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Global trends in motor vehicle pollution control: a 2011 update
Part 1

1. Introduction

Since the end of the Second World War there has been a strong and steady growth in the world's motor vehicle population. Initially, this growth was focused primarily in North America but over the past six decades it has gradually spread, first to Europe and now Asia and to a lesser extent, Latin America. Vehicles have brought many perceived improvements to the quality of lives – increased mobility, jobs, recreational opportunities – to name but a few. But they have also changed many cities into sprawling conurbations, developed a so far unquenchable thirst for precious and limited oil, become a major if not dominant source of urban air pollution and most recently the most rapidly growing contributor to climate change.

2. Trends in world motor vehicle production

Overall growth in the production of motor vehicles, especially since the end of World War II, has been quite dramatic, rising from about 5 million motor vehicles per year to almost 70 million. As shown in Fig. 1, between 1970 and 2008, approximately 1 million more vehicles have been produced each year compared to the year before with almost 70 million vehicles produced in 2008[1]. Data regarding motorcycle production is less precise but one major producer[2] estimates that global production exceeded 30 million units in 2003 and is increasing by approximately 1 million units each year.
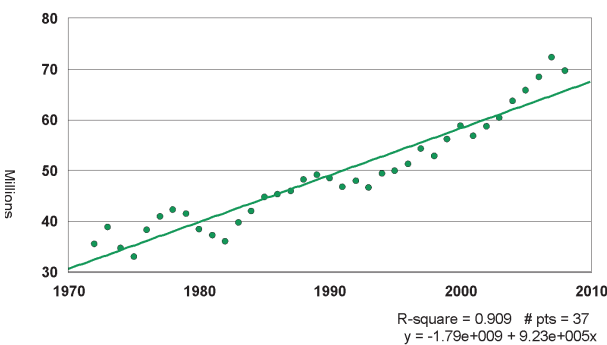

Fig. 1. Annual production of cars, trucks and buses

Nowhere has the growth been greater than in China which was an insignificant motor vehicle producer two decades ago but is now the largest producer of cars, trucks, and buses in the world and is rapidly becoming a major market as well (see Fig. 2). It is also far and away the largest producer and user of motorcycles.

[1] Wards Motor Vehicle Data, various issues
[2] Honda Motor Company, 2004 World Motorcycle Facts and Figures

3. Trends in world motor vehicle fleets

Historically, the three primary drivers leading to growth in the world's vehicle fleet have been population growth, urbanization, and economic improvement and all three continue to increase, especially in developing countries. According to the United Nations, the global population increased from approximately 2.5 billion people in 1950
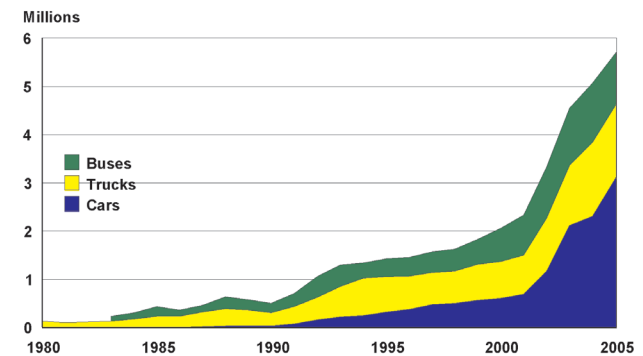

Fig. 2. Production of cars, trucks and buses in China

to more than 6 billion today and it is projected to increase to approximately 9 billion by 2050. Most of this growth will be in urban areas in developing countries.

Annual GDP growth rates over the next two decades are forecast to be highest in China, East Asia, Central and Eastern Europe and the former Soviet Union which will stimulate growth in vehicle populations in these regions.

As a result of these factors, one can anticipate steady and substantial growth in the global vehicle population [47] following the historical trends illustrated in Fig. 3. The global vehicle population exceeded 1 billion units in 2002 and has continued to climb steadily since then.

