# DIESEL PARTICULATE EMISSIONS: THE UNITED STATES, EUROPE, AND JAPAN

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## INTRODUCTION

In recent years, the popularity of diesel-powered motor vehicles has been steadily growing around the world, primarily in response to rising gasoline prices. As dieselization of the passenger car and light-duty truck markets has occurred, and as the number of traditionally diesel-powered line-haul trucks has increased, concern for the environmental impact of particulate emissions from diesel engines has also grown.

This paper presents an overview of the many and varied aspects of the environmental assessment and regulation of diesel particulate emissions, with primary focus on the situation in the United States (since this is the locus of the authors' personal experience), but with extrapolations to both Europe and Japan. The first section briefly summarizes some of the health and welfare concerns associated with diesel particulate emissions, including both carcinogenic and non-cancer health risks, visibility reduction, and soiling. Next, a review of U.S., European, and Japanese regulation of diesel particulate is presented, followed by estimated emissions inventories and ambient concentrations of diesel particulate in selected areas. The next section offers a comparison of dieselization in various countries, with focus on trends in fuel prices. The final section of the paper deals with techniques available to control diesel particulate emissions, including those related to the engine, the exhaust, and the fuel.

## HEALTH AND WELFARE EFFECTS OF DIESEL PARTICULATE EMISSIONS

As the diesel penetration of worldwide automobile and truck markets increases, the health and welfare consequences associated with diesel particulate emissions grow as well. Potential health problems resulting from exposure to diesel particulate, both carcinogenic and non-cancerous in nature, are briefly reviewed in the first two parts of this section. Next, the effect of ambient particulate matter on visibility in urban areas is discussed. Finally, the soiling of materials (primarily buildings) by diesel particulate is examined.

These health and welfare effects are examined in greater detail in EPA's Diesel Particulate Study[1], and in the draft and final Regulatory Impact Analyses in support of the heavy-duty diesel particulate standards published March 15, 1985.[2,3] The following paragraphs are merely brief overviews of the topics, and the reader is encouraged to refer to the previous works for more detailed information.

Cancer Risk Assessment

The carcinogenic potency of diesel particulate matter is primarily associated with its soluble organic fraction (SOF), particularly the heavier aromatic hydrocarbons with high-temperature boiling points -- those with three or more benzene rings. Included in this fraction is benzo-a-pyrene (BaP), a poly-nuclear aromatic hydrocarbon known to cause cancer in humans.

The potential risk of contracting lung cancer as a result of exposure to diesel particulate has been evaluated through both epidemiological and clinical studies. Of course, the most valuable is a long-term epidemiological study tracing the health of people who have been exposed to precisely known concentrations of diesel particulate over a period of time. One such study, conducted on London bus garage workers, was reviewed by EPA and others and appears to be somewhat flawed in its design (i.e., its results are quite uncertain, statistically).[1] Another epidemiological study -- this time on U.S. railroad workers -- is currently being conducted by Harvard University for EPA. Therefore, since human epidemiological data are extremely limited at this time, clinical data on animals and lower organisms must be relied upon in estimating the carcinogenic potency of diesel particulate.

EPA is basing its current estimates of the cancer risk associated with diesel particulate on a comparative potency method[1], wherein the relative potency results of clinical testing on lower organisms are extrapolated to humans. This method involves the comparison of results of a number of bioassays performed on diesel particulate with the results of the same bioassays performed on human carcinogens of known potency.

In a recently published Regulatory Impact Analysis[3], EPA estimated a "steady-state" cancer risk attributable to diesel particulate exposure. In making this assessment, EPA assumed that the average level of exposure to diesel particulate estimated for the year 2000 -- based on uncontrolled heavy-duty emissions in the U.S. -- would continue over a number of decades. Then, using the comparative potency method, the annual risk of contracting cancer from lifetime exposure to these levels of diesel particulate was estimated at up to eight individuals in a million.

Non-Cancer Health Effects

Particulate matter in general has long been regarded as hazardous to human health; in fact, EPA established an NAAQS for total suspended particulate (TSP) as early as 1971. Recently, because of growing evidence that it is the fraction of particles with diameters of 10 microns or less ($PM_{10}$) that is responsible for most of the human health effects associated with TSP, EPA has proposed that the primary NAAQS for TSP be revised to only include $PM_{10}$.

Because diesel particulates are essentially "fine" (less than 2.5 microns in diameter), they fall easily into the $PM_{10}$ category. From this small size stems one of the basic concerns associated with inhalation of diesel particulate -- its penetration of the deepest recesses of the lungs, the alveoli, where the oxygen/carbon dioxide exchange takes place with the circulatory system. The body requires months or years to clear foreign matter from the alveolar region, which is significantly longer than that required for the upper respiratory tract. The second basic concern is that diesel particulate may be composed of toxic materials or may have hazardous materials adsorbed onto its surface.[3]

The most obvious non-cancer health effect of an inhalable particulate, such as that produced by diesels, is injury to the surfaces of the respiratory system, which could result in reduced lung function, bronchitis or chronic respiratory symptoms. The hazardous chemicals that may be associated with particulate matter (e.g., organic compounds, lead, antimony, etc.) can either react with lung tissue or be transported to other parts of the body by the circulatory system. Particulate matter may also weaken the resistance of the body to infection and there are indications that it reacts adversely in conjunction with other atmospheric pollutants.[3]

Visibility Reduction

Probably the most apparent effect of diesel particulate in urban areas, where traffic is generally most concentrated, is reduced visibility. Because diesel particles are of a diameter most effective in scattering light and their carbon content of 65-80 percent produces a high degree of light absorption, they are especially effective in reducing visibility.[3]

The model used by EPA to determine the visibility impact of a specified level of diesel particulate is a fairly simple one based on Beer's Law, and requires inputs such as the urban ambient diesel particulate concentration, the extent (distance) of this concentration (assumed to be the city radius), the extinction coefficient of diesel particulate, and baseline visibility for the city being modelled.[1] In the absence of heavy-duty vehicle controls, EPA has projected that increased diesel particulate levels would result in significantly reduced urban visibility (compared to mid-1970's levels), ranging from a 22-percent reduction in the largest cities, to decreases of 4-9 percent in less populous urban areas by the year 2000.[3]

## Soiling Effects

Soiling refers to the build-up of a layer of deposited atmospheric particulates on an exposed surface, resulting in a loss of reflectance of visual light by an opaque material surface or a reduction in light transmission through a transparent material.[1] Due to the characteristics of diesel particulate -- its black color and oily nature -- it may be more detrimental, in terms of the amount of soiling per unit ambient concentration, than other types of particulate matter. The black color would make any buildup more apparent to the observer, and the oil content may make cleaning more difficult. The net effect is increased costs to the general public for more frequent and more thorough cleaning of homes, vehicles, and public buildings.[3]

## REGULATION OF DIESEL EMISSIONS AND AIR QUALITY

Based on the adverse health and welfare effects described in the previous section, control of diesel particulate emissions has been warranted in the United States. This section includes a review of regulatory actions taken with respect to particulate emissions from diesel vehicles and allowable levels of particulate matter in the ambient air. First, the development of U.S. particulate controls -- presently the most stringent in the world -- are reviewed. Following this discussion is a brief overview of the limited controls currently enforced in Europe and Japan.

