Division 44
Environment and Infrastructure
Sector project "Transport Policy Advisory Service"

Sustainable Transport:
A Sourcebook for Policy-makers in Developing Cities
Module 4a

Cleaner Fuels and Vehicle Technologies

– revised November 2005 –

Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH

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for Economic Cooperation
and Development

OVERVIEW OF THE SOURCEBOOK

Sustainable Transport: A Sourcebook for Policy-Makers in Developing Cities

What is the Sourcebook?

This *Sourcebook* on Sustainable Urban Transport addresses the key areas of a sustainable transport policy framework for a developing city. The *Sourcebook* consists of more than 20 modules.

Who is it for?

The *Sourcebook* is intended for policy-makers in developing cities, and their advisors. This target audience is reflected in the content, which provides policy tools appropriate for application in a range of developing cities.

How is it supposed to be used?

The *Sourcebook* can be used in a number of ways. It should be kept in one location, and the different modules provided to officials involved in urban transport. The *Sourcebook* can be easily adapted to fit a formal short course training event, or can serve as a guide for developing a curriculum or other training program in the area of urban transport. GTZ is elaborating training packages for selected modules, being available since October 2004.

What are some of the key features?

The key features of the *Sourcebook* include:

- A practical orientation, focusing on best practices in planning and regulation and, where possible, successful experience in developing cities.
- Contributors are leading experts in their fields.
- An attractive and easy-to-read, colour layout.
- Non-technical language (to the extent possible), with technical terms explained.
- Updates via the Internet.

How do I get a copy?

Please visit http://www.sutp.org or http://www.gtz.de/transport for details on how to order a copy. The *Sourcebook* is not sold for profit. Any charges imposed are only to cover the cost of printing and distribution. You may also order via transport@gtz.de.

Comments or feedback?

We would welcome any of your comments or suggestions, on any aspect of the *Sourcebook*, by e-mail to transport@gtz.de, or by surface mail to:

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Germany

Further modules and resources

Further modules are anticipated in the areas of *Financing Urban Transport* and *Benchmarking*. Additional resources are being developed, and an Urban Transport Photo CD-ROM is available.

Modules and contributors

Sourcebook Overview and Cross-cutting Issues of Urban Transport (GTZ)

Institutional and policy orientation

1a. *The Role of Transport in Urban Development Policy* (Enrique Peñalosa)
1b. *Urban Transport Institutions* (Richard Meakin)
1c. *Private Sector Participation in Urban Transport Infrastructure Provision* (Christopher Zegras, MIT)
1d. *Economic Instruments* (Manfred Breithaupt, GTZ)
1e. *Raising Public Awareness about Sustainable Urban Transport* (Karl Fjellstrom, GTZ)

Land use planning and demand management

2a. *Land Use Planning and Urban Transport* (Rudolf Petersen, Wuppertal Institute)
2b. *Mobility Management* (Todd Litman, VTPI)

Transit, walking and cycling

3a. *Mass Transit Options* (Lloyd Wright, University College London; Karl Fjellstrom, GTZ)
3b. *Bus Rapid Transit* (Lloyd Wright, University College London)
3c. *Bus Regulation & Planning* (Richard Meakin)
3d. *Preserving and Expanding the Role of Non-motorised Transport* (Walter Hook, ITDP)
3e. *Car-Free Development* (Lloyd Wright, University College London)

Vehicles and fuels

4a. *Cleaner Fuels and Vehicle Technologies* (Michael Walsh; Reinhard Kolke, Umweltbundesamt – UBA)
4b. *Inspection & Maintenance and Roadworthiness* (Reinhard Kolke, UBA)
4c. *Two- and Three-Wheelers* (Jitendra Shah, World Bank; N.V. Iyer, Bajaj Auto)
4d. *Natural Gas Vehicles* (MVV InnoTec)
4e. *Intelligent Transport Systems* (Phil Sayeg, TRA; Phil Charles, University of Queensland)
4f. *EcoDriving* (VTL; Manfred Breithaupt, Oliver Eberz, GTZ)

Environmental and health impacts

5a. *Air Quality Management* (Dietrich Schwela, World Health Organization)
5b. *Urban Road Safety* (Jacqueline Lacroix, DVR; David Silcock, GRSP)
5c. *Noise and its Abatement* (Civic Exchange Hong Kong; GTZ; UBA)

Resources

6. *Resources for Policy-makers* (GTZ)

Module 4a

Cleaner Fuels and Vehicle Technologies

About the authors

Reinhard Kolke is an engineer of environmental and energy science. He graduated from FH Aachen with a thesis on fuel chain analysis for alternative vehicles. Since 1993 he has worked at the German Federal Environmental Agency (UBA) as an expert for future technologies for road traffic and carbon dioxide reduction strategies in the traffic sector. Other interests include in-use compliance and inspection and maintenance. He is one of the authors of the UBA studies “Passenger Cars 2000” and “Heavy Duty Vehicles 2000”, prepared for the discussion of European emission standards EURO 3 and IV, as well as the author of a study about fuel cells in transportation.

Michael P. Walsh is a mechanical engineer who has spent his entire career working on motor vehicle pollution control issues at the local, national, and international level. For the first half of his career to date, he was in government service, initially with the City of New York and subsequently with the U.S. Environmental Protection Agency. With each, he served as Director of their motor vehicle pollution control efforts. Since leaving government, he has been an independent consultant advising governments and industries around the world. Michael P. Walsh has recently been selected as the first recipient of the U.S. Environmental Protection Agency lifetime achievement award for air pollution control. The award, in honour of Thomas W. Zosel, was given for “outstanding achievement, demonstrated leadership, and a lasting commitment to promoting clean air.”

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Karl Fjellstrom
A refueling station in Curitiba, Brazil, Feb. 2002

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1. Background and introduction

Motor vehicles emit large quantities of carbon monoxide, hydrocarbons, nitrogen oxides, and such toxic substances as fine particles and lead. Each of these, along with secondary by-products such as ozone, can cause serious adverse effects on health and the environment. Because of the growing vehicle population and the high emission rates from many of these vehicles, serious air pollution and health effect problems have been increasingly common phenomena in modern life.

Over the course of the past 30 years, pollution control experts around the world have come to realize that cleaner fuels must be a critical component of an effective clean air strategy. In recent years, this understanding has grown and deepened and spread to most regions of the world. Fuel quality is now seen as not only necessary to ***reduce or eliminate certain pollutants*** (*e.g.,* lead) directly but also a ***precondition for the introduction of many important pollution control technologies (lead and sulfur)***. Further, one critical advantage of cleaner fuels has emerged: its ***rapid impact on both new and existing vehicles***. (For example, tighter new car standards can take ten or more years to be fully effective whereas lowering lead in gasoline will reduce lead emissions from all vehicles immediately.)

Cleaner fuels and vehicle technologies in Thailand

Adapted from message of Horst Preschern to CAI-Asia list, 8 Oct. 2002

When excluding the "industrialized countries" what you have is a great mix of levels on emission legislation, fuel quality, manufacturing capabilities, buying power, and so on. Only the strongest amongst them (such as Thailand) have managed to bring sustainable improvements to all sectors: Thailand has EURO regulations in force, will soon switch to EURO 3 for diesel pick-ups, have consequently worked on fuel quality (invested good money in own fuel & lubricants research), have now low sulfur diesel available to allow EURO 3 emission levels to be met, and have built up the manufacturing infrastructure together with the Original Equipment Manufacturers or licensors so that a substantial amount of "vehicle" is manufactured locally; even including engines.

Many of the "others"? Spare me to name countries: No emission legislation in force, leaded gasoline prevailing, diesel with high sulfur component, fuel prices highly subsidised—thus little interest in improving quality.

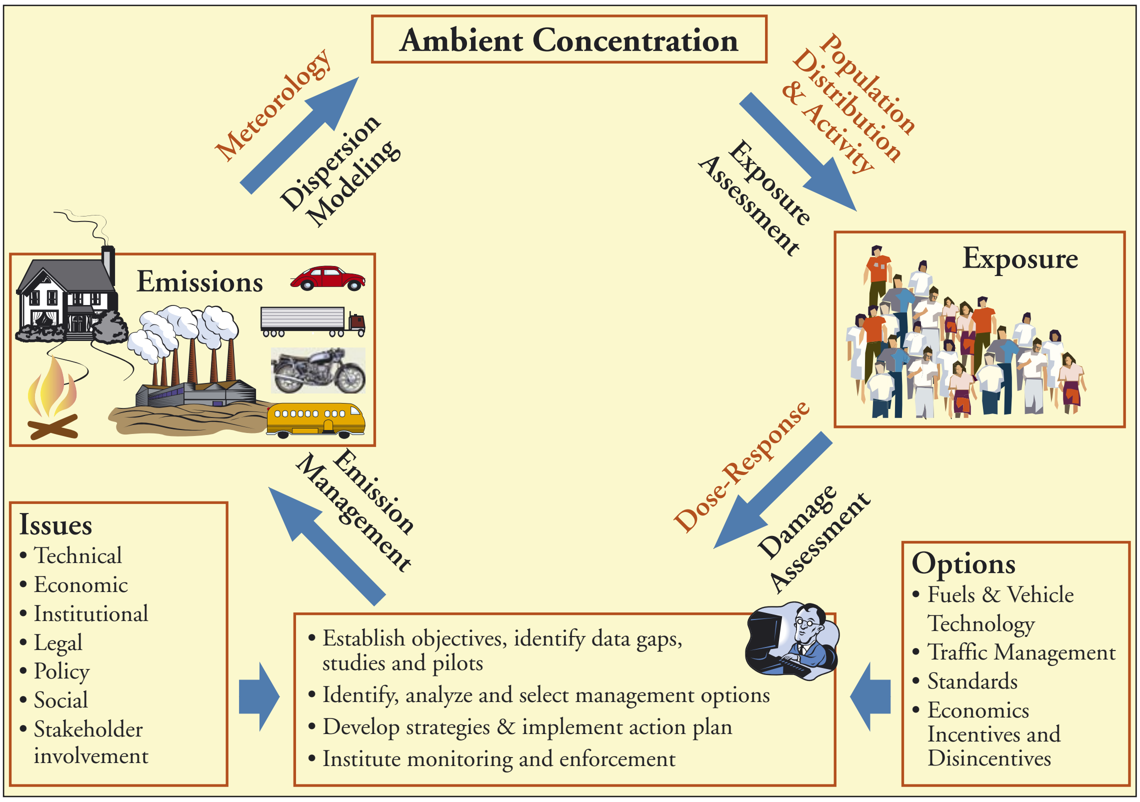


Fig. 1
Integrated air quality management framework.

2. Integrated strategies to reduce emissions from vehicles

In developing strategies to clean up vehicles, it is necessary to start from a clear understanding of the emissions reductions from vehicles and other sources that will be necessary to achieve healthy air quality. Depending upon the air quality problem and the contribution from vehicles, the degree of control required will differ from location to location. As illustrated in Figure 1 regarding an Integrated Air Quality Management Framework, one should start with a careful assessment of air quality and the sources that are contributing the most to the problem or problems.

Where vehicles are the major culprits, a broad based approach to the formulation and implementation of policies and actions aimed at reducing their pollution will be needed.

Effective and efficient coordination mechanisms for the management of pollution from vehicles must be established. This should also include a clear allocation of responsibilities for specific functions and tasks to individual agencies and organizations.

Reducing the pollution from motor vehicles will usually require a comprehensive strategy. Generally, the goal of a motor vehicle pollution control program is to reduce emissions from motor vehicles in-use to the degree reasonably necessary to achieve healthy air quality as rapidly as possible or, failing that for reasons of impracticality, to the practical limits of effective technological, economic, and social feasibility.

> *"One should start with a careful assessment of air quality and the sources that are contributing the most to the problem or problems."*

A comprehensive strategy to achieve this goal includes four key components (see Figure 2): increasingly stringent emissions standards for new vehicles, specifications for clean fuels, programs to assure proper maintenance of in-use vehicles, and transportation planning and demand management. These emission reduction goals should be achieved in the most cost effective manner available.