Since 1990, approximately 27 million additional motor vehicles have been added to the world's roads and highways each year. Newer manufactured vehicles are more durable
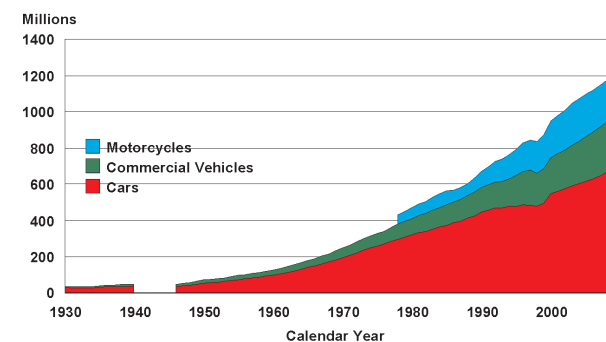

Fig. 3. World motor vehicle population

than in the past which will likely further increase the number of vehicles on the road.

4. Motor vehicle emissions and impacts

Motor vehicles emit large quantities of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), sulfur oxides (SO_x) and such toxic substances as benzene, formaldehyde, acetylaldehyde, 1.3-butadiene and (where lead is still added to gasoline) lead. Each of these, along with secondary by-products such as ozone and small particles (e.g. nitrates and sulfates), can cause serious adverse effects on health and the environment. Because of growing vehicle populations and resulting emissions, the fraction of health damaging pollution due to motor vehicles remains significant throughout the developed world and is rising in many cities in the developing world.

A. Local health concerns

Exposure to levels of air pollutants have been associated with a variety of adverse health effects. Based on available information, the World Health Organization (WHO) sets and periodically updates air quality guidelines. The following summary is based on the guidelines adopted by the World Health Organization (WHO) [44] and standards adopted by the United States Environmental Protection Agency (USEPA).

Particulate matter

Particulate matter (PM) represents a broad class of chemically and physically diverse substances. It can be principally characterized as discrete particles that exist in the condensed (liquid or solid) phase spanning several orders of magnitude in size. PM10 refers to particles generally less than or equal to 10 micrometers (μm). PM2.5 refers to fine particles, those particles generally less than or equal to 2.5 μm in diameter. Inhalable (or ''thoracic'') coarse particles refer to those particles generally greater than 2.5 μm but less than or equal to 10 μm in diameter. Ultrafine PM refers to particles less than 100 nanometers (0.1 μm). Larger particles tend to be removed by the respiratory clearance mechanisms (e.g. coughing), whereas smaller particles are deposited deeper in the lungs.

Fine particles are produced primarily by combustion processes and by transformations of gaseous emissions (e.g., SO_x, NO_x and VOCs) in the atmosphere. Thus, $PM_{2.5}$ may include a complex mixture of different pollutants including sulfates, nitrates, organic compounds, elemental carbon and metal compounds. These particles can remain in the atmosphere for days to weeks and travel through the atmosphere hundreds to thousands of kilometers.

The evidence on airborne PM and public health is consistent in showing adverse health effects at exposures experienced by urban populations in cities throughout the world, in both developed and developing countries. The range of effects is broad, affecting the respiratory and cardiovascular systems and extending to children and adults and to a number of large, susceptible groups within the general population. The risk for various outcomes has been shown to increase with exposure and there is little evidence to suggest

a threshold below which no adverse health effects would be anticipated. In fact, the lower range of concentrations at which adverse health effects has been demonstrated is not greatly above the background concentration which has been estimated at 3–5 μg/m³ in the United States and Western Europe for particles smaller than 2.5 micrometer, $PM_{2.5}$. The epidemiological evidence shows adverse effects of particles after both short-term and long-term exposures.