U.S. Regulations

Clean Air Act

Section 202(a)(3)(A)(iii) of the Clean Air Act, as amended by the U.S. Congress in 1977, authorizes EPA's Administrator to "prescribe regulations ... applicable to emissions of particulate matter from classes or categories of vehicles manufactured during and after model year 1981 ... ." This section specifically directs that particulate control regulations "shall contain standards which reflect the greatest degree of emission reduction achievable through the application of technology ... available for the model year to which such standards apply, giving appropriate consideration to the cost of applying such technology ... and to noise, energy, and safety factors associated with the application of such technology." It is this portion of the Clean Air Act that gave EPA the authority -- and indeed the responsibility -- to set exhaust particulate standards for on-highway diesel vehicles and engines sold in the United States. (The particulate standards currently in place are discussed later in this section).

Section 109 of the Clean Air Act provides that National Ambient Air Quality Standards (NAAQSs) be set forth by the EPA. This section of the Act defines a primary NAAQS as being that which is "requisite to protect the public health", and the secondary standard as that "level of air quality ... (that) is requisite to protect the public welfare."

Under these provisions, EPA established NAAQSs for total suspended particulate matter (TSP) in a rulemaking published November 25, 1971 (36 FR 22384); the same TSP standards still apply today. The primary standards, focusing on protection of human health, are 75 micrograms per cubic meter (ug/m$^3$) as an annual geometric mean and

260 $ug/m^3$ as the maximum daily average concentration (allowed to be exceeded only one day per year). The secondary TSP standards, established in the interest of public welfare, are an annual geometric mean of 60 $ug/m^3$ and a second maximum 24-hour average of 150 $ug/m^3$.

In an effort to further focus control on those particulates most hazardous to human health, EPA has proposed that an NAAQS on particles less than or equal to 10 microns in diameter ($PM_{10}$) be established to replace the primary standard for TSP. The $PM_{10}$ alternatives being considered, published on March 20, 1984 [49 FR 10408], range from 50-65 $ug/m^3$ as an annual arithmetic mean, and from 150-250 $ug/m^3$ as the second maximum daily average. Non-compliance with the proposed $PM_{10}$ standards is expected to be almost as widespread as with the current TSP standards -- between 105 and 329 non-attainment counties with the primary $PM_{10}$ standard, compared to 300-525 counties projected to be in non-attainment of the primary NAAQS for TSP in the 1987-89 timeframe.[3] This projected degree of non-compliance calls for further particulate emissions control and supports the Clean Air Act's mandate for specific action with respect to diesel particulate. The emissions standards currently in place in the U.S. -- designed to provide compliance with these current and proposed ambient standards -- are discussed below.

Passenger Car and Light-duty Truck Standards

The first exhaust diesel particulate standards for cars and light trucks were established in an EPA rulemaking published on March 5, 1980 [45 FR 14496]. This action set a limit of 0.37 g/km (0.60 g/mi) for both diesel cars and light-duty diesel trucks, to become effective with the 1982 model year. This rulemaking also established 1985 particulate standards of 0.12 g/km (0.20 g/mi) and 0.16 g/km (0.26 g/mi) for diesel automobiles and light trucks, respectively.

In a subsequent rulemaking, published January 24, 1984 [49 FR 3021], EPA delayed the 1985 particulate standards for cars and light trucks by two years. Therefore, the 0.37-g/km standard is applicable to model years 1982 through 1986, and the 0.12/0.16-g/km standards (cars/light trucks) come into effect with the 1987 model year. The 1987 standards will continue indefinitely until EPA determines the need for revision.

Because of California's more immediate need for pollution control, the California Air Resources Board adopted more stringent controls than those imposed for the rest of the United States. California's particulate standards for diesel passenger cars and light trucks are 0.25 g/km (0.40 g/mi) in 1985, 0.12 g/km (0.20 g/mi) in 1986, and 0.05 g/km (0.08 g/mi) in 1989.

Heavy-Duty Truck and Bus Standards

The very first particulate standards for heavy-duty diesel engines were promulgated in a recent EPA rulemaking, published March 15, 1985 [50 FR 10606]. This action established particulate standards of 0.80 g/kWh (0.60 g/bhph) for engines of model years 1988 through 1990; 0.34 g/kWh (0.25 g/bhph) for model years 1991 through 1993 (except for urban bus engines of these model years, which will be subject to a 0.13-g/kWh, or 0.10-g/bhph, standard); and finally, 0.13 g/kWh (0.10 g/bhph) for all heavy-duty diesel engines produced during model year 1994 and later. The State of California has proposed a heavy-duty diesel standard of 0.13 g/kWh (0.10 g/bhph) to be effective in 1990 (earlier than in the rest of the country).

Pre-1988 heavy-duty diesel engines are not subject to any particulate standards; however, exhaust smoke (opacity) limits for heavy diesels were among the first emissions standards set forth by the EPA. In a rulemaking established June 4, 1968 [33 FR 8304], smoke standards were promulgated and specified in terms of percent of light allowed to be blocked by the smoke in the diesel exhaust (as determined by a light extinction meter). Heavy-duty diesel engines produced during model years 1970 through 1973 were allowed a light extinction of 40 percent during the acceleration phase of the certification test and 20 percent during the lugging portion; 1974 and later model years are subject to smoke opacity standards of 20 percent during acceleration, 15 percent during lugging, and 50 percent at maximum power.

## European and Japanese Regulations

### Diesel Exhaust Standards

In Europe, the vehicle exhaust emissions standards recommended by the United Nations-sponsored organization, the Economic Commission for Europe (ECE), are generally adopted in total by the common-market European Economic

Community (EEC). In turn, member countries of the EEC are bound by the organization's charter to adopt the emissions regulations. With the exception of Sweden, all major countries within Europe apply the ECE exhaust regulations as national law.[4]

To date, the ECE has not developed any regulations pertaining to particulate emissions from diesel cars or trucks; however, no review of pending actions in Europe was performed. The only exhaust standards currently imposed on heavy-duty diesel engines in Europe are smoke limits. Due to individual delays in adopting various amendments to the ECE regulations, the stringency of the smoke standards varies from country to country. West Germany's limits are the most permissible in Europe, while the United Kingdom and Denmark are two of the more stringent regulators of diesel smoke. All European countries except Hungary, Ireland, and Luxemburg (as of 1980) have adopted smoke standards which are, on the whole, comparable to (or slightly more stringent than) U.S. diesel smoke regulations.[4]

As in Europe, Japan does not currently regulate exhaust particulate emissions from diesel engines.

However, standards on diesel smoke levels have been enforced on both new and in-use vehicles since 1972 and 1975, respectively. The maximum permissible limits for both are 50-percent opacity levels[4]; however,the new vehicle standard is the more stringent because smoke is measured at full load, while in-use vehicles are required to meet the standard under the less severe no-load acceleration test.[5] Japan's smoke standard for new vehicles is comparable to the U.S. standard of 50-percent opacity at maximum power.