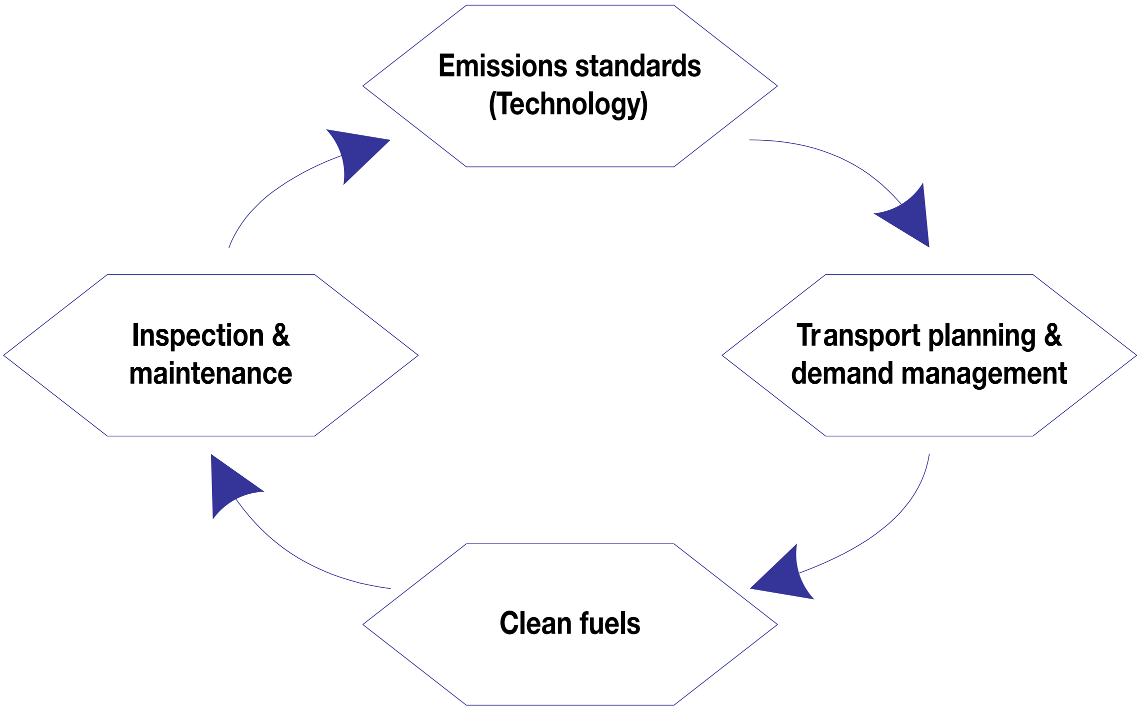


Fig. 2

Elements of a comprehensive vehicle pollution control strategy.

3. Fuel quality standards

In setting fuel quality standards, policy-makers should be guided by the following general principles:

- Because the environment and public health concerns are the driving force behind improvements in fuel quality the environment department should have a major role in setting fuel standards.
- All countries should develop a short and medium term strategy that outlines proposed standards to be adopted over the next several years so as to allow fuel providers and the vehicle industry sufficient time to adapt.
- The most important impediment to adopting state of the art new vehicle emission technology (equivalent to Euro 3 and 4) in many countries is the fuel quality, especially the level of lead and sulfur in gasoline and the level of sulfur in diesel. These parameters should receive highest priority in the development of medium and long-term strategies for fuel standards.
- In developing fuel standards, countries should attempt to work closely with neighboring countries and to harmonize standards where possible. This should not be used as an excuse for delaying or watering down requirements as harmonization does not mean that every country must follow the same time schedule.
- In order to implement stricter fuel standards and increase the acceptability of the associated costs to consumers, countries should institute more and better awareness campaigns. Such campaigns must emphasize the public health consequences of not improving fuel quality.
- Subsidies that favour fuels that result in high emissions should be eliminated and tax policies should be adopted which encourage the use of the cleanest fuels.

Conventional fuel improvements should clearly distinguish between primary steps—removing lead from gasoline and dramatically reducing sulfur in gasoline and diesel, and the addition of detergent additives—and secondary steps—such as reducing the vapour pressure and benzene content of gasoline.

4. Gasoline

The pollutants of greatest concern from gasoline-fuelled vehicles are carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X), lead and certain toxic hydrocarbons such as benzene. Each of these can be influenced by the composition of the gasoline used by the vehicle. The most important characteristics of gasoline with regard to its impact on emissions are lead content, sulfur concentration, volatility and benzene level. With regard to these characteristics, the following policies are recommended.

4.1 Lead additives

Lead does not exist naturally in gasoline but must be added to it. Since the early 1970s, however, there has been a steady movement toward reduced lead in leaded gasoline and increasingly, the elimination of lead. Approximately 85% of all gasoline sold throughout the world is now unleaded.

Several comprehensive studies of the health issue have been conducted over the past two decades with the result that health concerns are increasingly emerging at lower and lower levels. Lead is now recognized to have a physiologic role in biological systems, including human biology. Over the past century, a range of clinical, epidemiological and toxicological studies have continued to define the nature of lead toxicity and to identify young children as a critically susceptible population. At low doses, lead is particularly toxic to the brain, the kidney, the reproductive system, and the cardiovascular system. Its manifestations include impairments in intellectual function, including problems in learning among children, kidney damage, infertility, miscarriage, and hypertension. At relatively high exposures, lead is lethal to humans, usually causing death by inducing convulsions and irreversible hemorrhage in the brain. Long-term exposures may be associated with increased risks of kidney cancer.

A study by Schwartz estimated that in economic terms, the total benefit of a 1 microgram per deciliter reduction in blood lead levels for one year's cohort of children in the United States is $6.937 billion, with $5.060 billion due to earnings losses as a result of loss of cognitive

Reformulation of conventional fuels

Fuel modifications can take effect quickly and have a particularly marked impact in the case of existing vehicles on the road.

On the ***motor gasoline*** front the focus is on reducing:
- Lead and sulfur content (the primary steps)
- Benzene
- Aromatics content
- Vapour pressure
- Admixtures of oxygen-containing compounds.

For ***diesel fuels*** the key areas are:
- Reducing sulfur content
- Reducing density
- Reducing polyaromatics
- Improving ignition properties (cetane number).

ability and lower educational achievement and the remainder due to reduced infant mortality.[1] With a reduction in median blood lead levels in the US from 1980–1990 of 6.4 micrograms/deciliter, this reflects a savings of $44.4 billion over this time frame alone. Most of this improvement is due to the reduction of lead in gasoline during the same period.

The state of the art technology for reducing CO, HC and NO_X emissions from vehicles relies on the catalytic converter which converts large portions of the emissions to carbon dioxide, water vapour, oxygen and nitrogen; in fact approximately 90% of all new gasoline fueled cars manufactured last year contained a catalyst.

> ***"Sulfur in gasoline should be reduced to a maximum of 500 ppm as soon as new vehicle standards requiring catalysts are introduced."***

This technology cannot be used with leaded gasoline, however, since lead poisons the catalyst. The US Environmental Protection Agency carried out a study in which twenty-nine in use automobiles with three-way catalyst emission control systems were misfueled with leaded gasoline in order to quantify the emissions effects. The results of the program indicated that vehicle emissions are mainly affected by the amount of lead passing through the engine and secondarily by the rate of misfueling. Emissions of HC, CO and NO_X generally increase steadily with continuous misfueling.[2]

All modern gasoline fuelled vehicles being produced today can operate satisfactorily on unleaded fuel and approximately 90% of these are equipped with a catalytic converter that *requires* the exclusive use of lead-free fuel. There is no longer any doubt that lead is toxic and prevents the use of clean gasoline vehicle technology which can dramatically reduce CO, HC and NO_X emissions. The addition of lead to gasoline should be eliminated as rapidly as possible.

4.2 Sulfur

For cars without a catalytic converter, the impact of sulfur on emissions is minimal; however for catalyst-equipped cars, the impact on CO, HC and NO_X emissions can be substantial. Based on the Auto/Oil study, it appears that NO_X would go down about 3% per 100 parts per million (ppm) sulfur reduction for a typical catalyst equipped car.[3]

The situation is even more critical for *advanced* low pollution catalyst vehicles. Operation on gasoline containing 330 ppm sulfur will increase exhaust VOC and NO_X emissions from current and future new US vehicles (on average) by 40% and 150%, respectively, relative to their emissions with fuel containing roughly 30 ppm sulfur.

In light of these impacts, it is not surprising that Japan has had typical gasoline sulfur levels under 30 ppm for many years. The US has also adopted a 30 ppm sulfur limit and the EU requires gasoline with a maximum sulfur content of no more than 50 ppm in 2005 when Euro 4 standards go into effect. Even more recently, the European Union has proposed to limit sulfur levels to a maximum of 10 ppm.

In order to maximise the performance of current catalyst technology, sulfur concentrations in gasoline should be reduced to a maximum of 500 ppm as soon as new vehicle standards requiring catalysts are introduced. Emerging advanced catalyst technologies that are capable of achieving very low emissions will require a maximum of 50 ppm or less and a plan for introducing such fuel quality should be adopted at the early stages of development of a long term vehicle pollution control strategy.

4.3 Vapour pressure

Another important fuel parameter is vapour pressure. The vapour pressure for each season must be as low as possible in order to minimise evaporation from storage terminals and vehicles but still sufficiently high to give safe cold starts.

An important advantage of gasoline volatility controls is that they can affect emissions from vehicles already produced and in-use and from the gasoline distribution system.

Gasoline vapour pressure should be reduced to a maximum of 60 kilopascals whenever temperatures in excess of 20° C are anticipated to occur. In tropical or semi-tropical countries, this of course will be all the time.

4.4 Benzene

Benzene is an aromatic hydrocarbon that is present as a gas in both exhaust and evapourative emissions from motor vehicles. Benzene in the exhaust, expressed as a percentage of total organic gases (TOG), varies depending on control technology (*e.g.,* type of catalyst) and the levels of benzene and other aromatics in the fuel, but is generally about three to 5%. The benzene fraction of evapourative emissions depends on control technology and fuel composition and characteristics (*e.g.,* benzene level and the evaporation rate) and is generally about 1%[4]. As a general rule, benzene levels in gasoline should be capped at 1% as has been done in the European Union.

4.5 Oxygenates

Blending small percentages of oxygenated compounds such as ethanol, methanol, tertiary butyl alcohol (TBA) and methyl tertiary-butyl ether (MTBE) with gasoline has the effect of reducing volumetric energy content of the fuel, while improving the antiknock performance and thus making possible a potential reduction in lead and/or harmful aromatic compounds. Assuming no change in the settings of the fuel metering system, lowering the volumetric energy content will result in a leaner air-fuel mixture, thus helping to reduce exhaust CO and HC emissions.

Impact of oxygenate used

MTBE

MTBE (methyl tertiary butyl ether) can be added to gasoline up to 2.7% without any increase in NO_X. There are two opposing effects taking place with the addition of oxygenates: enleanment, which tends to raise NO_X, and lower flame temperatures, which tend to reduce NO_X. With MTBE levels above 2.7%, the lower flame temperature effect seems to prevail.

While the use of MTBE has been found to be very attractive from an air pollution point of view, recent evidence in the US has shown that leaks and spills are a serious threat to drinking water. This has led to a movement toward a ban on its use in gasoline in the future. The European Union has not reached a similar conclusion but prefers to improve the quality of underground storage tanks.

Countries considering the use of MTBE should carefully weigh the potential air quality benefits with the potential water quality risks.

Ethanol

Ethanol can be added to gasoline at levels as high as 2.1% oxygen without significantly increasing NO_X levels but above that point NO_X levels could increase somewhat. For example, EPA test data on over 100 cars indicates that oxygen levels of 2.7% or more could increase NO_X emissions by 3–4%.[5] The auto/oil study concluded that there was a statistically significant increase in NO_X of about 5% with the addition of 10% ethanol (3.5% O_2).

Since ethanol has a higher volatility than gasoline, the base fuel volatility must be adjusted so as to prevent increased evapourative emissions. As a general rule, without adjustment, volatility will increase by about 1 psi when ethanol is added to gasoline.

Countries considering the use of ethanol should carefully evaluate and weigh the tailpipe CO and HC benefits versus the potential NO_X and evaporative hydrocarbon increases.

4.6 Other gasoline properties

According to the Auto/Oil study:

NO_X emissions were lowered by reducing olefins, raised when T_{90} was reduced, and only marginally increased when aromatics were lowered.[6]

In general, reducing aromatics and T_{90} caused statistically significant reductions in exhaust mass NMHC and CO emissions. Reducing olefins increases exhaust mass NMHC emissions; however, "the ozone forming potential" of the total vehicle emissions was reduced.[7]

With regard to toxics, the reduction of aromatics from 45%–20% caused a 42% reduction in benzene but a 23% increase in formaldehyde, a 20% increase in acetaldehyde and about a 10% increase in 1,3-Butadiene.[8] Reducing olefins from 20%–5% brought about a 31% reduction in 1,3-Butadiene but had insignificant impacts on other toxics. Lowering the T_{90} from 360 to 280F resulted in statistically significant reductions in benzene, 1,3-Butadiene (37%), formaldehyde (27%) and acetaldehyde (23%).