The WHO Air Quality Guidelines for PM are:
$PM_{2.5}$: 10 μg/m³ annual mean, 25 μg/m³ 24-hour mean
PM_{10}: 20 μg/m³ annual mean, 50 μg/m³ 24-hour mean

Health effects associated with short-term exposures (hours to days) to ambient PM include premature mortality, increased hospital admissions, heart and lung diseases, increased cough, adverse lower-respiratory symptoms, decrements in lung function and changes in heart rate rhythm and other cardiac effects. Studies examining populations exposed to different levels of air pollution over a number of years, including the Harvard Six Cities Study [11] and the American Cancer Society Study [32], show associations between long-term exposure to ambient $PM_{2.5}$ and both total and cardiovascular and respiratory mortality. In addition, a reanalysis of the American Cancer Society Study shows an association between fine particle and sulfate concentrations and lung cancer mortality [28].

The health effects of $PM_{2.5}$ have been further documented in local impact studies which have focused on health effects due to $PM_{2.5}$ exposures measured on or near roadways. Taking account of all air pollution sources, including both spark-ignition (gasoline) and diesel powered vehicles, these latter studies indicate that exposure to $PM_{2.5}$ emissions near roadways, dominated by mobile sources, are associated with potentially serious health effects. For instance, a recent study found associations between concentrations of cardiac risk factors in the blood of healthy young police officers and $PM_{2.5}$ concentrations measured in vehicles [36]. Also, a number of studies have shown associations between residential or school outdoor concentrations of some constituents of fine particles found in motor vehicle exhaust and adverse respiratory outcomes, including asthma prevalence in children who live near major roadways [4, 27, 43].

The WHO annual average guideline value of 10 μg/m³ for $PM_{2.5}$ was chosen to represent the lower end of the range over which significant effects on survival have been observed in the American Cancer Society Study (ACS) [33]. Adoption of a guideline at this level places significant weight on the long-term exposure studies using the ACS and Harvard Six-Cities data. In these studies, robust associations were reported between long-term exposure to $PM_{2.5}$ and mortality. Thresholds were not apparent in either of these studies.

In addition to $PM_{2.5}$ and PM_{10}, ultra-fine particles (UF) have recently attracted significant scientific and medical attention. These are particles smaller than 0.1 micrometer and are measured as number concentration. While there is considerable toxicological evidence of potential detrimental effects of UF particles on human health, the existing body of epidemiological evidence is insufficient in the view of WHO

to reach a conclusion on the exposure/response relationship to UF particles. Therefore no recommendations have been provided by the WHO as to guideline concentrations of UF particles at this point.

A study led by UCLA researchers has revealed that the smallest particles from vehicle emissions may be the most damaging components of air pollution in triggering plaque buildup in the arteries, which can lead to heart attack and stroke[3]. In the study, researchers exposed mice with high cholesterol to one of two sizes of air pollutant particles from downtown Los Angeles freeway emissions and compared them with mice that received filtered air that contained very few particles. Researchers found that mice exposed to ultrafine particles exhibited 55 percent greater atheroscleroticplaque development than animals breathing filtered air and 25 percent greater plaque development than mice exposed to fine-sized particles.

Another study published in the New England Journal of Medicine linked exposure to diesel exhaust with asthma[4]. The researchers recruited 60 adults with either mild or moderate asthma to participate in a randomized, crossover study. Each participant walked for 2 hours along a London street (Oxford Street) and, on a separate occasion, through a nearby park (Hyde Park). Detailed real-time exposure, physiological, and immunologic measurements were taken. Participants had significantly higher exposures to fine particles (< 2.5 μm in aerodynamic diameter), ultrafine particles, elemental carbon, and nitrogen dioxide on Oxford Street than in Hyde Park. Walking for 2 hours on Oxford Street induced asymptomatic but consistent reductions in the forced expiratory volume in 1 second (FEV_1) (up to 6.1%) and forced vital capacity (FVC) (up to 5.4%) that were significantly larger than the reductions in FEV_1 and FVC after exposure in Hyde Park ($P = 0.04$ and $P = 0.01$, respectively, for the overall effect of exposure, and $P < 0.005$ at some time points). The effects were greater in subjects with moderate asthma than in those with mild asthma. These changes were accompanied by increases in biomarkers of neutrophilic inflammation (sputum myeloperoxidase, 4.24 ng per milliliter after exposure in Hyde Park vs. 24.5 ng per milliliter after exposure on Oxford Street; $P = 0.05$) and airway acidification (maximum decrease in pH, 0.04% after exposure in Hyde Park and 1.9% after exposure on Oxford Street; $P = 0.003$). The changes were associated most consistently with exposures to ultrafine particles and elemental carbon.