These current smoke standards provide some degree of emissions control; however, because they do not focus on particulate levels over an average driving cycle and are not particularly stringent, their effect on particulate emissions is somewhat limited. This is evidenced by recent U.S. regulation of heavy-duty diesels -- the particulate standards recently promulgated represent an 85-percent reduction from the emission rates existing under the current smoke standards. Based on U.S. test data showing current European diesel engines emitting basically the same levels as in the U.S., diesel particulate emissions throughout the world remain essentially uncontrolled at the present time.

## Ambient Air Quality Standards

In addition to imposing vehicle exhaust regulations, the EEC is also responsible for establishing ambient standards for suspended particulate matter (SPM) in European countries. Prior to development of the EEC standards, member countries based their air quality standards primarily on black smoke measurements; EEC's standards are expressed two ways -- in terms of black smoke and mass concentration. For purposes of comparison to U.S. standards, the gravimetric-based EEC standards are highlighted here.

Although direct comparison is somewhat difficult because of the differing form of the standards, EEC's current ambient SPM regulations appear to be less stringent than the U.S. NAAQS for TSP. The European standards are an annual arithmetic mean of 150 $ug/m^3$ (compared to the U.S.'s annual geometric mean of 75 $ug/m^3$) and 300 $ug/m^3$ as an annual 95th percentile of daily values in a year (roughly speaking,, the eighteenth highest daily value, compared to 260 $ug/m^3$ as a second maximum daily average in the U.S.).[6] Again, no pending regulations in Europe were reviewed.

In Japan, ambient standards have been established for suspended particulate matter -- defined (by the Japanese) as airborne particles of 10 microns or less in diameter.[6] As this classification corresponds to the definition of $PM_{10}$ in the U.S., Japanese limits are most appropriately compared to the EPA-proposed $PM_{10}$ standards. Japan allows a maximum daily average of 100 $ug/m^3$, with hourly values not permitted to exceed 200 $ug/m^3$.[5] Compared to the maximum allowable daily average of 150-250 $ug/m^3$ proposed by the U.S. EPA, Japan's standard appears to be more stringent. However, because the U.S. is also proposing an allowable annual mean between 50 and 65 $ug/m^3$, the U.S. standards may be somewhat more stringent than those in Japan, where (by nature of the daily standards) the annual mean could be as high as 100 $ug/m^3$ if the daily averages were very consistent. Thus, a precise comparison of the U.S. and Japanese standards cannot be made without using actual monitoring data to simulate typical daily and seasonal variations.

## ENVIRONMENTAL IMPACT

The need for control (or further control) of diesel particulate is based primarily on estimates of the environmental impact associated with a particular level of emissions. Environmental impact is generally evaluated both in terms of emissions inventories (tons of pollutant per year) and ambient air quality (pollutant concentrations) estimated for selected areas. This section begins with a summary of diesel particulate emissions and ambient concentrations for urban areas across the U.S.; both current and future projections are shown. The discussion on the U.S. is followed by estimated ambient diesel particulate concentrations for selected cities in Europe and Japan, based on methodologies used in the United States.

United States

In support of the recently published particulate standards for heavy-duty diesel engines for 1988 and later model years, the U.S. EPA evaluated the current in-use situation and made projections of future diesel particulate emissions and ambient concentrations for the urban United States. Future projections were based on two scenarios: 1) assuming uncontrolled heavy-duty diesel emissions (at 0.94 g/kWh), and 2) assuming the levels of control promulgated on March 15, 1985 (0.80, 0.34, and 0.13 g/kWh in 1988, 1991, and 1994, respectively).[50 FR 10606] Results of EPA's analysis were published in the final Regulatory Impact Analysis for the NOx/particulate rulemaking[3], and are briefly reviewed below.

## Emissions Inventories

Diesel particulate emissions inventories were constructed for urban areas across the U.S. in aggregate; estimates are shown in Tables I and II. Inventories are broken down into various vehicle classes, designated as follows: light-duty diesel vehicles (passenger cars) as LDDV, light-duty diesel trucks (less than 8,500 pounds rated gross vehicle weight, or GVW) as LDDT, and heavy-duty diesel vehicles as HDDV. In Table II, the HDDV category is further divided by weight classification, with Classes 2B-8A including trucks with GVWs between 8,500 and 50,000 pounds, Class 8B designating "line-haul" diesels over 50,000 pounds GVW (with trailer GVW, if applicable), and buses. "Base" and "controlled" scenarios differ in the future HDDV standards (as explained above), but both assume the same LDV/LDT standards -- 0.12/0.16 g/km, beginning with the 1987 model year.

As shown in Table I, diesel particulate emissions in the urban U.S. were expected to grow to twice the current level by the year 2000 if no further HDDV control had been imposed. It is the HDDV category that makes up the majority of total emissions, currently representing over 80 percent; Table II shows that line-haul diesels (Class 8B) are the largest contributor of all, accounting for 50 percent of current HDDV emissions, or over 40 percent of total diesel particulate emissions in 1984.

The effect of HDDV control (including the more stringent control on urban buses) is significant, with the combined 1988/91/94 standards bringing about an estimated 46 percent decrease from the base (uncontrolled) case in the year 2000. This level of control essentially prevents significant growth beyond current levels, with about an 11-percent increase projected between 1984 and 2000.

Air Quality

Because it is difficult (if not impossible) to distinguish diesel particulates from the other particles collected at ambient monitors, a surrogate method of estimating ambient concentrations of diesel particulate alone was used. The most commonly used surrogate for diesel particulate matter is lead, since motor vehicle emissions represent the primary source of lead in the atmosphere. (Of course, the lead surrogate method is not valid for cities in which lead smelting operations are found.) Carbon monoxide has also been used as a surrogate by EPA, particularly in estimating average urban exposure in determining cancer risk.[1]

The lead surrogate method uses historical ambient lead concentrations in urban areas as indices of mobile source pollutant levels. Both the automotive fleet's lead emission factor for the year in which the ambient lead measurements were made and the expected diesel particulate emission factor for the year of projection are estimated and assumed to have a proportional effect on ambient concentrations. Taking into account future growth in vehicle miles travelled (VMT) and the differing dispersion characteristics of lead and diesel particulate, ambient concentrations of diesel particulate are estimated. (For more details on the methodology used in EPA's projections, see the Diesel Particulate Study[1].)

The EPA's lead-based projections of current and future ambient diesel particulate concentrations for urban areas in the U.S. are presented in Table III. (The future scenarios shown are the same as those presented earlier.) As indicated, the impact of growth in diesel particulate emissions on urban air quality is significant. Current ambient diesel particulate concentrations in large U.S. cities are projected to grow from an average of 1-3 ug/m$^3$ to levels of 3-7 ug/m$^3$ by the year 2000 with no control on HDDVs. With the HDDV standards recently promulgated, diesel particulate concentrations in large cities will be lowered to 1.5-4 ug/m$^3$, a reduction to almost half of baseline concentrations in the year 2000.