To the extent that the long-term vehicle emissions standards strategy is to adopt European step 4 (so called Euro 4) standards for light

Cetane number

The cetane number/value/index is a measure of diesel fuel ignition quality. In compression-ignition (diesel) engines, it refers to the fuel's ability to react with oxygen under explosion conditions and hence enable the engine to produce shaft power. The higher the cetane number, the better the performance.

Stoichiometric mixture

A stoichiometric mixture is a mixture of substances that can react to give products with no excess reactant.

duty vehicles, the European gasoline standards as summarized in Table 1 should be adopted in the same timeframe.

Detergent or engine deposit control additives are critically important with modern engines and should be mandatory as well.

Table 1:
European Union fuel specification limits.

Petrol/ Gasoline Parameter	2000 (Linked to Euro 3 Vehicle Standards)	2005 (Linked to Euro 4 Vehicle Standards)
RVP summer kPa, max.	60	60
Aromatics %v/v, max.	42	35
Benzene %v/v, max.	1	1
Olefins %v/v, max.	18	18
Oxygen %m/m, max.	2.7	2.7
Sulfur, ppm, max.	150	50

Table 2: Summarised influence of fuel properties on heavy duty diesel emissions.

Fuel Modification	NO_X	Particulates
Reduce Sulfur*	0	↓↓[D]
Increase Cetane	↓	0
Reduce Total Aromatics	↓[C]	0
Reduce Density	↓	0[A] / ↓↓[B]
Reduce Polyaromatics	↓[C]	0[A] / ↓↓[b]
Reduce T90/T95	⇩	0

Key: ↓↓/↑↑ = Relatively large effect, ↓/↑ = small effect, ⇧/⇩ = very small effect, 0 = no effect

[A]) Low emission emitting engine

[B]) High emission emitting engine

[C]) Polyaromatics are expected to give a bigger reduction than mono-aromatics. Further studies (*e.g.,* EPA HD engine working group) are investigating these parameters.

[D]) Reducing S from 0.30%–0.05% gives relatively large benefits; reducing S from 0.05% to lower levels has minimal direct benefit but as discussed below is necessary to enable advanced technologies.

* for engines *without* aftertreatment systems

5. Diesel fuel

Diesel vehicles emit significant quantities of both NO_X and particulate. Reducing PM emissions from diesel vehicles tends to be the highest priority because PM emissions in general are very hazardous and diesel PM, especially, is likely to cause cancer. To reduce PM and NO_X emissions from a diesel engine, the most important fuel characteristic is sulfur because sulfur in fuel contributes directly to PM emissions and because high sulfur levels preclude the use of the most effective PM and NO_X control technologies.

5.1 Impact on emissions from heavy duty engines

A recent review addressed the impact of changes in fuel composition on emissions from current ***heavy duty, direct-injection*** diesel engines based only on studies where there were no significant correlations among germane fuel

Fuel policy gets more teeth in India

Adapted from: Times of India, 28 Sept. 2002; CAI-Asia list, 1 Oct. 2002

Eleven cities in India are slated for more stringent vehicular emission norms under the auto fuel policy formulated by an expert committee set up last year to look into the issues of fuel quality and auto technology, submitted this week to the ministry of petroleum and natural gas. The report proposes two separate road maps; one for new vehicles and one for old ones, to improve fuel quality and vehicle emissions. It marks out Delhi, Kolkata, Mumbai, Chennai, Hyderabad, Ahmedabad, Surat, Pune, Bangalore, Kanpur and Agra for stricter standards.

According to the schedule set by the report, new vehicles in these cities would have to meet Euro 3 norms by 2005 and Euro 4 emission norms by 2010. The rest of the country will only get these standards five years later.

For two and three wheelers, the committee recommends Bharat stage II norms, the equivalent of Euro 2, by 2005. Vehicles that are already in use, however, will have it much easier. The report recommends that emission norms for buses and taxis registered before 2004 should be required to meet 1996 norms or Euro 1 by that time, and those registered before 2008, meet Euro 2 norms by that year.

[Note: This report covers many other areas of transport policy. To download a copy, please see http://www.petroleum.nic.in/afp_con.htm].

properties.[9] Conclusions from this review are summarized in Table 2. As shown, compositional properties of at least some importance with respect to emissions are sulfur, aromatic, and oxygenate content; the physical properties identified are density and the T90 or T95 distillation temperature. The cetane number/index was also identified as a factor with respect to emissions. The directional changes in these fuel properties, which will result in a "cleaner" fuel, are shown by the arrows in the first column of the table. The directional impact on emissions of NO_X, PM, HC, and CO resulting from changes in each property in the direction indicated are also shown, along with an indication of the relative magnitude of the effect.

As shown in Table 2, emissions from engines with high base emission rates (generally older designs) tend to be more sensitive to changes in fuel composition than those from engines with lower base emissions rates (which tend to be newer designs). In addition, changes in all of the fuel properties have been found to have, at most, small impacts on emissions from engines with low base emission rates.

5.2 Impact on emissions from light duty vehicles

The most recent, comprehensive, study of fuel composition impacts on light-duty diesel emissions was performed as part of the European Programs on Emissions, Fuels and Engine Technologies (EPEFE).[10] The generalized results of this study are presented in Table 3. As shown, although there are some differences in terms of the magnitude of fuel composition effects on emissions from vehicles with indirect- and direct-injection engines, the directional impact on emissions is usually the same.

A comparison of the heavy duty and light duty tables indicates that there are some instances where changing a given diesel fuel property is expected to have the opposite directional impact on emissions depending on whether the fuel is being used in a heavy duty engine or light-duty vehicle. The most notable are the increase in NO_X emissions from light-duty direct-injection engines in response to a decrease in fuel density and the increases in NO_X emissions from both light-duty indirect- and direct-injection engines in response to a decrease in the T95 temperature.[11]

5.3 Sulfur

Sulfate particulate and SO_x emissions, both of which are harmful pollutants, are emitted in direct proportion to the amount of sulfur in diesel fuel. Sulfate PM contributes to PM_{10}, and $PM_{2.5}$ emissions directly with their associated adverse health and environmental effects. SO_2, one fraction of the SO_x, is a criteria pollutant with associated adverse effects. The health and welfare effects of SO_2 emissions from diesel vehicles are probably much greater than those of an equivalent quantity emitted from a utility stack or industrial boiler, since diesel exhaust is emitted close to the ground level in the vicinity of roads, buildings, and concentrations of people. Further some of the SO_x are also transformed in the atmosphere to sulfate PM with the associated adverse effects noted for PM.

> *"The presence of sulfur in diesel fuel effectively bars the path to low emissions of conventional pollutants."*

Diesel PM consists of three primary constituents—a carbonaceous core, a soluble organic fraction (SOF) which sits on the surface of this core and a mixture of SO_x and water, which also sits on the surface of the core. Lowering the sulfur in the fuel lowers the SO_x fraction of PM thus lowering the overall mass of PM emitted. Diesel fuel evaluations carried out in Europe show the benefits of reduced sulfur in diesel fuel for lowering particulates. For example, lowering the diesel fuel sulfur level from 2000 ppm to 500 ppm reduced overall particulate

Table 3: Impact of fuel composition changes on emissions of current light-duty diesel vehicles.

Change	NO_x Emissions		PM Emissions	
	IDI[a]	DI[b]	IDI	DI
⬇ Cetane (50–58)	⇧	⇩	None	⬆
⬇ Density (0.855–0.828 g/cm^3)	None	⬆	⬇⬇	⬇⬇
⬇ T95 (700–6201F)	⇧	⬆	None	⬇
⬇ Polycyclics (8–1 vol %)	⇩	⇩	⇩	⬇

Key: Relatively large effects denoted ⬇⬇/⬆⬆ (10% or greater change in emissions); Small effects denoted ⬇/⬆ (5–10% change); Very small effects denoted ⇧/⇩ (~1–5% change).

[a]) Indirect-injection engines

[b]) Direct-injection engines

from light duty diesels by 2.4% and from heavy duty diesels by 13%.[12] The relationship between particulates and sulfur level was found to be linear; for every 100 ppm reduction in sulfur, there will be a 0.16% reduction in particulate from light duty vehicles and a 0.87% reduction from heavy duty vehicles.

Sulfur in diesel fuel has a comparable technology enabling effect as lead and sulfur in gasoline. Catalytic converters or NO_X adsorbers can eliminate much of the NO_X emissions from new diesel engines, but sulfur disables them in much the same way that lead poisons the three-way catalyst. Thus, the presence of sulfur in diesel fuel effectively bars the path to low emissions of conventional pollutants. As stated by the German government in a petition to the European Commission in support of low sulfur fuel:

> *A sulfur content of 10 ppm compared to 50 ppm increases the performance and durability of oxidizing catalytic converters, DeNO*$_X$ *catalytic converters and particulate filters and therefore decreases fuel consumption. There are also lower particulate emissions (due to lower sulfate emissions) with oxidizing catalytic converters. For certain continuously regenerating particulate filters, a sulfur content of 10 ppm is required for the simple reason that otherwise the sulfate particles alone (without any soot) would overstep the future [European] particulate value of 0.02 g/kWh.*

In addition to its role as a technology enabler, low sulfur diesel fuel gives benefits in the form of reduced sulfur induced corrosion and slower acidification of engine lubricating oil, leading to longer maintenance intervals and lower maintenance costs. These benefits can offer significant cost savings to the vehicle owner without the need for purchasing any new technologies.

5.4 Other diesel fuel properties

Volatility

Diesel fuel consists of a mixture of hydrocarbons having different molecular weights and boiling points. As a result, as some of it boils away on heating, the boiling point of the remainder increases. This fact is used to characterise the range of hydrocarbons in the fuel in the form of a "distillation curve" specifying the temperature at which 10%, 20%, etc. of the hydrocarbons have boiled away. A low 10% boiling point is associated with a significant content of relatively volatile hydrocarbons. Fuels with this characteristic tend to exhibit somewhat higher HC emissions than others.

Aromatic hydrocarbon content

Aromatic hydrocarbons are hydrocarbon compounds containing one or more "benzene-like" ring structures. They are distinguished from paraffins and napthenes, the other major hydro-

Table 4: Current and proposed sulfur levels in diesel in Asia, EU and USA.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Bangladesh							5,000									
Cambodia					2,000											
Hong Kong, China		500					50									
India	5,000				2,500					500					350	
Indonesia	5,000															
Japan	500				100					50		10				
Malaysia	5,000		3,000				500 marketed									
Pakistan	10,000						5,000									
Philippines	5,000					2,000			500							
PRC	5,000		2,000													
Republic of Korea	500							430			30				10	
Singapore	3,000		500													
Sri Lanka	10,000							3,000								
Taipei,China	3,000			500			350					50				
Thailand	2,500			500					350							
Viet Nam	10,000							2,000		500						
European Union					350					50				10		
United States	500														15	

> 500 ppm　51–500 ppm　< 50 ppm

carbon constituents of diesel fuel, which lack such structures. Compared to these other components, aromatic hydrocarbons are denser, have poorer self-ignition qualities, and produce more soot in burning. Ordinarily, “straight run” diesel fuel produced by simple distillation of crude oil is fairly low in aromatic hydrocarbons. Catalytic cracking of residual oil to increase gasoline and diesel production results in increased aromatic content, however. A typical straight run diesel might contain 20–25% aromatics by volume, while a diesel blended from catalytically cracked stocks could have 40–50% aromatics.

Aromatic hydrocarbons have poor self-ignition qualities, so that diesel fuels containing a high fraction of aromatics tend to have low Cetane numbers. Typical Cetane values for straight run diesel are in the range of 50–55; those for highly aromatic diesel fuels are typically 40–45, and may be even lower. This produces more difficulty in cold starting, and increased combustion noise, HC, and NO_X due to the increased ignition delay.

Increased aromatic content is also correlated with higher particulate emissions. Aromatic hydrocarbons have a greater tendency to form soot in burning, and the poorer combustion quality also appears to increase particulate soluble organic fraction (SOF) emissions. Increased aromatic content may also be correlated with increased SOF mutagenicity. There is also some evidence that more highly aromatic fuels have a greater tendency to form deposits on fuel injectors and other critical components. Such deposits can interfere with proper fuel/air mixing, greatly increasing PM and HC emissions.

