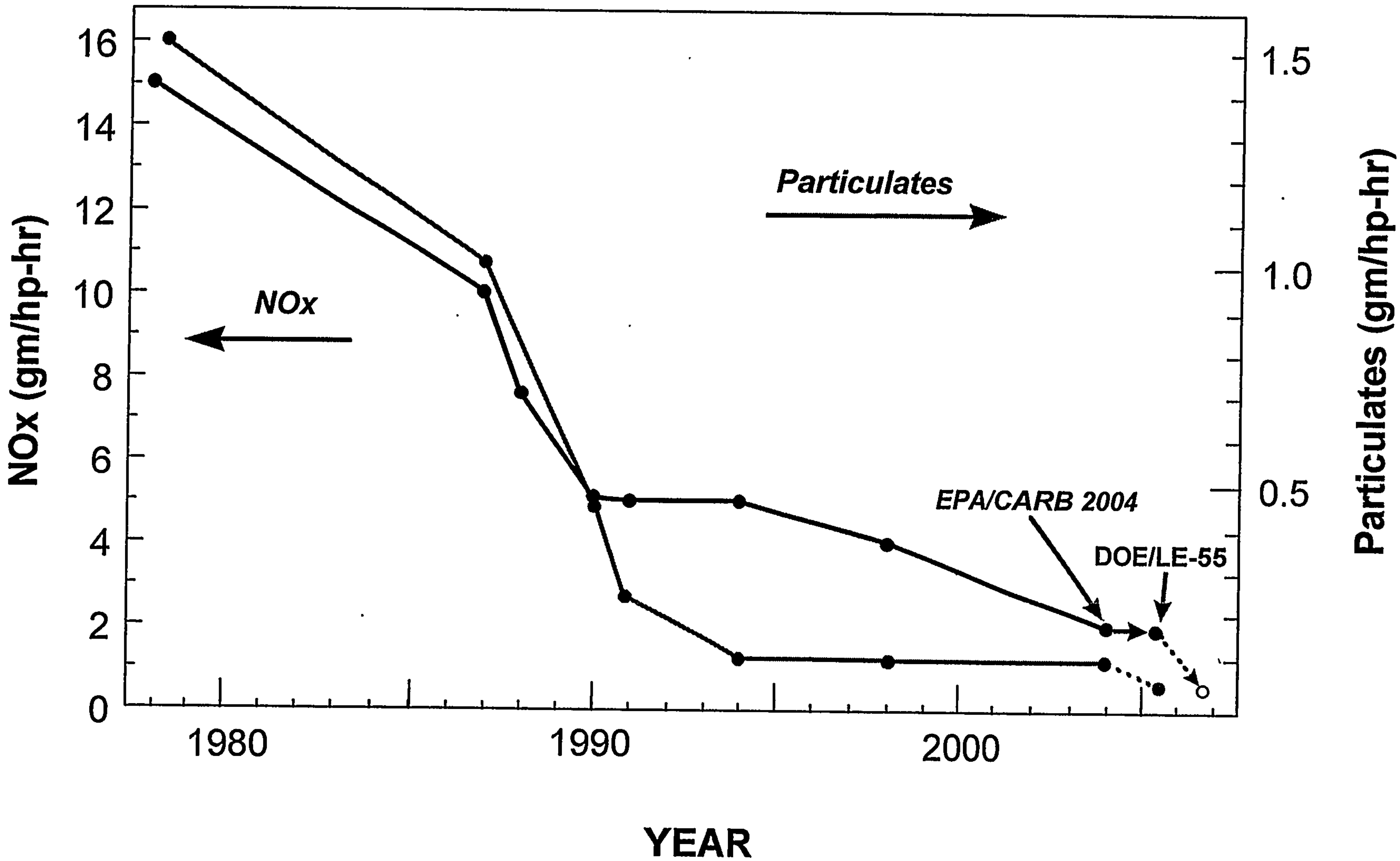


Figure 5. Evolution of Heavy Duty Class 7-8 Truck Diesel Engine Emissions Control