Europe and Japan

Background and Methodology

Information on levels of diesel particulate emissions and ambient concentrations outside of the U.S. was rather limited. However, for selected cities in Europe and Japan, a review of the American literature provided adequate information to allow use of the lead surrogate model to roughly estimate recent (1982) ambient diesel particulate levels, which is the same approach used by the EPA to project concentrations in U.S. cities.

The three European and nine Japanese cities included in this part of the study were chosen based on the availability (in the American literature) of information on local ambient lead levels in any base year; in this analysis, base years range from 1975 to 1981, depending on the area. Given this, the remaining factors necessary for calculation of ambient diesel particulate levels for these cities were: 1) a fleet-wide lead emission factor for the base year, 2) a fleet-wide diesel particulate emission factor for the year of projection (1982), 3) estimated VMT growth between the base year and year of projection, and 4) the ratio of diesel particulate dispersion to lead dispersion. This dispersion ratio was estimated at 1.00 to 0.43 in the Diesel Particulate Study.[1] The other three factors had to be calculated for each area using data available in the American literature; because this information was usually not provided for a specific city, data for the appropriate countries were used. The three factors calculated for each of the five countries examined are shown in Table IV, along with monitored ambient lead concentrations; the approaches used to determine the various factors are described below. (The table includes U.S. factors for comparison.)

Before the fleet-wide composite lead and diesel particulate emission factors could be calculated, the VMT breakdown by vehicle class to be used in weighting the class-specific emission factors had to be estimated for the two years of interest. If such a breakdown was not already provided in the literature, data on per-vehicle annual VMT, annual fleet registrations and fleet diesel penetrations were used to estimate the percentage of travel by each of the four classes: gasoline-fueled cars, diesel-powered cars, gasoline-fueled trucks, and diesel-powered trucks. (If possible, the gasoline and diesel truck classes were further broken down into light-duty trucks, heavy-duty trucks, and buses.)

Next, base-year lead emission factors were estimated for the gasoline-fueled car and truck classes, using the lead content of gasoline and the manufacturer-weighted average fuel consumption value for the appropriate country. Assuming that 75 percent of the lead contained in the gasoline is eventually emitted with the exhaust[1], the estimated class-specific lead factors (in g/km) were averaged for the fleet using the VMT breakdown calculated above. (Of course, the lead emission factors for the diesel-powered vehicles and trucks were zero.)

The fleet-wide diesel particulate emission factor for the year of projection was calculated using estimates of uncontrolled emissions from each of the vehicle classes. Based on relative engine sizes, diesel cars and light trucks were assumed to emit 0.31 g/km (0.50 g/mi) in the European countries and 0.22 g/km (0.35 g/mi) in Japan. All heavy-duty diesel truck and bus emissions were estimated at 0.94 g/kWh, which was converted to g/km using factors developed in an EPA technical report.[7] Again using the VMT breakdown calculated earlier, these class-specific estimates were averaged to yield the fleet-wide diesel particulate emission factor for 1982.

Finally, growth in VMT between the base year and year of projection (which vary with available data) was estimated for each of the areas being examined. Because Japan's annual compound growth rate was calculated between 1975 and 1982, instead of during the economically depressed 1980-82 period used for the European countries, Japan's rate is significantly higher than the others.

Combining all of the above factors, and multiplying by 0.9 to account for the estimated mobile source contribution to total lead emissions[1], ambient diesel particulate concentrations were calculated for the selected European and Japanese cities. Lead-based estimates are shown in Tables V and VI for cities in Europe and Japan, respectively.

Europe

As indicated in Table V, 1982 levels of ambient diesel particulate in European cities appear to be significantly higher than current estimates for U.S. cities. Within urbanized portions of Naples, Birmingham, and Stockholm, estimated concentrations range from 2.5-35.1 $ug/m^3$, compared to 1.3-3.0 $um/m^3$ in the largest U.S. cities. This relationship is expected for two reasons: 1) lack of any controls on diesel particulate emissions in European countries and 2) significantly higher diesel penetration of European passenger car and light truck markets (to be discussed in further detail in the next major section).

Of the three European cities examined, Naples has the highest estimated ambient concentrations; again, this seems reasonable in view of the significantly high diesel penetration of Italian markets in comparison to English and Swedish sales -- among the lowest diesel penetrations in Europe. As countries with the lowest and highest diesel sales fractions in Europe are represented in Table V, ambient diesel particulate concentrations in other European cities could be very roughly estimated using relative gasoline prices and gasoline/diesel price differentials (to be analyzed in the next major section).

## Japan

Lead-based estimates of ambient diesel particulate in selected Japanese cities are presented in Table VI. The nine cities are ranked according to population; as in the U.S., in general, the most heavily-populated cities tend to have the higher concentrations due to higher levels of motor vehicle activity. In Japan, cities with populations over 1,000,000 are estimated to have ambient diesel particulate levels ranging from 1.4 to 10.2 ug/m$^3$, compared to the estimate of 1.3-3.0 ug/m$^3$ for the largest U.S. cities. As in Europe, the higher diesel particulate levels in Japan (as compared to the U.S.) are expected due to higher diesel penetration and lack of diesel particulate controls.

## WORLDWIDE DIESEL PENETRATION -- PRESENT AND FUTURE

Over the past decade, rising fuel prices in the United States and abroad have enhanced the popularity of the diesel engine as a fuel-saving technology. In the early 1970's, the use of diesel engines -- formerly only found in the heavier trucks -- spread into the passenger car and lighter truck markets. Because the popularity of diesel-powered vehicles is naturally linked to fuel prices, the first part of this section focuses on the price of gasoline versus that of diesel fuel in the U.S., Europe, and Japan. Following this, the relative fuel prices are compared to trends in diesel penetration of the automobile and truck markets in the countries examined.

### Gasoline versus Diesel Fuel Prices

In comparison to European countries and Japan, the U.S. traditionally has significantly lower prices for both gasoline and diesel fuel, with U.S. pump prices at times less than half the cost of fuel abroad. As Table VII shows[6,8,9], of the countries examined, Italy has recorded the highest gasoline prices in recent years, with the cost over $3/gallon at times during 1983. Japan's gasoline prices have come down since 1980 (when they were comparable to Italy's high rate), but have been surpassed in price by only one to two European countries in more recent years.

As relevant as the absolute cost of gasoline is the price differential between gasoline and diesel fuel, since it is the traditional price advantage of diesel fuel that helps make diesel-powered vehicles more attractive to consumers. Although gasoline prices in Italy are high, the price of Italy's diesel fuel tends to be among the lowest in Europe; therefore, consumers in Italy are offered a more substantial diesel price advantage than that available in the other countries examined. As indicated in Table VII, gasoline prices in Italy tend to be roughly double the cost of diesel fuel, while the U.S. price differential over the last decade has been only 25-30 percent (i.e., the ratio of gasoline price to diesel fuel price was between 1.25 and 1.30, as shown in the table). However, recently, the price differential in the U.S. has become even smaller. In Japan, gasoline has been priced roughly 40 percent more than diesel fuel. The advantage of diesel fuel is smallest in the United Kingdom and West Germany -- with differentials of less than 10 percent -- and Switzerland, where diesel fuel actually costs more than gasoline.