Ozone

Ground-level ozone pollution is formed by the reaction of VOCs and NO_x in the atmosphere in the presence of heat and sunlight. The science of ozone formation, transport, and accumulation is complex. Ground-level ozone is produced and destroyed in a cyclical set of chemical reactions, many of which are sensitive to temperature and sunlight. When ambient temperatures and sunlight levels remain high for several days and the air is relatively stagnant, ozone and its precursors can build up and result in more ozone than typically would occur on a single high- temperature day. Ozone also can be transported from pollution sources into areas hundreds of miles downwind, resulting in elevated ozone levels even in areas with low local VOC or NO_x emissions.

The health and welfare effects of ozone are well documented [41, 42]. Ozone can irritate the respiratory system, causing coughing, throat irritation, and/or uncomfortable sensation in the chest. It can reduce lung function and make it more difficult to breathe deeply, and breathing may become more rapid and shallow than normal, thereby limiting a person's activity. Ozone can also aggravate asthma, leading to more asthma attacks that require a doctor's attention and/or the use of additional medication. Animal toxicological evidence indicates that with repeated exposure, ozone can inflame and damage the lining of the lungs, which may lead to permanent changes in lung tissue and irreversible reductions in lung function. People who are more susceptible to effects associated with exposure to ozone include children, the elderly, and individuals with respiratory disease such as asthma. There is suggestive evidence that certain people may have greater genetic susceptibility. Those with greater exposures to ozone, for instance due to time spent outdoors (e.g., children and outdoor workers), are also of concern.

Short-term exposure to current levels of ozone in many areas is likely to contribute to premature deaths, according to a National Research Council report[5]. Evidence of a relationship between short-term – less than 24 hours – exposure to ozone and mortality has been mounting, but interpretations of the evidence have differed, prompting EPA to request the Research Council report. Based on a review of recent research, the committee found that deaths related to ozone exposure are more likely among individuals with pre-existing diseases and other factors that could increase their susceptibility. However, premature deaths are not limited to people who are already within a few days of dying.

In addition, the committee examined research based on large population groups to find how changes in ozone air concentration could affect mortality, specifically to determine the existence of a threshold – a concentration of ozone below which exposure poses no risk of death. The committee concluded that if a threshold exists, it is probably at a concentration below the current public health standard. As people have individual susceptibilities to ozone exposure, not everyone may experience an altered risk of death if ozone

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[3] The findings appear in the January 17th online edition of the journal Circulation Research.

[4] Respiratory Effects of Exposure to Diesel Traffic in Persons with Asthma, James McCreanor, M.R.C.P., Paul Cullinan, M.D., Mark J. Nieuwenhuijsen, Ph.D., James Stewart-Evans, M.Sc., Eleni Malliarou, M.Sc., Lars Jarup, Ph.D., Robert Harrington, M.S., Magnus Svartengren, M.D., In-Kyu Han, M.P.H., Pamela Ohman-Strickland, Ph.D., Kian Fan Chung, M.D., and Junfeng Zhang, Ph.D.

[5] Estimating Mortality Risk Reduction and Economic Benefits from Controlling Ozone Air Pollution", National Academies Press, National Research Council, Division on Earth and Life Studies, Board on Environmental Studies and Toxicology, Committee on Estimating Mortality Risk Reduction Benefits from Decreasing Tropospheric Ozone Exposure, John C. Bailar III (chair), Professor Emeritus, Department of Health Studies University of Chicago.

air concentration also changes. The research on short-term exposure does not account for all ozone-related mortality, and the estimated risk of death may be greater than if based solely on these studies, the committee noted.