Polycyclic aromatic hydrocarbons (PAH) are included in the great number of compounds present in the group of unregulated pollutants emitted from vehicles. Exhaust emissions of PAH (here defined as three ringed and larger) are distributed between particulate- and semi-volatile phases. Some of these compounds in the group of PAH are mutagenic in the Ames test and even in some cases causes cancer in animals after skin painting experiments. Because of this fact, it is of importance to limit the emissions of PAH from vehicles especially in densely populated high traffic urban areas. An important factor affecting the emissions of PAH from vehicles is selection of fuel and fuel components. A linear relationship exists between fuel PAH input and emissions of PAH. The PAH emission in the exhaust consists of uncombusted through fuel input PAH and PAH formed in the combustion process. By selection of diesel fuel quality with low PAH contents (≥ 4 mg/l, sum of PAH) the PAH exhaust emissions will be reduced by up to approximately 80% compared to diesel fuel with PAH contents larger than 1 g/l (sum of PAH). By reducing fuel PAH contents in commercial available diesel fuel the emissions of PAH to the environment will be reduced.[13]

Table 5: European Union fuel specification limits.

Diesel Fuel Parameter	2000 (Linked with Euro 3 vehicle Standards)	2005 (Linked with Euro 4 vehicle Standards)
Cetane number (min.)	51	51
Density (15°C kg/m^3, max.)	845	845
Distillation (95%, v/v °C, max.)	360	360
Polyaromatics (% v/v, max.)	11	11
Sulfur (ppm, max.)	350	50

Other properties

Other fuel properties may also have an effect on emissions. Fuel density, for instance, may affect the mass of fuel injected into the combustion chamber, and thus the air/fuel ratio. This is because fuel injection pumps meter fuel by volume, not by mass, and the denser fuel contains a greater mass in the same volume. Fuel viscosity can also affect the fuel injection characteristics, and thus the mixing rate. The corrosiveness, cleanliness, and lubricating properties of the fuel can all affect the service life of the fuel injection equipment; possibly contributing to excessive in-use emissions if the equipment is worn out prematurely.

To the extent that the long term vehicle emissions standards strategy is to adopt European step 4 (so-called Euro 4) standards for light duty vehicles and step 5 (so-called Euro 5) standards for heavy duty vehicles, the European diesel fuel standards as summarized in Table 5 should be adopted in the same timeframe.

5.5 Fuel Additives

Several generic types of diesel fuel additives can have a significant effect on emissions. These include Cetane enhancers, smoke suppressants, and detergent additives. In addition, some additive research has been directed specifically at emissions reduction in recent years.

Cetane enhancers are used to enhance the self-ignition qualities of diesel fuel. These compounds (usually organic nitrates) are generally added to reduce the adverse impact of high aromatic fuels on cold starting and combustion noise. These compounds also appear to reduce the aromatic hydrocarbons' adverse impacts on HC and PM emissions, although PM emissions with the Cetane improver are generally still somewhat higher than those from a higher quality fuel able to attain the same Cetane rating without the additive.

> ***"The use of detergent additives to reduce deposits on injector components is highly recommended, especially on more modern engines."***

Smoke suppressing additives are organic compounds of calcium, barium, or (sometimes) magnesium. Added to diesel fuel, these compounds inhibit soot formation during the combustion process, and thus greatly reduce emissions of visible smoke. However, they tend to significantly increase the number of very small ultrafine particles that are suspected of being even more hazardous to health. Their effects on the particulate SOF are not fully documented, but one study has shown a significant increase in the PAH content and mutagenicity of the SOF with a barium additive. Particulate sulfate emissions are greatly increased with these additives, since all of them readily form stable solid metal sulfates, which are emitted in the exhaust. The overall effect of reducing soot and increasing metal sulfate emissions may be either an increase or decrease in the total particulate mass, depending on the soot emissions level at the beginning and the amount of additive used.

While smoke suppressing additives may appear attractive, their use is not recommended because of the potentially more hazardous emissions of ultrafine particles and mutagenicity.

Detergent additives (often packaged in combination with a Cetane enhancer) help to prevent and remove coke deposits on fuel injector tips and other vulnerable locations. By thus maintaining new engine injection and mixing characteristics, these deposits can help to decrease in-use PM and HC emissions. A study for the California Air Resources Board estimated the increase in PM emissions due to fuel injector problems from trucks in use as being more than 50% of new-vehicle emissions levels. A significant fraction of this excess is unquestionably due to fuel injector deposits. The use of detergent additives to reduce deposits on injector components is highly recommended, especially on more modern engines.

Environmentally-friendly cars?

The Environment and Transport Working Party of Germany's Standing Conference of Environment Ministers formulated requirements for ecologically acceptable cars (Table 6).

For the purposes of the present module, an ecologically acceptable car is a family car equipped with the best existing technology to mitigate environmental impacts without sacrificing safety, comfort and convenience. It provides the following environmental benefits:

- Low fuel consumption
- Low pollutant and noise emissions
- Environmentally sound manufacturing
- Lightweight and compact design ensuring optimum use of materials and recyclability
- Environmentally relevant extras.

The resolutions adopted were published in UBA (1999c). The vehicle type largely satisfies the requirements for an ecologically acceptable passenger car.

Manufacturers have already announced their plans for series-production cars with internal combustion engines and a fuel consumption of 3 liters per 100 km (78.4 miles per gallon). These vehicles are to be sold at affordable prices and satisfy requirements for everyday use, providing space for 4–5 adults and incorporating the convenience, comfort and safety standards of a medium-sized car.

6. Alternative fuels

In addition to conventional fuels, gasoline and diesel fuel, many countries around the world have identified significant benefits associated with a shift to alternative fuels, especially compressed natural gas (CNG), liquefied petroleum gas (LPG or propane) and ethanol.

Alternative fuels include compressed natural gas (mainly composed of methane), methanol, ethanol, hydrogen, electricity, vegetable oils (including biodiesel), liquefied petroleum gas (composed of propane or butane), synthetic liquid fuels derived from coal and various fuel blends, such as gasohol.

6.1 Natural Gas (NG)

Natural gas (85–99% methane) is clean burning, cheap and abundant in many parts of the world. Because natural gas is mostly methane, natural gas vehicles (NGVs) have much lower non-methane hydrocarbon emissions than gasoline vehicles, but higher emissions of methane. Since the fuel system is sealed, there are no evapourative emissions and refueling emissions are negligible. Cold-start emissions from NGVs are also low, since cold-start enrichment is not required. In addition, this reduces both VOC and CO emissions. NO_X emissions from uncontrolled NGVs may be higher or lower than comparable gasoline vehicles, depending on the engine technology, but are typically slightly lower. Light-duty NGVs equipped with modern electronic fuel control systems and three-way catalytic converters have achieved NO_X emissions more than 75% below the stringent California Ultra Low-Emission Vehicle (ULEV) standards.

As a substitute for diesel, NGVs should have somewhat lower NO_X and substantially lower PM emissions unless the diesel vehicle is burning ULSD and is equipped with a PM filter.

Given equal energy efficiency, GHG emissions from NGVs will be approximately 15%–20% lower than from gasoline vehicles, since natural gas has lower carbon content per unit of energy than gasoline. NGVs have about the same GHGs as diesel fuel vehicles. For the use of NG which would otherwise be flared in the refinery or wasted, the greenhouse gas reduction can be up to 100% in comparison with using any other fossil-based fuel, such as gasoline or diesel, which can thereby be saved.

Comparison of the primary energy use for the production processes of CNG and petrol shows that the primary energy consumption for both fuels is comparable. In its demonstration project for CNG-usage, UBA—the German Federal Environmental Agency—considered a scenario of 10% NG heavy duty vehicles in Germany and calculated a slight increase of equivalent greenhouse gas emissions of +0.07%. Clearly the use of NG in heavy duty vehicles will not result in a significant increase of greenhouse gases.

Furthermore the noise emission of NG buses is in the order of 3–5 dB(A) lower, while the subjective annoyance is much lower, because the gas engine runs much more smoothly.

Obstacles to the widespread use of NGVs include the absence of transportation and storage infrastructure, cost, loss of cargo space, increased refueling time, and lower driving range.

Refueling and storage of the gas must be carefully considered to meet operational and safety requirements. For storing compressed natural gas at 200-bar pressure, a large tank is needed. The kind of heavy duty vehicle for which the use of natural gas has the most advantages is the urban bus where the tank is usually installed on the roof. But heavy duty vehicles have also

Table 6: Proposal by the Standing Conference of Environment Ministers for phased introduction of ecologically acceptable passenger cars.

Criterion		Unit	1999–2004	from 2005
CO_2 emissions 93/116/EEC		g/km	120 g CO_2/km	90 g CO_2/km
Consumption (petrol/diesel)		l/100 km mpg	5,15 / 4,46 45,5 / 52,7	3,88 / 3,42 60,6 / 68,8
Emission Standard 1)		–	EURO 4	EURO 4
	CO	g/km	1,0	1,0
	HC	g/km	0,1	0,1
	NO_X	g/km	0,08	0,08
	PM	g/km	0,025	0,025
Noise (vehicle in motion) 2)		dB (A)		
Environmentally compatible choice of meterials		–	Yes	Yes
Recycling (recyclability)		(% by wt.)	Yes (85%)	Yes (95%)
Eco-audit		–	Yes	Yes

1) As laid down in 98/69/EC including relevant low-temperature, useful life and on-board diagnostics requirement.

2) Noise levels to be redefined by the EU following revision of the testing method.

Comparing different emission standards

Californian emission standards are known to be the most stringent in the world. Since new types of vehicle have been introduced and advanced mainly in response not to European, but to Californian legislation, we must consider the major differences.

While the reduction of direct emissions laid down in EURO 4 (see margin note) for petrol-engine vehicles will be sufficient to satisfy the requisite air quality objectives in Germany and further cuts in direct exhaust gas emissions from such vehicles will therefore not be necessary in Germany in the foreseeable future, the limits for diesel-powered cars in Europe will be well above those for their petrol-engine counterparts, even well into this millennium. The following comparisons therefore address only the European requirements for petrol-engine cars incorporating the best available low emission techniques.

Californian clean air legislation is rather different. It does not propose any across-the-board standards for all new vehicles from a specific date, but various limits to be introduced step by step with a declining fleet average year by year. Manufacturers are required to comply with a fleet average for non-methane organic gases (NMOG).

The comparison of emission limits adjusted to the US FTP75 cycle indicates that the EURO 4 standard for petrol-engine cars is comparable with the ULEV (Ultra Low Emission Vehicle) standard in the proposed LEV I legislation (Figure 3). The graph also shows that the currently valid LEV and ULEV limits for NO_X (see Figure 3: [LEV I]) permit emission levels more than four times as high as those for a EURO 4 vehicle. The LEV II legislation therefore tightened NO_X and particulate limits and is substantially more stringent than Euro 4. Distinctive features of LEV II include an in use durability requirement of at least 120,000 miles, expanded OBD requirements, supplemental FTP standards which limit emissions under hard acceleration conditions, very low evaporative HC limits and a requirement that almost all cars and light commercial vehicles using petrol of diesel fuel must comply with the same NO_X and PM limits.

The once familiar demands for certain automotive technologies, such as Zero Emission Vehicles (ZEVs) in the form of electric cars, are no longer warranted by clean air requirements in the transport sector in the European Union.