Diesel Penetration of the Automobile and Truck Markets

As one would expect, sales of diesel-powered automobiles tend to be highest in those countries that offer the greatest price advantage with diesel fuel and the highest gasoline prices. As Table VIII shows[8,9,10], diesel penetration of the passenger car market in recent model years has been highest in Belgium, Italy, and Spain, where roughly one in every four new cars sold is equipped with a diesel engine. As shown previously in Table VII, Italy has traditionally offered the greatest pump price advantage, selling diesel fuel for roughly half the cost of gasoline. Although Belgium's fuel price differential is lower than Italy's and Spain's, and even lower than that in Sweden and the Netherlands, diesel-powered cars have been more popular in Belgium than in any other European country since the late 1970's. This is primarily due to the relatively high cost of gasoline in Belgium. Of the countries examined, diesel vehicles have traditionally been the least popular in the United Kingdom and Switzerland, where diesel fuel costs roughly the same or even more than gasoline.

Although the price differential between gasoline and diesel fuel in the U.S. is comparable to that in France (as shown in Table VII), the absolute cost of gasoline in the U.S. is roughly half that in France and other European countries. Therefore, it is not surprising that U.S. diesel sales fractions have always been significantly lower than those in the majority of the European countries (see Table VIII). The popularity of diesel automobiles in the U.S. peaked in 1981, when 6 percent of new car sales were diesels. Since then, the figures have declined and are currently comparable to diesel fractions in the United Kingdom and Switzerland, which are the lowest in Europe. This decline in U.S. diesel penetration has followed the recent reduction in the gasoline/diesel price differential. Even though several American auto manufacturers have reduced their diesel sales projections, some growth in diesel share is still projected both by manufacturers and EPA. In its air quality projections in support of the recently published diesel particulate standards for heavy-duty vehicles [50 FR 10606, March 15, 1985], EPA assumed a 5-percent diesel penetration of new automobile sales by 1990; General Motors also predicts diesel growth, but estimates that the 5-percent level will not be reached until 1995.[3]

Limited data (from American literature) on the diesel fraction of new car sales in Japan[8], presented in Table VIII, indicate that diesels are slightly more popular in Japan than in the U.S., but are less popular than in most of Europe. This trend is supported by the relative fuel price advantages shown in Table VII -- gasoline in Japan costs roughly double that in the U.S., and Japan currently has a significantly larger price differential between gasoline and diesel fuel. Because information on new diesel car sales in Japan was limited, available data on the diesel fraction of the in-use automobile fleet in Japan was examined as well. These in-use registration data confirmed the trend cited above -- diesel penetration of Japan's passenger car fleet in 1982 was at roughly 2.6 percent[5], compared to a 1.8-percent diesel penetration of the U.S. fleet in the same year[11]. Future projections for both countries are consistent with historic trends; Japan predicts a 10-percent diesel penetration of the fleet by 1992[8], compared to a U.S. estimate of 4 percent for the same year [12].

Because dieselization of the heaviest truck fleet began decades before diesel-powered passenger cars became popular, and because heavy-duty dieselization is less in a state of flux, there generally tends to be limited information published on the diesel penetration of the heavy-duty fleet. This is particularly true in European countries, where heavy-duty vehicles represent a relatively small fraction of road vehicles (compared to Japan or the U.S.).[8] However, diesel penetration of the light-duty truck market is changing almost as rapidly as with automobiles; but, unfortunately, light-duty and heavy-duty trucks are often reported within the same general category of "trucks", making it difficult to separate the two.

Adequate information on the current diesel penetration of new light-duty truck sales was available in the American literature only for the U.S., where diesels presently account for approximately 8 percent of new light trucks. This figure is projected to grow to 15 percent of new sales by 1990, according to the EPA.[3] The only Japanese projection found estimated that, by 1992, 50 percent of the <u>in-use</u> light-duty truck fleet in Japan will be diesels.[12] This figure compares to a U.S. projection of 10-percent penetration of the in-use fleet by 1992.[11] Based on this, the same trend noted for passenger cars seems to hold true for light-duty passenger trucks as well -- due to higher Japanese gasoline prices and diesel price advantages, diesels appear to be more popular in Japan than in the United States.

Based on the relative trends in diesel penetration shown in Table VIII, it is not surprising that current ambient diesel particulate concentrations in European and Japanese cities are estimated to be significantly higher than in the United States. Even though the popularity of diesel engines in cars and light trucks is lower in the U.S., EPA has determined that there is a substantial need to regulate diesel particulate emissions in the future. In view of current ambient particulate levels and the growing popularity of diesel engines in Europe and Japan, it appears that the environmental need to control particulate emissions from diesel vehicles in these countries is perhaps even greater than in the United States. The final section of this analysis focuses on various techniques available to control these particulate emissions, including approaches already being implemented and those under consideration in the United States.

## DIESEL PARTICULATE CONTROL TECHNIQUES

Particulate emissions from diesel-powered vehicles can be controlled using various techniques, involving either reduction of the actual formation of particulate or the use of exhaust treatment to reduce levels allowed to reach the atmosphere. Three basic approaches to controlling diesel particulate emissions will be discussed in this section, beginning with engine modifications to reduce emissions of unburned particles from the engine. The second approach reviewed is exhaust aftertreatment, primarily the use of trap-oxidizer systems to capture particulate and combust it periodically. Finally, the third approach reviewed is to modify the fuel to reduce particle formation either in the engine or exhaust.

### Engine Modifications

Diesel combustion occurs around the surface of tiny fuel droplets where the fuel-air ratio is quite rich. The rate and extent of combustion is quite sensitive to numerous parameters, such as combustion chamber geometry, piston bowl or prechamber design, injector design, and injection pressure and timing. Because diesel particulate is comprised mainly of the carbon residue of unburned fuel droplets, any modifications to the parameters described above are likely to have an effect on particulate emissions. However, as each manufacturer's engine design is somewhat unique, beneficial modifications for one engine do not always translate to another and assessments of the benefits of engine modifications are difficult to perform generically. Suffice it to say that nearly all of the techniques attempt to enhance complete combustion of each fuel droplet. This can be done by increasing the amount of oxygen present via turbocharging, decreasing the amount of fuel available (fuel governing), increasing the amount of time available for combustion (advanced injection timing), or increasing fuel-air mixing (increased swirl, higher injector pressure).

Unfortunately, most of these techniques also increase nitrogen oxides (NOx) emissions, which represent another significant environmental impact of diesel engines.[3] The use of engine modifications must be balanced to obtain reductions of both pollutants. Electronic controls are very useful in performing this balance because of their flexibility and precision. In addition, general reductions in brake-specific fuel consumption also lead to commensurate reductions in both particulate and NOx emissions, since fuel-specific emissions tend to be constant under these conditions.[3]

On small (1.6-2.5-liter) LDDVs, engine controls have reduced emissions to levels below 0.12 g/km particulate and less than 0.62 g/km NOx. On larger LDDVs (4.3-5.7-liter engines), engine controls have achieved levels of 0.16-0.22 g/km particulate at NOx levels of 0.62-0.93 g/km.[1,13]. With respect to HDDVs, EPA projects that engine controls can achieve 0.80 g/kWh particulate and 8.0 g/kWh NOx by the 1988 model year. By 1991, engine-out emission levels of 0.67 g/kWh particulate and 6.7 g/kWh NOx are projected to be achievable.