The second edition of the WHO AQG [1] set the guideline value for ozone at 120 µg/m³ for an 8-hour daily average. Since the mid-1990s there has been no major addition to the evidence from chamber studies or field studies. There has however been a marked increase in health effects evidence from epidemiological time-series studies. Combined evidence from those studies shows convincing, though small, positive associations between daily mortality and ozone levels, independent of the effects of particulate matter. Similar associations have been observed in both North America and Europe. These time-series studies have shown effects at ozone concentrations below the previous guideline of 120 µg/m³ without clear evidence of a threshold. Evidence from both chamber and field studies also indicate that there is considerable individual variation in response to ozone. In view of these considerations, there was a good case for reducing the WHO AQG from the previous level of 120 µg/m³. WHO, therefore, recommended that the air quality guideline for ozone be set at the level of:

Ozone: 100 µg/m³ for daily maximum 8-hour mean

As concentrations increase above the guideline value, health effects at the population level become increasingly numerous and severe. Such effects can occur in places where concentrations are currently high due to human activities or during episodes of very hot weather.

Nitrogen dioxide

Evidence from animal toxicological studies indicates that long-term exposure to NO_2 at concentrations above current ambient concentrations has adverse effects. In population studies NO_2 has been associated with adverse health effects even when the annual average NO_2 concentration complied with the WHO-2000 annual guideline value of 40 µg/m³. Also some indoor studies suggest effects on respiratory symptoms among infants at concentrations below 40 µg/m³. Together these results support a lowering of the annual NO_2 guideline value. However, NO_2 is an important constituent of combustion-generated air pollution and is highly correlated with other primary and secondary combustion products; it is unclear to what extent the health effects observed in epidemiological studies are attributable to NO_2 itself or to other correlated pollutants. The current scientific literature, therefore, has not accumulated sufficient evidence to change the WHO 2000 guideline value of 40 µg/m³ for annual NO_2 concentrations.

Many short term experimental human toxicology studies show acute health effects at levels higher than 500 µg/m³, and one meta-analysis has indicated effects at levels exceeding 200 µg/m³. The current scientific literature has not accumulated evidence to change from the WHO 2000 guideline value of 200 µg/m³ for 1-hour NO_2 concentration.

In conclusion, the WHO guideline values remain unchanged at the following levels:

NO_2 concentration: 40 µg/m³ for annual mean;
NO_2 concentration: 200 µg/m₃ for 1-hour mean.

The California Air Resources Board approved staff recommendations to amend its NO_2 standard on February 22, 2007. The recommendations were based on a review of the scientific literature on the health effects of NO_2 that was conducted by staff from the Air Resources Board and the Office of Environmental Health Hazard Assessment. On January 5, 2007, staff recommended lowering the existing 1-hour-average standard for NO_2 of 0.25 ppm to 0.18 ppm, not to be exceeded, and established a new annual-average standard of 0.030 ppm, not to be exceeded.

An Environmental Protection Agency draft risk assessment finds evidence from recent studies is "sufficient to infer a likely causal relationship" between short-term exposure to nitrogen dioxide and adverse effects on the respiratory system[6]. According to the draft report, a 30-minute exposure to nitrogen dioxide concentrations between 0.2 ppm and 0.3 ppm has been shown to irritate airways in asthmatics. Children, whose lung function continues to develop into adolescence, and those over the age of 65 are also particularly susceptible to nitrogen dioxide exposure. The risk assessment also identified as an at-risk group those whose jobs require significant periods of driving. Mean nitrogen dioxide levels inside vehicles are often two to three times the outdoor concentrations.

Sulfur dioxide

Short-term exposures

Controlled studies with exercising asthmatics indicate that some of them experience changes in pulmonary function and respiratory symptoms after periods of exposure as short as 10 minutes. Based on this evidence, it is recommended by WHO that a value of **500 µg/m³** should not be exceeded over **averaging periods of 10 minutes**. Because exposure to sharp peaks depends on the nature of local sources and meteorological conditions, no single factor can be applied to this value in order to estimate corresponding guideline values over somewhat longer periods, such as an hour.