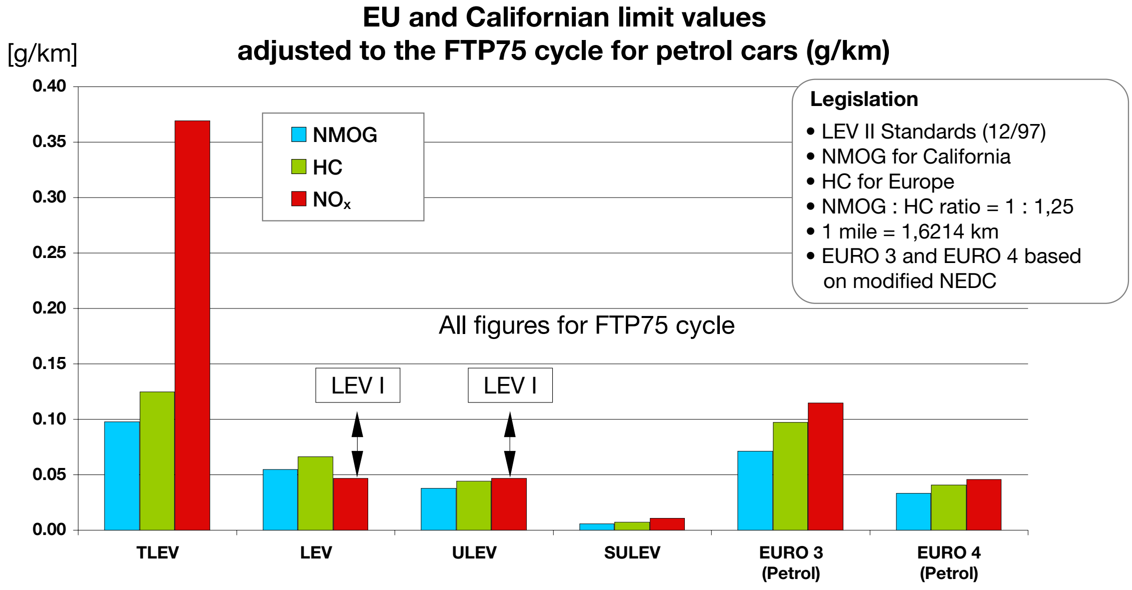
Whether zero emissions vehicles or other advanced technology vehicles will be needed in any country depends on a careful assessment of the air quality problem in that country.

EURO 4

The European step 4 standard, or so-called EURO 4, is the emission standard set out in Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998 relating to measures to be taken against air pollution by emissions from motor vehicles. It will apply from January 2005. The full text of the preamble and the standard can be downloaded at http://europa.eu.int/eur-lex/en/consleg/main/1998/en_1998L0069_index.html.

Further information on natural gas vehicles

Please refer to Module 4d: *Natural Gas Vehicles* for a more detailed discussion of practical aspects related to natural gas vehicle applications. NG applications for three-wheelers are discussed in Module 4c: *Two- and Three-Wheelers*.



TLEV	Transitional Low Emission Vehicle
LEV	Low Emission Vehicle
ULEV	Ultra Low Emission Vehicle
SULEV	Super Ultra Low Emission Vehicle
ZEV	Zero Emission Vehicle

Fig. 3

Comparison of emission limits for petrol engine cars, between Europe and LEV II, California.

been fitted with under floor installations. Using CNG in passenger cars can result in a reduction of useful space inside the vehicle's trunk because of the storage tank.

Natural gas engines cause additional capital costs for the vehicle's engine and the storage tank system and further cost for the compression of natural gas, covering investment, operation and maintenance of the filling station.

To store natural gas, it has to be compressed to 200 bar (2,900 psi) at the filling station. The configuration of the filling station according to the individual demands of the customer is of great importance in minimising costs. The quality of the natural gas and the pre-pressure of the supply are also important factors. A high pre-pressure reduces the compression power required and hence the operating costs. The pre-pressure of a filling station influences the ratio of the specific costs per volume of compressed natural gas.[14]

The additional costs of NG bus fleets were calculated in the THERMIE project at 7% including all costs for additional staff, filling station, etc.[15] Figure 4 shows that the cost premium for natural gas buses compared with diesel-powered buses will decline as this technology gains a firmer foothold in new markets over the next decade (see margin note).

To smooth the way for gas power technology into series production through fleet testing and verification of fitness for use under practical conditions, the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety and the UBA take promotional measures in the form of investment projects providing for considerable grants to be paid out to operators of new NG vehicles to compensate them for the extra cost they incur compared to diesel fuelled vehicles.[16] In Germany, about 80 natural gas filling stations are currently available. NG vehicles are therefore operated mainly in fleets that are based close to filling stations.

In connection with the above-mentioned investment project "Model operation of NG vehicles", the UBA drew up a list based on information provided by the manufacturers. This list shows the NG Vehicles available in all categories, which satisfy the emission requirements for the vehicles taking part (Table 7).

6.2 Liquefied Petroleum Gas (LPG)

Engine technology for LPG vehicles is very similar to that for natural gas vehicles. As a fuel for spark-ignition engines, it has many of the same advantages as natural gas, with the additional advantage of being easier to carry aboard the vehicle.

LPG has many of the same emissions characteristics as natural gas. The fact that it is primarily propane (or a propane/butane mixture) rather than methane affects the composition of

Cost differentials between CNG and standard buses

The cost premium in Europe in the year 2000 for heavy-duty vehicles with a natural gas engine and a CNG tank was between 20,500 and 35,800€. This amounts to between 8% and 16% of the selling price of a standard service bus. In 2002 the cost differential was already reduced to 25,000€. In the longer term, it will be possible to reduce the cost premium for natural gas buses as this technology gains a firmer foothold in new markets.

In several major developing country markets locally manufactured regular and CNG buses are available at a much lower cost than in Europe. New diesel buses complying with Euro 2 emission standards reportedly are available for less than 50,000 € in China and India, both of which also manufacture CNG buses for the domestic market at a substantially lower cost than in Europe.

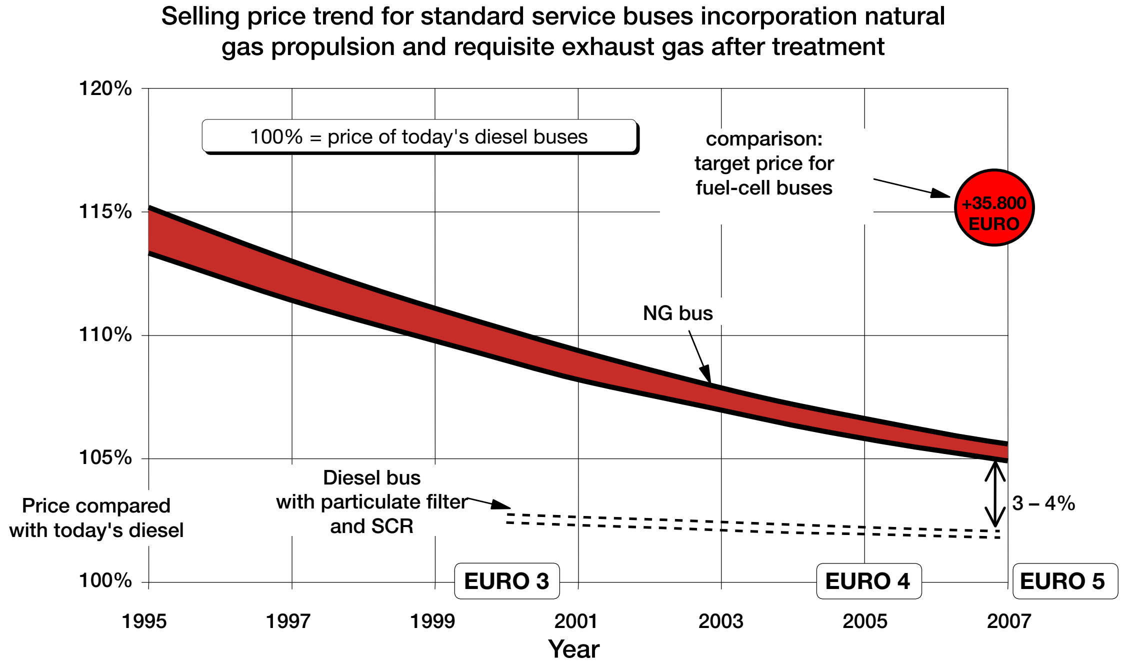


Fig. 4

Selling price of natural gas buses compared to current diesel buses.

exhaust VOC emissions and their photochemical reactivity, and its global warming potential but otherwise the two fuels are similar.

Using LPG in transport instead of burning it as a waste gas at the oil fields or in the refinery will immediately result in fossil fuel savings. The use of LPG results in an energy efficiency for the energy chain of exploitation, refinery and use, comparable to that of gasoline and diesel.

The emissions during use of LPG in the vehicles are comparable to the emissions of petrol engines. In the Netherlands, in-use compliance tests were conducted for LPG passenger cars (Rijkeboer, Binkhorst, 1998)[17]. The conclusion from these tests was that the maintenance situation for the vehicles tested was in fact very good. LPG vehicles easily complied with the current emission limits. The engine technologies are already in their third generation, described in the in-use compliance program as follows:

a) 1st generation:
Mechanical system with mechanical control of the metering; no closed loop.

b) 2nd generation (analogue):
Mechanical system with mechanical control. Additional closed loop control by means of a lambda sensor. This closed-loop control works relatively slowly.

c) 2nd generation (digital):
System whereby the flow takes place as previously via the venturi, but whereby the metering is regulated by a microprocessor with pre-programmed "engine maps". Closed loop control is also by means of a lambda sensor. The control can be more accurate, but the closed-loop is still relatively slow.

d) 3rd generation:
This system distinguishes itself from the 2nd generation in that it is a self-adaptive system. Observed deviations in the air/fuel ratio are stored in the memory and processed in the digital control metering. In practice these are often multi-point injections.

The emissions of the different generations of LPG systems are given in the Figure 5.

The emissions of LPG in heavy duty vehicle engines are far below the emission standards for EURO 3 heavy duty vehicles, which are implemented in Europe for the year 2000.[18]

The heavy duty vehicle was equipped with a closed-loop fuel system and a 3-way catalyst. The 6 cylinders, 135 kW engine with stoichiometric mixture and natural aspiration has a compression ratio of 10:1. The maximum engine efficiency is high, ranging from 33–37% at full load. Over the 13-mode test, the engine

Table 7: Overview of NG vehicles available which meet the requirements of the investment project "Model Operation Of NG Vehicles" (2/1998).

	New Vehicles				Retrofitted	
	Cars	Light-duty vehicles	Trucks	Buses	Cars	Light-duty vehicles
Manufacturers	6	5	5	3	2	1
Types	18	15	9	7	13	6
Rated power in kW	44–95	44–105	75–175	140–228	44–85	51–95
Maximum permissible weight in tons	1.4–2.8	1.6–3.5	4.3–26	11.5–28	1.4–2.0	2.8–3.5
Mixture formation:						
lambda = 1	18	15	7	3	13	6
Lean burn	–	–	2	4	–	–
Operation:						
monovalent	1	1	9	7	4	4
bivalent	5	1	–	–	–	–
optional	12	13	–	–	9	2
Extra costs in US$ (thousands)	1.3–5.4	3.2–7.3	5.5–51.0	38.8–52.0	3.1–6.9	3.3–3.6

shows favourable emission values with an aged catalyst (30,000 km) as summarized in Table 8.

With a more sophisticated fuel system (for example, electronically controlled fuel injection) there is potential for further emission reductions.

The costs of converting from gasoline to propane are considerably less than conversions to natural gas, due primarily to the lower cost of the fuel tanks. As with natural gas, the cost of conversion for high-use vehicles can typically be recovered through lower fuel costs within a few years.

LPG is produced in the extraction of heavier liquids from natural gas, and as a by-product in petroleum refining. Presently, LPG supply exceeds the demand in most petroleum-refining countries, so the price is low compared to other hydrocarbons. Depending on the locale, however, the additional costs of storing and transporting LPG may more than offset this advantage.

Liquefied petroleum gas is already widely used as a vehicle fuel in the U.S., Canada, the Netherlands, Japan and elsewhere. In Japan, 260,000 taxis, 94% of the total number of taxis, use LPG as their fuel. Many diesel-fuelled taxis in Hong Kong have shifted to LPG.

The biggest fleet of LPG buses is running in Vienna. The additional costs for a bus with liquefied gas (LPG) engine were calculated at US$22,000, which means additional costs of 9% compared to a standard diesel bus and in comparison to the additional $20,500–$35,800 required for a natural gas engine.[19]

Table 8: Emissions in the 13-Mode Test for a 7.4 litre LPG engine running with aged catalyst (lamba = 1).

g/kWh		**HC**	**CO**	**NO_x**	**PM**
LPG		0.5	1.8	0.5	–
Emission Limits for Diesel Engines					
EURO 1	1992	1.25	5	9	0.40
EURO 2	1996	1.10	4	7	0.15
EURO 3	2000	0.60	2	5	0.10

For the use of LPG there are no higher additional costs for the filling station in comparison to a filling station for diesel fuel, as needed for a bus fleet (Vagt, 1995). The author calculated, for a German diesel fleet of 40 buses, overall costs of $1.60/km with regard to the costs of the vehicles, operational costs and fuel station costs. For a comparable fleet with vehicles running on liquefied gas, overall costs of $1.60/km, which are additional costs of only 0.3%, were calculated.