In the longer term, adiabatic or heat-retaining combustion techniques may hold great promise for particulate control. Early testing has shown dramatic particulate reductions at constant NOx emissions. However, there is some doubt about whether these results will be indicative of production technology.[3]

The cost of engine-related particulate controls tends to be small since the modifications are usually integral to the engine itself and involve no new hardware. Electronic controls and turbocharging are the exceptions. However, many manufacturers, especially those of heavy-duty diesel engines, are moving to these technologies for reasons other than emission control (i.e., fuel economy), so even here the cost attributable to emission control may be small.

## Trap-Oxidizer Systems

The second type of particulate control is exhaust aftertreatment, with the primary technique being a trap-oxidizer system. This device, placed at the end of the exhaust manifold, serves as a "filter", removing solid particles from the exhaust flow. Periodically, the trap undergoes regeneration, during which the particulate matter captured is burned off, since space is not available to capture a lifetime supply of particulate. The most common filter media used to date is a porous ceramic material, usually an automotive catalyst substrate with alternate ends of each channel plugged to force exhaust flow through the thin ceramic wall; stainless wire-mesh or steel-wool traps are also being researched.[2,3]

The particulate reductions achievable via trap oxidizers are substantially greater than those possible with engine modifications alone. In tests performed on various makes of diesel-powered passenger cars equipped with ceramic traps, an average of 80 percent of the total particulate matter generated was captured by the trap. Removal of the soluble organic fraction (SOF) of the particulate emissions, which is the portion regarded as the most carcinogenic, was just slightly less efficient at 70 percent. Limited data on heavy-duty vehicles equipped with ceramic traps produced roughly the same results.[1] Wire-mesh traps are generally less efficient with respect to total particulate (a rough average of 65-percent removal), but can be somewhat more efficient with respect to the SOF.[1]

Regeneration techniques aim at either raising the exhaust temperature or lowering the temperature of particle combustion, since typical exhaust temperatures alone are not sufficient. Fuel burners and electrical heaters are the most popular among the former, and catalysts -- either on the filter material, in the fuel or injected into the exhaust -- are prominent among the latter. Catalytic fuel additives, while appearing to be the most effective, are potentially an environmental concern themselves if they contain toxic metals which reach the atmosphere. Their potential use is being watched carefully by EPA.

Particulate traps are currently installed on only one model sold in the United States -- a 1985 Mercedes 300D sold in California and other western states (so equipped to meet California's particulate standard). However, the diesel particulate emission standards that EPA has promulgated for future model years are technology-forcing and traps will be necessary on some 1987 and later model year passenger cars and light trucks and on most 1991 and later model year HDDVs. As substantial research and development of traps suitable for the light-duty vehicles have already been performed, manufacturers are expected to have little difficulty meeting these standards. Development of traps for heavy-duty vehicles is not as far along, but since the first trap-based standards for this heavy class (0.34 g/kWh for trucks and 0.13 g/kWh for urban buses) are not effective until 1991, additional time exists for proper development.

EPA has estimated the cost and cost-effectiveness associated with the trap-forcing standards promulgated for the various vehicle classes.[1,3] For 1987 and later diesel passenger cars and light trucks, the lifetime consumer cost associated with reducing a vehicle's emission rate from 0.37 to 0.12 g/km (via a trap) is approximately $250-270, or an annualized cost of roughly $40. Because averaging is permitted in meeting this standard, traps will be installed only on a portion of each manufacturer's sales. Based on the fleet cost at appropriate trap usage rates and the estimated reductions in emissions resulting from the 0.12-g/km standard, the cost-effectiveness of this technique is approximately $13,500/Mg.[1]

Depending on engine size, heavy-duty traps are projected to cost $580-1850 (including a fuel economy penalty of 1.0-1.5 percent); these estimates represent lifetime costs discounted to the year of vehicle purchase at a rate of 10 percent per annum. In order to meet the 1991 heavy-duty particulate standards of 0.34 g/kWh for trucks and 0.13 g/kWh for urban buses, both of which permit averaging, approximately 60 percent of the trucks and 100 percent of the urban buses will likely require traps. Based on the emissions reductions projected, the cost-effectiveness associated with the 1991 trap standards is approximately $11,900-13,900/Mg.[3]

In 1994, heavy-duty truck engines are required to meet a 0.13-g/kWh standard (with averaging), which represents a long-term trap-usage rate of 90 percent; urban buses will still be subject to the 0.13-g/kWh standard set for 1991, requiring 100 percent of the buses to be equipped with traps. Based on these trap-usage rates, the cost-effectiveness of the additional emissions benefit associated with the 1994 standard is between $17,000 and $20,000/Mg.[3]

## Fuel Variations

A number of recent studies have focused on the impact of fuel characteristics on diesel particulate emissions. Initial published findings on the effect of variations in such diesel fuel parameters as aromatics content, 90-percent distillation temperature, and sulfur content are briefly summarized in the first section below. The second section reviews recent tests on the conversion of diesel engines to methanol fuel.

Diesel Fuel Modifications

Recent research has identified the following three fuel parameters as those having the greatest impact on the level and composition of particulate emissions from diesel engines: 1) sulfur content, 2) aromatics content, and 3) back-end volatility (90-percent distillation temperature). Fuel sulfur contributes to particulate emissions through the formation of sulfate and associated bound water, and also by increasing the amount of soluble organic material absorbed on the carboneous particles. Aromatics and volatility ($T_{90}$) affect the amount of carboneous material formed.[14]

Chevron's steady-state tests on a heavy-duty diesel engine showed that an 88-percent decrease in fuel sulfur content (from 0.4 percent to 0.05 percent) resulted in a 36-percent reduction in particulate emissions. A two-thirds reduction in aromatics content (from 30 percent to 10 percent) resulted in an additional particulate decrease of 16 percent. And, finally, an 18-percent decrease in $T_{90}$ (from 316° C to 260° C) lowered particulate emissions by another 8 percent.[14] Unfortunately, such changes in diesel fuel composition appear to be prohibitively expensive, though they are currently being evaluated in greater detail.