Exposure over a 24-hour period and long-term exposure

Day-to-day changes in mortality, morbidity or lung function related to 24-hour average concentrations of sulfur dioxide are necessarily based on epidemiological studies in which people are in general exposed to a mixture of pollutants, with little basis for separating the contributions of each to the effects, which is why guideline values for sulfur dioxide were linked before 1987 with corresponding values for particulate matter. This approach led to a guideline value before 1987 of 125 µg/m³ as a 24-hour average, after applying an uncertainty factor of 2 to the lowest-observed-adverse-effect level. In the 2000 revision, it was noted that recent epidemiological studies showed separate and independent adverse public health effects for particulate matter and sulfur dioxide, and this led to a separate WHO AQG for sulfur dioxide of 125 µg/m³ as

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[6] EPA published a request for comment on the draft assessment in the Federal Register on April 14th 2008.

a 24-hour average. More recent evidence, beginning with the Hong Kong study of a major reduction in sulfur content in fuels over a very short period of time, shows an associated substantial reduction in health effects (childhood respiratory disease and all age mortality outcomes) [17]. In time-series studies on hospital admissions for cardiac disease, there is no evidence of a concentration threshold within the range of 5-40 µg/m³ in both Hong Kong and London [46]. Daily SO_2 was significantly associated with daily mortality in 12 Canadian cities with an average concentration of only 5 µg/m³ [6]. If there were an SO_2 threshold for either the Burnett et al. study of daily mortality, or the annual mortality study of Pope et al. (2002), they would have to be very low. For the significant associations in the ACS cohort for 1982-1998 in 126 US metropolitan areas, the mean SO2 was 6.7 µg/m³.

Nevertheless, there is still considerable uncertainty as to whether sulfur dioxide is the pollutant responsible for the observed adverse effects or, rather, a surrogate for ultra-fine particles or some other correlated substance. For example, in Germany [45] and the Netherlands [5] a strong reduction of SO_2 concentrations occurred over a decade. Although mortality also decreased with time, the association of SO_2 and mortality was judged to not be causal and was attributed to a similar time trend of a different pollutant (PM). In consideration of: (1) the uncertainty of SO_2 in causality; (2) the practical difficulty of reaching levels that are certain to be associated with no effects; and (3) the need to provide greater degrees of protection than those provided by the guidelines published in 2000, and assuming that reduction in exposure to a causal and correlated substance is achieved by reducing sulfur dioxide concentrations, then there is a basis for revising the 24 hour guideline downward for sulfur dioxide, and the following guideline is recommended as a prudent precautionary level:

Sulfur dioxide: 20 µg/m³ for 24-hour mean
500 µg/m³ for 10-minute mean (unchanged)

The WHO has determined that an annual guideline is not needed, since compliance with the 24-hour level will assure low levels for the annual average.

B. Summary of the updated WHO AQG levels

Table 1 summarizes the updated WHO Air quality guideline levels presented in the previous sections. They are recommended to be achieved everywhere in order to significantly reduce the adverse health effects of pollution.

Carbon monoxide

Carbon monoxide – an odorless, invisible gas created when fuels containing carbon are burned incompletely – also poses a serious threat to human health. Persons afflicted with heart disease and fetuses are especially at risk. Because the affinity of hemoglobin in the blood is 200 times greater for carbon monoxide than for oxygen, carbon monoxide hinders oxygen transport from blood into tissues. Therefore, more blood must be pumped to deliver the same amount of oxygen. Numerous studies in humans and animals have demonstrated that those individuals with weak hearts are placed under additional strain by the presence of excess CO in the blood. In particular, clinical health studies have shown a decrease

in time to onset of angina pain in those individuals suffering from angina pectoris and exposed to elevated levels of ambient CO [13, 15]. Some recent epidemiologic studies have found relationships between increased CO levels and increases in mortality and morbidity [14].