LPG can, as with CNG, turn the additional costs into an effective investment, because the low emissions of gas vehicles contribute significantly to the improvement of air quality in comparison to the usually used diesel engines in heavy duty vehicles.

LPG's major disadvantage is the limited supply, which would rule out any *large-scale* conversion to LPG fuel.

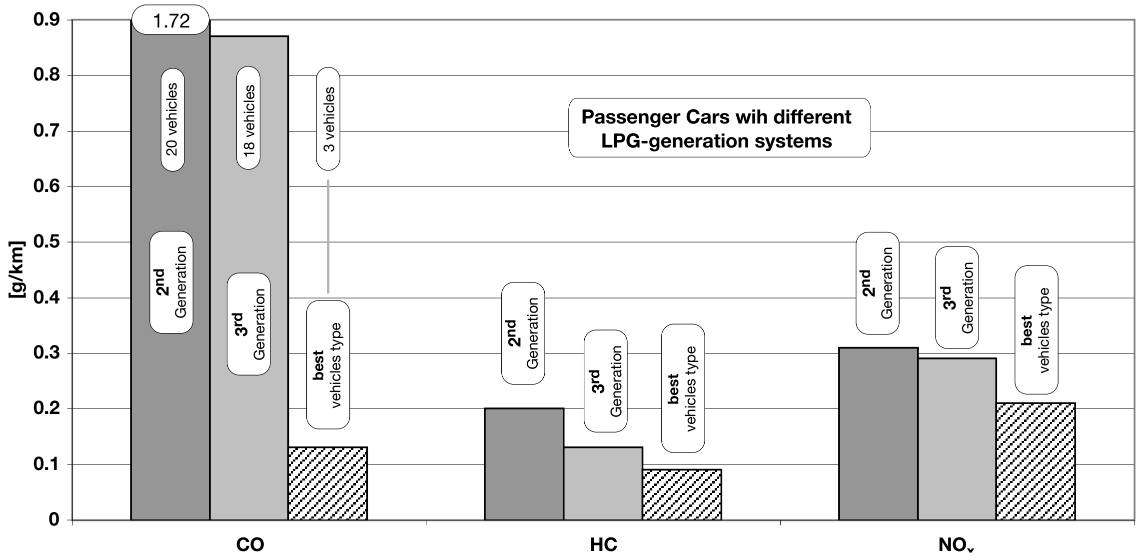


Fig. 5

Emissions of dedicated LPG vehicles in the new European Driving Cycle (NEDC).

Rijkeboer, Binkhorst 1998

6.3 Methanol

Methanol has many desirable combustion and emissions characteristics, including lean combustion capability, low flame temperature (leading to low NO_X emissions) and low photochemical reactivity. It is also a liquid, which makes its storage and handling much simpler than with gaseous fuels. At current and foreseeable prices, the most economical feedstock for methanol production is natural gas, especially natural gas found in remote regions where it has no ready market. The most common methanol fuel is M-85, a methanol-gasoline blend.

Light-duty methanol vehicles have emissions of NO_X and CO similar to gasoline vehicles. Emissions of VOCs are roughly half those of gasoline vehicles and lower ozone reactivity of the VOC results in lower ozone impacts. Emissions of formaldehyde (a primary combustion product of methanol) are higher than those from gasoline or other alternative-fuelled vehicles but can be controlled with a catalyst.

> *"There is little prospect for [methanol] to become price-competitive with conventional fuels unless oil prices increase greatly."*

The GHG reduction potential of methanol is dependent on the feedstock. Burning M-85 derived from methane results in total life cycle GHG emissions very slightly lower than a gasoline vehicle. But life cycle GHG emissions from wood or cellulose derived methanol are approximately 60% lower than from gasoline.

The major barrier to the widespread use of methanol is its high cost and price volatility. There is little prospect for it to become price-competitive with conventional fuels unless world oil prices increase greatly.

6.4 Ethanol

Ethanol is produced primarily by the fermentation of starch from grains (mostly corn) or sugar from sugar cane. It is most commonly used as an oxygenate in reformulated gasoline and in a gasoline blend called "gasohol." These fuels can be burned in gasoline engines. Specialized engines are necessary in order to burn pure ethanol.

In engines burning reformulated gasoline using ethanol, VOCs and CO are reduced but NO_X tends to increase slightly.

Vehicles burning gasohol will emit slightly more GHG emissions than conventional gasoline fuelled vehicles. Reductions associated with burning pure ethanol depend on the feedstock. Ethanol produced from corn has life cycle GHG emissions about 15% less than gasoline vehicles. Ethanol produced from woody biomass (E-100) has GHG emissions 60–75% below conventional gasoline.

A gasohol-fuelled automobile costs no more than a comparable gasoline vehicle. Since ethanol is derived from grains and sugars, the production of ethanol for fuel is in direct competition with food production in most countries. This keeps ethanol prices relatively high, which has effectively ruled out its use as a motor fuel except where, such as in Brazil and the U.S., it is heavily subsidised.

The Brazilian "Prooalcool" program (Figure 6) to promote the use of fuel ethanol in motor vehicles has attracted worldwide attention as a successful alternative fuel program. Despite the availability of a large and inexpensive biomass resource, however, this program still depends on massive government subsidies for its viability.

The high cost of producing ethanol (compared to hydrocarbon fuels) remains the primary barrier to widespread use.

6.5 Biodiesel

Biodiesel is produced by reacting vegetable or animal fats with methanol or ethanol to produce a lower-viscosity fuel that is similar in physical characteristics to diesel, and which can be used neat or blended with petroleum diesel in a diesel engine.

Over the years, many factors have stimulated interest in biofuels including biodiesel. For example, the primary initial motivation for the Brazilian Alcohol program was energy related concerns. However, it seems that the greatest motivation today for increased interest in biomass-based fuels in many countries is concern over the environment, especially with urban air pollution and global warming. Further, there is growing interest in providing a profitable market for excess farm production.

Biodiesel is a zero sulfur diesel fuel. Therefore many of the points noted above, especially with regard to the potential impact on advanced diesel control technologies, apply equally to biodiesel.

In general, biodiesel will soften and degrade certain types of elastomers and natural rubber compounds over time. Using high percent blends can impact fuel system components (primarily fuel hoses and fuel pump seals) that contain elastomer compounds incompatible with biodiesel. Manufacturers recommend that natural or butyl rubbers not be allowed to come in contact with pure biodiesel as this will lead to degradation of these materials over time, although the effect is lessened with biodiesel blends.

The general consensus is that blended or neat biodiesel has the potential to reduce diesel CO emissions (although these are already low), smoke opacity, and measured HC emissions. However, many studies show an increase in NO_X emissions for biodiesel fuel when compared to diesel fuel at normal engine conditions. While research shows a reduction in HC emissions when biodiesel is used, the effect of the organic acids and/or oxygenated compounds found in biodiesel may be affecting the response of the instrument that measures HC, the flame ionization detector, thus understating the actual HC emissions. Particulate data are mixed. Most studies show a reduction but some show increases under certain conditions. For example, one study found that:

Biodiesel gave generally higher particulate emissions and the highest levels of particulate associated soluble organic fraction for all driving cycles.[20]

The high cost of biodiesel fuel is one of the principal barriers making it less attractive to substitute for diesel fuel.

6.6 Hydrogen (H_2)

Hydrogen is usually used as compressed hydrogen (CH_2) with 200 bar or liquefied hydrogen (LH_2) at -252°C (422°F). Hydrogen is a secondary energy, which means that it has to be produced from other fossil or non-fossil energy sources.

It is often proposed to use hydrogen in road transport instead of carbon-containing gases, to provide a CO_2 advantage. Evaluating the

Fig. 6

A range of cleaner fuels, both conventional and alternative, are available in Curitiba, Brazil.

Karl Fjellstrom, Feb. 2002

total fuel life cycle, however, shows that using other fossil primary energy for the production of H_2 does not result in a net CO_2 advantage. Hydrogen as a fuel for road applications will be most advantageous when it is produced with renewable resources, such as electricity from renewable energy or from biomass.

Hydrogen can be used in internal combustion (IC) engines or fuel cells. If hydrogen is used in a heavy duty IC engine, emissions of CNG engines are comparable to hydrogen engines for NO_X, and for low PM exhaust emissions. Data for IC engines of passengers cars is not yet available. Instead of using a combustion engine, research efforts are focusing on the use of hydrogen in fuel cells in vehicles, which can be more efficient than using methanol in a fuel cell.

> ***"The total fuel life cycle shows that using other fossil primary energy for the production of H_2 does not result in a net CO_2 advantage"***

Costs, other restrictions

Hydrogen from renewable sources will have additional costs in comparison to the costs needed to generate renewable electricity. One study carried out in 1997 concluded that the energy content of gaseous hydrogen is reduced to 65% of the solar production electricity. In addition, the costs including transport were found to be twice the costs of the solar electricity at that time. Using liquefied hydrogen resulted in a 50% reduction of the solar electricity and resulted in costs more than four times higher than costs of solar electricity.[21]

6.7 Electric vehicles

A comprehensive field test study about Electric Vehicles (EVs) was made with about 60 vehicles on the German Baltic island Rügen in 1996. The German IFEU—Institute for Energy and Environmental Research, Heidelberg, performed the comparative eco-balance. The following passages are a short summary from Daug (1996).

Greenhouse gases, other emissions

Energy consumption and emissions of the vehicles depend on a large number of parameters. The most important of these energy consumption parameters are the *driving energy*, the *battery consumption* (internal resistance consumption, battery heating, recharging energy, efficiency of charging, self-discharge), the *secondary energy consumption* (charging converter) and the *additional heating*.

The comparison of electric motorcars with conventional cars are highly dependent on the electricity generation in each country, and varies substantially even within the same country. For example, in 2005 more than 50% of the electricity in Germany will be generated by coal power plants and around 5% of the electricity will be renewable. In Brazil, on the other hand, a large fraction of the electricity is from renewable hydropower.

The advantages of the electric motorcar over the conventional car include that the electric car does not generate emissions which are toxic to humans and which damage physical assets directly at the site of deployment. The electric cars generate less noise and contribute to a lesser degree to summer smog and nitrogen input into soils and water bodies depending on the source of the electricity. The disadvantages of the electric motorcar include that it could have a higher acidification potential and a stronger climatic impact if the electricity is generated for example from coal burning. These disadvantages can increase with decreasing daily kilometre performance and can only be compensated under special conditions of deployment such as very frequent short distance drives.

Costs, other restrictions

In the UBA's view, the EV has to be compared with the best available technology of internal combustion engines. Because of the EV's advantage of local zero emissions, the comparisons are made between the additional costs of an EV—dominated by the battery costs—and the additional costs for an Ultra Low Emission Vehicle (ULEV-) standard, in comparison to the then (1996) current TIER I emission standard vehicle.

The additional incremental cost of an ULEV was estimated to be between US$84 and US$200, depending on the size of the engine (Carb, 1996). The incremental costs were estimated to be 2.7–5.3 cents/mile for the battery depending on the type and specific costs of the battery. UBA calculated from these data costs of US$2,700–$6,400 for the additional incremental lifetime cost of the battery for an EV at that time (Kolke, 1995).

It was concluded by UBA that on the basis of a TIER I vehicle, the additional incremental cost of only one electric vehicle could finance the additional incremental costs of up to 75 ULEV vehicles. From the urban environmental point of view, the cost effectiveness of a complete introduction of a ULEV standard for all vehicles was estimated to be higher than having some 10% of EVs, 15% of ULEV and 75% of Transitional-Low-Emission Vehicle (TLEV).

The use of EVs makes sense in ecologically sensitive areas or enclosed indoor facilities that have a proven need for zero local emissions. In typical traffic situations, based on UBA's 1996 study, it may be more cost effective to introduce stringent emission limits, such as the ULEV standard or the EURO 4 standard for petrol vehicles.

> ***"On the basis of a TIER I vehicle, the additional incremental cost of only one electric vehicle could finance the additional incremental costs of up to 75 ULEV vehicles"***

6.8 Fuel cells

Fuel cell (FC) vehicles are currently being discussed as one of the most promising technologies for the future. Hydrogen, methanol and even petrol are discussed as fuels for the vehicles. Further differentiation must be done for the various possibilities of producing the fuel.