Fuel sulfur, unlike the other two properties, also influences the composition of diesel particulate, primarily by increasing the amounts of sulfate, bound water, and soluble organics. However, the change in solid carboneous material formed is not significantly affected by a change in sulfur. Chevron's test results show that an increase in fuel sulfur content from 0.20 percent to 0.55 percent caused the following: 1) a three-fold increase in the amount of sulfate and bound water produced, 2) more than double the amount of soluble organics collected on the particulate, and 3) only an 8-percent increase in solid carboneous material produced. The overall effect of the increased fuel sulfur content was a 63-percent increase in the level of diesel particulate emitted.[14]

Data published in a 1979 EPA report suggest that the impact of certain fuel parameters -- aromatics content, in particular -- on particulate emissions may be greater for light-duty diesel vehicles (cars) than that demonstrated with the heavy-duty engines. Test results show that a two-thirds reduction in aromatics content resulted in a decrease in particulate ranging from 21 to 54 percent.[15] Using the same reduction in aromatics, these figures can be compared to Chevron's heavy-duty results -- lower at a 16-percent decrease in particulate. The noted difference between the light-duty and heavy-duty results is not particularly surprising in view of the contrast in combustion chamber design between the two classes. However, part of the difference may also be due to the fact that EPA's light-duty testing involved transient operation (a known source of high particulate emissions), while Chevron's heavy-duty study only involved steady-state testing. Thus, the heavy-duty test results must be used with some caution since they may or may not be indicative of emission trends under more realistic conditions.

Conversion to Methanol

While modifications to diesel fuel are limited by both cost and refinery capacity, the use of an entirely different fuel -- methanol -- in converted diesel engines appears to hold great promise for emission control. Available data from tests conducted on two types of diesel bus engines modified to operate on neat methanol show methanol to be significantly cleaner-burning than diesel fuel, without use of a trap-oxidizer.

The two methanol-fueled engines were developed by M.A.N. of Germany and General Motors of the U.S. and both are currently being used in public transit buses in the San Francisco area.[16] The M.A.N. engine (equipped with a catalyst) was tested over the transient cycle for EPA at Southwest Research Institute and found to have emissions of 0.06 g/kWh (0.04 g/bhph) particulate and 8.9 g/kWh (6.6 g/bhph) NOx.[17] GM's steady-state (13-mode) tests of their engine without a catalyst showed emissions of 0.23 g/kWh (0.17 g/bhph) particulate and 2.9 g/kWh (2.2 g/bhph) NOx.[18] Transient testing of an aftermarket conversion of a GM diesel bus engine equipped with a catalyst showed emissions of 0.08 g/kWh (0.06 g/bhph) particulate and 2.8 g/kWh (2.1 g/bhph) NOx; steady-state (13-mode) tests on the same engine indicate emissions of 0.03 g/kWh (0.02 g/bhph) particulate with 4.0 g/kWh (3.0 g/bhph) NOx.[19,20]

Although particulate and NOx data on methanol-fueled diesel engines are limited, the results to date appear very promising as typical emissions from these engines are 0.7-0.9 g/kWh (0.5-0.7 g/bhph) particulate and 9-12 g/kWh (7-9 g/bhph) NOx. Of course, such factors as the cost-effectiveness of methanol fuel and the practicality of converting diesel engines to methanol operation must be considered in evaluating this approach as a viable diesel particulate control technique. However, for transit buses, their use of a central fuel depot makes distribution of methanol quite simple and their extensive use in crowded urban areas makes the control of their emissions a number-one priority.

## CONCLUSIONS

The environmental impact of diesel particulate emissions is a prime concern in the United States. Both health (carcinogenic and non-carcinogenic) and welfare (visibility and soiling) effects are significant. Legislative action has mandated stringent control and EPA has followed with regulations requiring up to an 85-percent reduction from uncontrolled levels, holding year 2000 particulate levels at only slightly greater than 1982 levels, despite the projected large growth in diesel usage. Traditional engine-related controls provide only a small part of this reduction. Rapidly developing trap-oxidizer technology is expected to provide the lion's share. The use of methanol in specially designed diesel engines also appears capable of providing this substantial degree of reduction.

The current environmental impact of diesel particulate in Europe and Japan appears to generally exceed that in the United States. Given that gasoline prices are much higher in Europe and Japan than in the United States, making diesels more popular, diesel particulate levels in the future can be expected to increase in these areas even faster than in the United States. To date, however, no particulate emission standards have been implemented in Europe and Japan (only smoke standards of very limited effectiveness), and emission levels are generally analogous to those in the United States prior to regulation. The technology to significantly reduce these emissions is now or will soon be available. Thus, worldwide reduction of the environmental impacts of diesel-powered motor vehicles awaits only a decision to act.

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Table I. Current and Future Diesel Particulate Emissions in Urban Areas of the United States (Mg/year)[6]*

| Vehicle Classes | 1984 Levels | 1995 HDDV Scenarios Base (0.70) | 1995 HDDV Scenarios Controlled (0.60/.25/.10) | 2000 HDDV Scenarios Base (0.70) | 2000 HDDV Scenarios Controlled (0.60/.25/.10) |
|---|---|---|---|---|---|
| LDDV | 5,181 (11%)** | 12,175 (15%) | 12,175 (23%) | 17,909 (18%) | 17,909 (33%) |
| LDDT | 2,265 (5%) | 11,884 (15%) | 11,884 (23%) | 18,830 (19%) | 18,830 (35%) |
| HDDV | 40,925 (84%) | 55,895 (70%) | 27,970 (54%) | 62,298 (63%) | 17,185 (32%) |
| Total | 48,371(100%) | 79,954(100%) | 52,029(100%) | 99,037(100%) | 53,924(100%) |

* Mg = Metric ton.

** Figures in parentheses indicate percent of total.

Table II. Breakdown of HDDV Emissions in the Urban Areas of the United States (Mg/year)[6]*

| Vehicle Classes | 1984 Levels | 1995 HDDV Scenarios Base (0.70) | 1995 HDDV Scenarios Controlled (0.60/.25/.10) | 2000 HDDV Scenarios Base (0.70) | 2000 HDDV Scenarios Controlled (0.60/.25/.10) |
|---|---|---|---|---|---|
| 2B-8A | 14,025 (34%)** | 21,875 (39%) | 11,232 (40%) | 24,857 (40%) | 6,855 (40%) |
| 8B | 19,828 (49%) | 24,282 (44%) | 12,536 (45%) | 26,281 (42%) | 7,405 (43%) |
| Buses | 7,073 (17%) | 9,739 (17%) | 4,202 (15%) | 11,160 (18%) | 2,924 (17%) |
| Total | 40,926(100%) | 55,896(100%) | 27,970(100%) | 62,298(100%) | 17,184(100%) |

* Mg = Metric ton.

** Figures in parentheses indicate percent of total.

Table III. Current and Future Ambient Concentrations of Diesel Particulate in U.S. Cities (micrograms per cubic meter)[6]

| U.S. City Population | 1984 | 1995 Base | 1995 Controlled | 2000 Base | 2000 Controlled |
|---|---|---|---|---|---|
| Greater than 1,000,000 | 1.3-3.0 | 2.3-5.5 | 1.5-3.6 | 2.9-6.8 | 1.6-3.7 |
| 500,000-1,000,000 | 0.8-2.0 | 1.5-3.6 | 1.0-2.4 | 2.0-4.6 | 1.1-2.5 |
| 250,000-500,000 | 1.0-1.6 | 1.8-3.0 | 1.2-2.0 | 2.2-3.7 | 1.2-2.0 |
| 100,000-250,000 | 0.7-1.7 | 1.2-3.2 | 0.8-2.1 | 1.5-4.0 | 0.8-2.2 |

* Ranges are average values plus and minus one standard deviation.

Table IV. Inputs to the Lead Surrogate Model

| Country | Fleetwide EF (g/km) Lead* | Fleetwide EF (g/km) Diesel Particulate** | VMT Growth (%/Year) | Ambient Lead Concentration (ug/m$^3$) |
|---|---|---|---|---|
| U.S. | .079 | .035 | 2.5 | 0.29-3.03 (1975) |
| Italy | .026 | .080 | 2.0 | 0.52-5.12 (1980) |
| U.K. | .047 | .069 | 1.0 | 0.16-1.75 (1980) |
| Sweden | .015 | .089 | 1.0 | 0.20-1.30 (1981) |
| Japan | .025 | .182 | 4.0 | 0.03-0.50 (1975) |

* Lead emission factors (EFs) were calculated for the base year in which ambient lead data were taken (shown in parentheses in last column).

** Diesel particulate EFs were calculated for year of projection (1984 for U.S.; 1982 for other countries).

*** Annual compound VMT growth rates were calculated between the base year and year of projection (vary with area).

Table V. Estimated Ambient Diesel Particulate Concentrations in Selected European Cities*

| Location | 1982 Concentration (ug/$m^3$) |
|---|---|
| Naples, Italy | -- |
| -urban | 7.2 - 35.1 |
| -industrial | 3.6 - 31.0 |
| Birmingham, England | -- |
| -urban | 3.2 - 20.3 |
| -rural | 0.5 |
| -university campus | 0.8 - 5.5 |
| Stockholm, Sweden | |
| -inner city | 2.5 - 16.4 |

* Estimates based on lead surrogate method.

Table VI. Estimated Ambient Diesel Particulate Concentrations in Selected Japanese Cities*

| City | Population | 1982 Concentration (ug/m³) |
|---|---|---|
| Tokyo | 8,350,000 | 10.2 |
| Osaka | 2,648,000 | 6.6 |
| Nagoya | 2,086,000 | 3.9 |
| Sapporo | 1,337,000 | 1.4 |
| Sendai | 617,000 | 2.1 |
| Amagasaki | 536,500 | 4.1 |
| Ichihara | 207,000 | 1.6 |
| Ube | 166,392 | 2.1 |
| Matsue | 133,000 | 0.6 |

* Estimates based on lead surrogate method.

Table VII. Worldwide Fuel Prices (U.S. Dollars/Gallon)[6,8,9]

| Country | 1982* | | | 1983* | | | 1985* | | |
|---|---|---|---|---|---|---|---|---|---|
| | Gas | Diesel | (Ratio)** | Gas | Diesel | (Ratio)** | Gas | Diesel | (Ratio)** |
| U.S. | 1.26 | 1.01 | (1.25) | 1.15 | 0.89 | (1.29) | - | - | - |
| Japan | 2.46 | 1.74 | (1.41) | 2.70 | 1.92 | (1.41) | - | - | - |
| U.K. | 2.46 | - | - | - | - | - | 1.76 | 1.75 | (1.00) |
| France | 2.24 | 1.83 | (1.22) | 2.51 | 2.07 | (1.21) | 2.26 | 1.70 | (1.33) |
| W. Germany | 2.04 | 2.00 | (1.02) | 2.14 | 2.12 | (1.01) | 1.69 | 1.58 | (1.07) |
| Italy | 2.65 | 1.35 | (1.96) | 3.16 | 1.64 | (1.93) | 2.51 | 1.32 | (1.90) |
| Sweden | 2.35 | 1.42 | (1.65) | 2.18 | 1.35 | (1.61) | 1.94 | 1.25 | (1.55) |
| Switzerland | - | - | - | 2.29 | 2.42 | (0.95) | 1.74 | 1.93 | (0.90) |
| Netherlands | 2.47 | 1.65 | (1.50) | 2.36 | 1.73 | (1.36) | 1.97 | 1.34 | (1.47) |
| Belgium | 2.64 | 1.85 | (1.43) | 2.53 | 1.98 | (1.28) | 2.01 | 1.48 | (1.36) |
| Spain | 2.22 | 1.47 | (1.51) | 2.38 | 1.57 | (1.52) | - | - | - |

* 1982 figures for July; 1983 and 1985 for January.

** Ratio equals gasoline price divided by diesel fuel price.

Table VIII. Worldwide Diesel Penetration of New Car Sales (% of Total Sales)[8,9,10]

| Model | Country | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | U.S. | Japan | U.K. | France | Germ. | Italy | Swed. | Switz. | Nether. | Belg. | Spain |
| 1970 | 0.1 | - | 0.1 | 1.8 | 2.8 | 0.4 | 4.1 | 0.1 | 0.9 | 1.6 | - |
| 1971 | 0.1 | - | 0.1 | 2.1 | 2.8 | 0.6 | 4.5 | 0.1 | 1.2 | 1.9 | - |
| 1972 | 0.1 | - | 0.1 | 2.4 | 3.4 | 0.8 | 4.2 | 0.1 | 1.6 | 2.1 | - |
| 1973 | 0.1 | - | 0.1 | 2.0 | 3.7 | 1.2 | 3.2 | 0.1 | 1.6 | 3.3 | - |
| 1974 | 0.2 | - | 0.1 | 3.3 | 4.6 | 1.6 | 4.5 | 0.1 | 2.2 | 4.3 | - |
| 1975 | 0.3 | - | 0.5 | 4.5 | 4.3 | 2.5 | 3.9 | 0.2 | 2.2 | 4.3 | - |
| 1976 | 0.2 | 0.4 | 0.5 | 4.3 | 3.8 | 2.9 | 4.4 | 0.1 | 2.1 | 3.9 | - |
| 1977 | 0.4 | 1.1 | 0.5 | 6.4 | 4.7 | 4.0 | 3.7 | 0.2 | 3.6 | 4.9 | - |
| 1978 | 1.1 | 1.5 | 0.4 | 6.5 | 5.8 | 4.4 | 4.1 | 0.1 | 3.7 | 7.6 | - |
| 1979 | 2.6 | 2.0 | 0.5 | 7.3 | 7.0 | - | 6.5 | 0.6 | 6.4 | 11.0 | - |
| 1980 | 4.3 | - | 0.4 | 9.9 | 8.0 | - | 7.2 | 0.8 | 6.0 | 12.3 | - |
| 1981 | 6.1 | - | 0.7 | 11.7 | 14.3 | 14.8 | 6.7 | - | 9.5 | 17.3 | - |
| 1982 | 3.9 | - | - | - | - | - | - | - | - | - | - |
| 1983 | 1.9 | - | 1.4 | 9.6 | 11.0 | 18.5 | 5.4 | 1.7 | 9.5 | 23.7 | 15.1 |
| 1984 | 2.3* | - | 2.4 | 12.6 | 12.5 | 24.1 | 4.4 | 2.4 | 12.6 | 25.7 | 24.0 |

* EPA best estimate.