In the UBA's view, the first step of a Research and Development program must be the detailed and realistic estimation of the environmental effects and the costs for the applications, in comparison to the best available conventional technology. Only if a transparent analysis shows a cost competitiveness of fuel cells, assuming that they reach a sustainable emission reduction, should the fuel cell application be considered a realistic alternative technological solution for reducing emissions in the road transport sector.

Greenhouse gases, other emissions

The efficiency of the fuel cell vehicle and their costs will be one of the main problems on its way to becoming the "car of the future". The UBA did investigations for different cars of the future, based on its assumptions of likely developments. The comparisons were made relative to a competitive fuel-efficient vehicle with a petrol engine, which is available as a prototype; the SMILE Concept developed with assistance from Greenpeace (1996). This car has room for four passengers, a curb weight of 650 kg, a fuel consumption of 3.25 liters per 100km (72 mpg) and can reach ULEV emission levels. The calculations of the incremental costs were made for the efficient ULEV with a 40 kW engine and for a fuel cell vehicle with a mechanical power of 15 kW, a nominal engine power of about 18 kW (peak about 32 kW) and a fuel cell power of 40 kW. Two types of vehicle were examined:

- The fuel cell vehicle with compressed hydrogen storage,
- The fuel cell vehicle with methanol and reformer.

The calculations showed that the weight for the storage system and the propulsion components (engine, fuel cell, reformer, etc.) will be between 2 and 3 times higher than for the petrol fuelled car of the future.

The main current advantage of the fuel cell vehicle is the very low emissions. The UBA calculated the emissions of the efficient ULEV and the fuel cell vehicles under consideration of the emissions for fuel production, and compared them to a 1996 EURO 2 petrol vehicle (fuel consumption 6 liters per 100km or 39 mpg). The fuel consumption data for the fuel cell vehicles were given by Daimler (1997) with 20 kWh/100km and 26 kWh/100km (hydrogen, methanol) for a 730 kg vehicle.

The efficient ULEV gives already noticeable emission reductions of about 50%, up to 85%. The reduction of the direct emissions is sufficient for achieving the air quality targets in Germany. A further reduction of the direct emissions will not be necessary in Germany if all vehicles comply with this or a comparable emission standard. Comparing the directly and indirectly caused emissions, the fuel cell vehicles with very optimistic fuel consumption data can reduce emissions further in all cases.

The main rating parameter will be given by the relation of the additional costs for the new technologies to the benefit, which is the reduction of emissions and primary energy use in comparison to a vehicle achieving EURO 2 with 39 miles per gallon). These parameters will describe the specific emission avoidance costs. A summary of the additional calculations is given in the following section.

Costs, other restrictions

To calculate the emission avoidance costs for passenger cars in comparison to a EURO 2 standard vehicle, the emission reductions are compared to the extra vehicle costs. The extra vehicle costs are composed of various cost components, which contain for the most part the drives and storage costs, as well as energy costs for operation. The determination of the extra costs for the drives is carried out on the basis of an analysis and calculation of the specific costs. Figure 7 shows the basis of the calculation of the cost distribution with fuel cell costs of 50 €/kW. Further calculations are summarized following.

As in the long term the most important consideration will be the reduction of greenhouse-relevant CO_2 emissions, the following results summarize the calculations for the reduction of greenhouse gases. UBA also took the further US target data for fuel cell technology into account, which are characterised by the costs published in the Ford/DOE program and summarized in Sims (1997), with US$18–24/kW manufacturing costs for the FC-stack. Another calculation was made with the development goal of US$50/kW for an implementation strategy for the whole FC propulsion drive.

Even assuming the successful development of fuel cell technology for transport (US$50/kWFC Drive Line), the costs for emissions avoidance of the greenhouse gas CO_2 can rise up to US$200 per metric ton.

> ***"The avoidance costs are at least US$83 per metric ton of CO_2 more than the avoidance costs of an efficient vehicle with internal combustion petrol engine and ultra low emissions."***

The UBA made further comparisons of the costs and the possible emission reductions of fuel cell buses to be driven with hydrogen, and buses with internal combustion engine and natural gas (NG). While the first system can reduce the critical emission components of NO_X and particulate matter (PM) completely in comparison to a diesel bus, the natural gas bus can reduce NO_X by 85% and PM by more than 99%. The cost comparison shows that fuel cell technology is not a cost competitive technology for public buses in the near future, perhaps for the next 20 years.

As there is no real data for the future costs of FC buses available, the comparison has to be

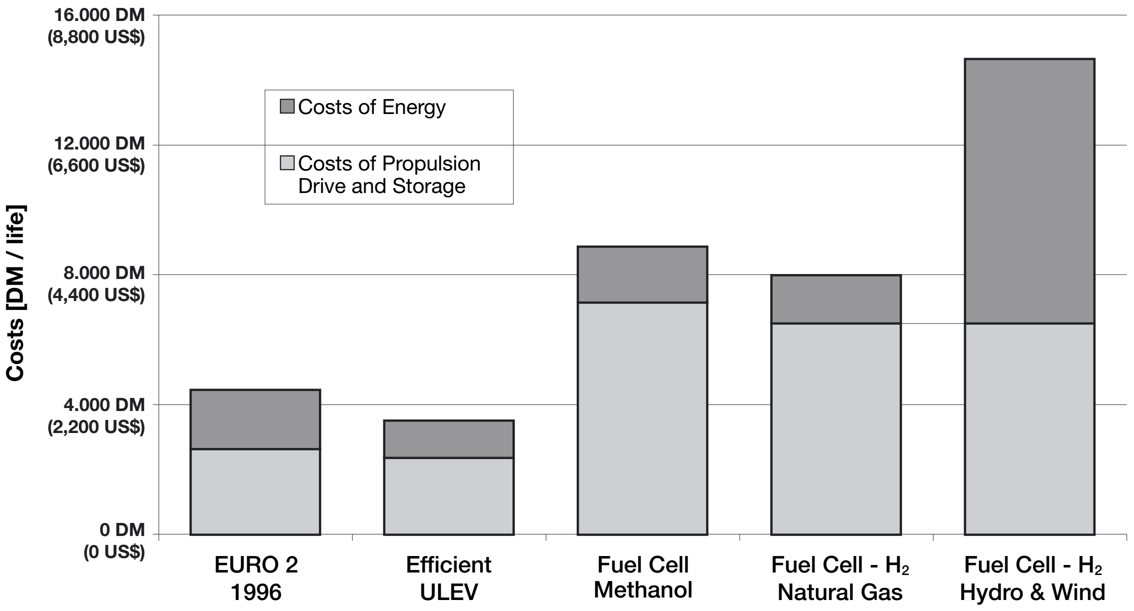


Fig. 7

Ratio of distribution of costs of new passenger car concepts with a lifetime of 10 years.

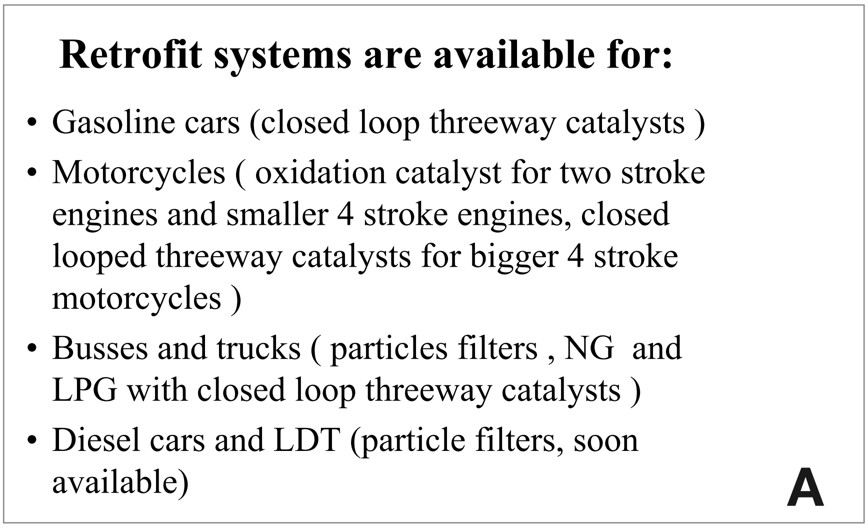
Retrofit policies and experiences in Germany

Source: Axel Friedrich, German Federal Environmental Agency
Note: 1 DM is approximately 0.5 €

The retrofit of in-use vehicles (Figure “A”) is one of the major instruments available to reduce emissions from the transport sector in a short time frame. In spite of this fact, most attempts made in different parts of the world have not been very successful. In Germany a high environmental consciousness caused by reports on the forest dying and other harmful effects of air pollution lead to ambitious legislation to reduce emissions from industry and transport. In the early 1980s the retrofit of power plants with scrubbers and catalysts for the reduction of sulfur dioxide and nitrogen oxides (NO_X) were required. After the introduction of three-way catalysts in the mid-1980s, there were calls for retrofitting gasoline cars with open loop three-way catalysts or exhaust gas recirculation (EGR). The open loop three-way catalyst reduces the emissions of a gasoline car with carburetor by about 50%. The retrofitted EGR reduces the NO_X by about 30% within the lower speed range where the NO_X emissions are lower. This retrofit program was supported by tax incentives. The devices had to have a type approval for each vehicle family. Because of the loophole that no durability requirement was established, inadequate systems were also used.

In the second phase, in addition to the open loop three-way catalysts, emission limits, which require the installation of three-way catalysts with lambda control, were included in the legislation. The retrofit kits which are able to meet the Euro 1 car emission standards were not required to pay the annual car tax until the total amount reached 1,250DM (about US$650) and afterwards the owner had to pay the reduced annual tax fee for a Euro 1 car. The legal requirement included the same procedure for type approval as for new cars. After the installation, each individual car had to be checked by licensed test centres and a change of the vehicle identification card had to be made by the authorities. Due to this legal requirement the industry developed retrofit kits which met the Euro 1 standards and the retrofit costs for a middle-size car came down to about 1,250DM (around 640€).

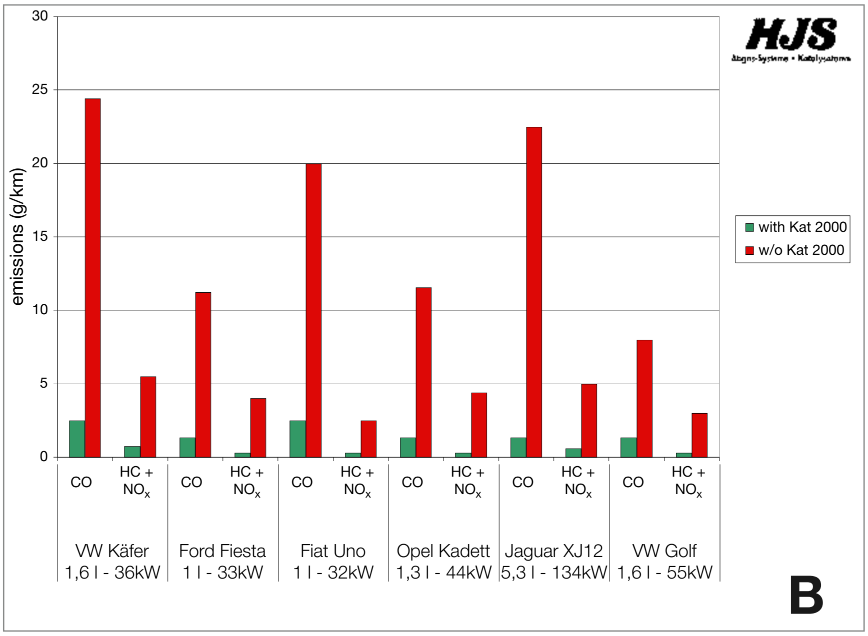
The retrofit kit includes the three-way catalyst (including the tubing made in stainless steel), the electronic control unit including the lambda sensor, as well as the parts for the introduction



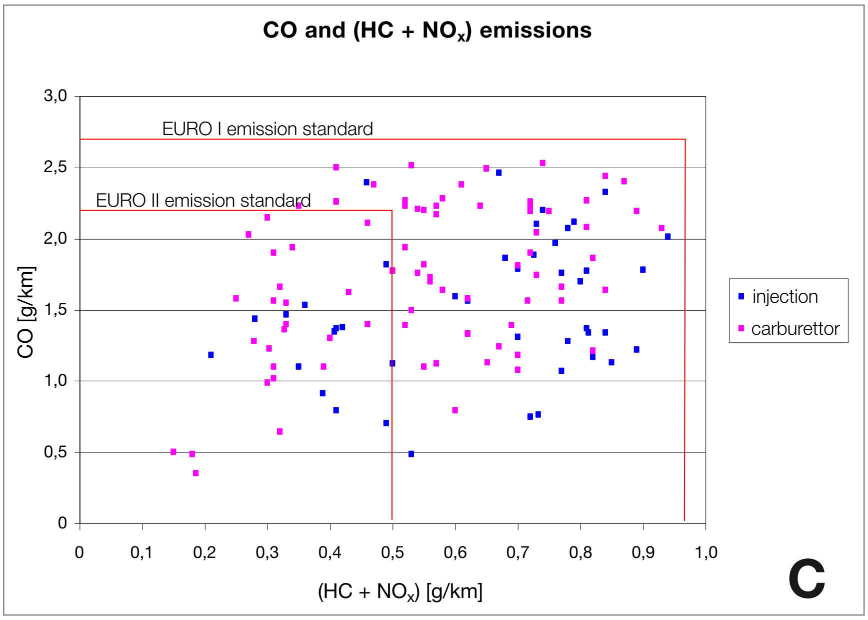
Retrofit systems are available for:

- Gasoline cars (closed loop threeway catalysts)
- Motorcycles (oxidation catalyst for two stroke engines and smaller 4 stroke engines, closed looped threeway catalysts for bigger 4 stroke motorcycles)
- Busses and trucks (particles filters , NG and LPG with closed loop threeway catalysts)
- Diesel cars and LDT (particle filters, soon available)

A



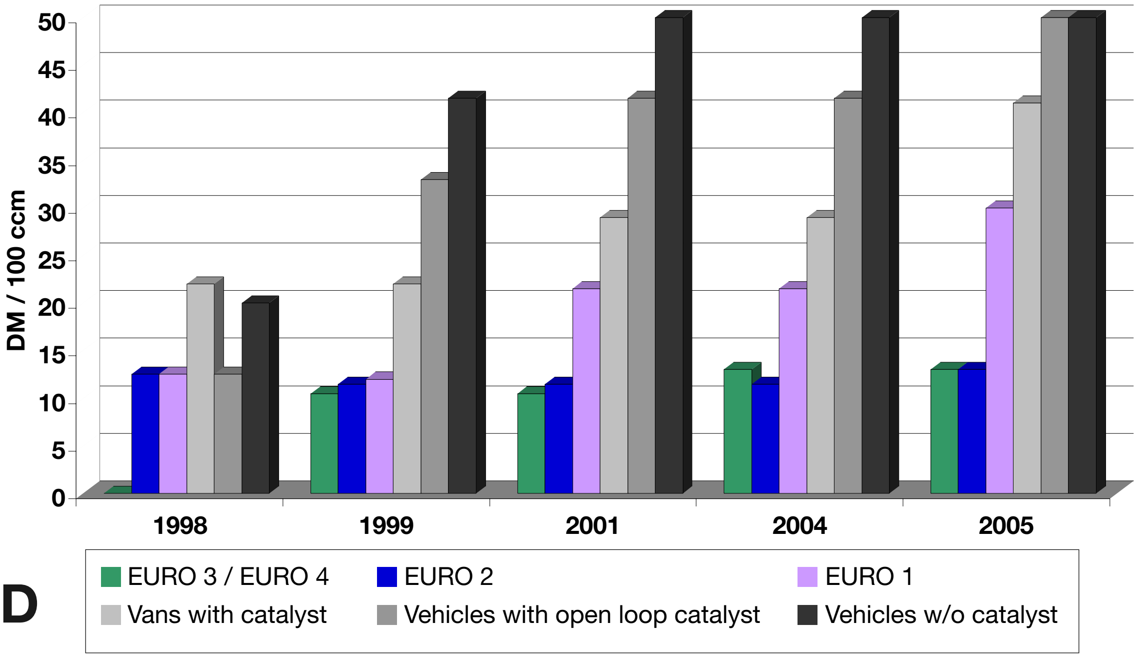
B



C

Fig. 8
Annual emission-related vehicle tax in Germany (in DM/100ccm)

D



of additional air below the carburetor and if necessary an adapter for the carburetor. The certification documents were added. The garages got a calibration unit for the correct setting of the engine and the lambda value.

In Figure "B", the emissions before and after retrofit are shown for some vehicles of different size and age. One of the oldest vehicles retrofitted is the Fiat Topolino from the model year 1936! The conversion achieved emission reductions in the range of 90%.

In Figure "C", the type approval data from many different vehicles are shown. It can be seen that a considerable number of vehicles also meet the Euro 2 standards for all three pollutants.

In the year 1998 the annual vehicle tax was changed in order to reflect the emission behaviour in the tax rate. Because of the social implications of this tax change—the higher polluting cars belong to poorer people—the adoption of this tax took some time, and was watered down. The tax structure is shown in Figure "D". The changes are made in two steps in order to allow owners of old polluting cars either to retrofit or to scrap the vehicle. The aim of the reform was also that the tax changes are fiscally neutral. A total number of about 800,000 cars are up to now retrofitted. For an average car a time period of about 2–2.5 years is necessary to pay for the catalyst by the tax reduction. Today it is quite difficult to sell an old car without a closed loop three-way catalyst. For this reason, vehicle resellers made most of the recent retrofits.

In addition to the tax incentives, other instruments are used to promote the retrofit of cars. In different laws and ordinances driving restriction upon incidence of high levels of air pollutants (in the last decade winter smog, now summer smog (ozone) and in street canyons) are only applied to highly polluting cars. This means retrofitted cars are also exempted. To ease the enforcement, the cars with closed loop catalyst are marked with a sticker at the wind shield. In spite of the fact that until now these instruments have been used only twice in Germany, the adoption of this legislation considerably influenced the rate of scrapping and retrofitting. Retrofit kits which fulfill additional requirements were entitled to use the environmental label (*Umweltzeichen*) for advertisement.

made on the basis of the best available competitive technology, which is the NG bus. The production-ready and available NG technology has additional costs of US$22,000–39,000 which can be reduced to US$14,000 in the next 10 years (see margin note).

Nevertheless, fuel cell technology is a promising future technology. But a differentiated look at the use of fuel cells is required from an environmental point of view, according to the energy services that they are going to provide and the available or foreseeable alternatives in each case. The FC use in the stationary area appears to be sensible and capable of development, since they can already convert fossil energy sources (*e.g.,* natural gas) into electricity and heat or be coupled with cooling production much more efficiently than previous power plants or heat producers.

7. Conclusions

It is now well established that cleaner fuels must be an integral part of a comprehensive and effective motor vehicle pollution control effort. The elimination of lead in gasoline as well as the dramatic reduction if not virtual elimination of sulfur from both gasoline and diesel fuel are now well-established elements of a clean fuels program. The major lesson of the past twenty-five years with regard to these components is to move quickly.

Today, an internal combustion engine fuelled by a fossil fuel powers the vast majority of vehicles around the world. This technology is advancing rapidly and especially where ultra low sulfur fuel is available is capable of achieving very low levels of conventional pollutants. In addition fuel efficiency increases are possible that could reduce the rate of growth of greenhouse gas emissions and in some cases actual reduce the absolute amount of greenhouse gases emitted from the transport sector.

However, alternative fuels and technologies offer opportunities for significant reductions in emissions and increases in efficiency for certain niche vehicle categories. The different alternative fuels and technologies are in various stages of development and each has unique performance and emission characteristics. Considering the current stage of development and emissions reduction potential, the following policy conclusions seem most appropriate:

Where compressed natural gas is readily available in a given locality, and where ULSD is not readily and reliably available, strong consideration should be given to replacing diesel buses with CNG buses. Other centrally fuelled fleets such as refuse trucks or local delivery trucks are also attractive candidates for replacement.

Where compressed natural gas or LPG is readily available in a given locality, strong consideration should be given to replacing other high polluting vehicle types such as two stroke engined autorikshaws with CNG or LPG. Conversions to both LPG and CNG have been well established as a viable technology. In terms of PM and HC emissions reductions, the most successful strategy for three wheelers is to replace the existing petrol fuelled, two stroke engine with a CNG or LPG fuelled 4 stroke engine.

There are several obstacles to the widespread use of natural gas and LPG fuelled vehicles including the absence of transportation and storage infrastructure, additional cost (primarily of the fuel storage tanks), loss of cargo space, increased refueling time, and lower driving range. Therefore, economic incentives in the form of lower taxes on fuels or other incentives should be considered as a means to stimulate the introduction and acceptance of these fuels

Where LPG is readily available, and where ULSD is not readily and reliably available, strong consideration should be given to replacing diesel or petrol taxicabs with LPG.

Conversion of existing diesel vehicles to natural gas is difficult and problematical and very often results in higher actual NO_X emissions. Therefore, for diesel vehicles, replacement should be considered rather than conversion.

Conversion of existing gasoline fuelled vehicles to CNG or LPG is not very difficult and if done well can result in emissions reductions.

An inherent advantage of gaseous fuels is the assurance that adulteration will not be a problem.

Depending upon the feedstock and the process used to make these fuels, they can be very low or very high in GHG emissions. For example, methanol made from coal would approximately double GHG emissions compared to conventional gasoline, whereas methanol made from natural gas would be slightly lower than gasoline and made from cellulose would be about 60% lower.

Looking to the future, it is clear that the vehicle population continues to grow rapidly in many parts of the world continuing to put pressure on the local and global environment. After more than 40 years of effort to reduce vehicle pollution, over 100 million people in the US still live in areas where one or more health based air quality standard is exceeded. With regard to global warming, the transportation sector is now the fastest growing contributor of greenhouse gases and the rapid growth in CO_2 from this sector continues unabated in spite of significant efforts in such regions as Europe. Even in Europe where CO_2 reductions are being most aggressively pursued through the increased use of diesel technology, recent evidence indicates that black carbon emissions from these vehicles may be undercutting these modest gains. While conventional technologies are increasingly demonstrating the ability to achieve lower and lower levels of CO, HC, NO_X and PM, they are rapidly consuming the world's limited supply of oil.

Therefore, as one considers these issues in the aggregate, along with other issues such as noise pollution, water contamination, etc., one must ask whether it is prudent to expand the technological and fuel choices available to future generations of vehicle owners. The question is whether it is good public policy to commit all available resources to existing technologies and fuels which are very mature and which continue to make incremental progress or whether some resources should also be redirected to fuels and power plants which while very expensive today in their early stages of development hold promise of being attractive in the not to distant future. With regard to developing countries, where resources are most limited, the question is even more acute. However, in some of these countries such as China, where explosive growth in vehicle production is underway, decision makers have concluded that some investments (on the order of $100 million) in longer-term technologies hold sufficient promise to be justified. Each country must answer these questions on their own, considering their environmental challenges, their resources, oil imports costs, technological capabilities, and so on.

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Some common abbreviations

APU	auxiliary power unit
BET	best existing technologies
CNG	Compressed Natural Gas
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
EURO 1	emission standard 91/441/EEC
EURO 2	emission standard 94/12/EEC
EURO 3	emission standard 98/69/EC
EURO 4	emission standard 98/69/EC
FC	fuel cell
FCV	fuel cell vehicle
FTP75	US driving cycle
H_2	hydrogen
HC	hydrocarbons
ICE	internal combustion engine
LEV	Low Emission Vehicle
mpgge	miles per gallon petrol equivalent
MTBE	methyl tertiary-butyl ethyl; a lead-free antiknock gasoline additive
NEDC	New European Driving Cycle
NG(V)	natural gas (vehicle)
NMOG	Non-Methane Organic Gas
NMVOC	Non-Methane Volatile Organic Compounds
NO_X	oxides of nitrogen
PAH	Polycyclic Aromatic Hydrocarbons; a class of very stable organic molecules made up of only carbon and hydrogen
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicle
psi	pounds per square inch
SO_2	sulfur dioxide
SOF	Soluble Organic Fraction; portion of particles emitted in diesel exhaust that can be extracted into solution
SULEV	Super Ultra Low Emission Vehicle
TLEV	Transitional Low Emission Vehicle
THC	total hydrocarbons
TWC	three-way catalyst
UBA	Federal Environmental Agency (Umweltbundesamt)
ULEV	Ultra Low Emission Vehicle
UMK	Germany's Standing Conference of Environment Ministers, (Umwelt-ministerkonferenz)
ZEV	Zero Emission Vehicle
ZLEV	Zero Level Emission Vehicle

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