Table 1. Updated WHO Air quality guideline values

Pollutant	Averaging time	AQG value
Particulate matter PM$_{2.5}$	1 year	10 µg/m³
	24 hour (99th percentile)	25 µg/m³
PM$_{10}$	1 year	20 µg/m³
	24 hour (99th percentile)	50 µg/m³
Ozone, O$_3$	8 hour, daily maximum	100 µg/m³
Nitrogen dioxide, NO$_2$	1 year	40 µg/m³
	1 hour	200 µg/m³
Sulfur dioxide, SO$_2$	24 hour	20 µg/m³
	10 minute	500 µg/m³

Healthy individuals also are affected, but only at higher levels. Exposure to elevated CO levels is associated with impairment of visual perception, work capacity, manual dexterity, learning ability and performance of complex tasks.

Air toxics

People experience elevated risk of cancer and other non-cancerous health effects from exposure to air toxics. Mobile sources are a major source of this exposure. According to the US National Air Toxic Assessment (NATA) for 1999, mobile sources were responsible for 44 percent of outdoor toxic emissions and almost 50 percent of the cancer risk among the 133 pollutants quantitatively assessed. Benzene is the largest contributor to cancer risk of all the assessed pollutants and mobile sources were responsible for about 68 percent of all benzene emissions in 1999.

According to the 1999 NATA, nearly the entire U.S. population was exposed to an average level of air toxics that has the potential for adverse respiratory noncancerous health effects[7]. Mobile sources were responsible for 74 percent of the potential noncancerous hazard from outdoor air toxics. It is important to note that NATA estimates of noncancerous hazard do not include the adverse health effects associated with particulate matter.

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[7] To express chronic noncancerous hazards, US EPA uses the RfC as part of a calculation called the hazard quotient (HQ), which is the ratio between the concentration to which a person is exposed and the RfC. (RfC is defined by EPA as, ''an estimate of a continuous inhalation exposure to the human population, including sensitive subgroups, with uncertainty spanning perhaps an order of magnitude, that is likely to be without appreciable risks of deleterious noncancerous effects during a lifetime.'') A value of the HQ less than one indicates that the exposure is lower than the RfC and that no adverse health effects would be expected. Combined noncancerous hazards were calculated using the hazard index (HI), defined as the sum of hazard quotients for individual air toxic compounds that affect the same target organ or system. As with the hazard quotient, a value of the HI at or below 1.0 will likely not result in adverse effects over a lifetime of exposure. However, a value of the HI greater than 1.0 does not necessarily suggest a likelihood of adverse effects. Furthermore, the HI cannot be translated into a probability that adverse effects will occur and is not likely to be proportional to risk.

The following section provides a brief overview of air toxics which are associated with vehicles and provides a discussion of the health risks associated with each.

Diesel exhaust (DE)

Diesel exhaust (DE) is a complex mixture comprised of carbon dioxide, oxygen, nitrogen, water vapor, carbon monoxide, nitrogen compounds, sulfur compounds and numerous low-molecular-weight hydrocarbons. A number of these gaseous hydrocarbon components are individually known to be toxic including aldehydes, benzene and 1.3-butadiene. The diesel particulate matter (DPM) present in diesel exhaust consists of fine particles (< 2.5 μm), including a subgroup with a large number of ultrafine particles (< 0.1 μm). These particles have a large surface area which makes them an excellent medium for adsorbing organics and their small size makes them highly respirable and able to reach the deep lung. Many of the organic compounds present on the particles and in the gases are individually known to have mutagenic and carcinogenic properties. Diesel exhaust varies significantly in chemical composition and particle sizes between different engine types (heavy-duty, light-duty), engine operating conditions (idle, accelerate, decelerate), and fuel formulations (high/low sulfur fuel). After being emitted, diesel exhaust undergoes chemical and physical changes in the atmosphere.

(1) Diesel exhaust: potential cancer effects

In the US EPA's 2002 Diesel Health Assessment Document (Diesel HAD) [38], diesel exhaust was classified as likely to be carcinogenic to humans by inhalation at environmental exposures, in accordance with the revised draft 1996/1999 EPA cancer guidelines. A number of other agencies (National Institute for Occupational Safety and Health, the International Agency for Research on Cancer, the World Health Organization, California EPA, and the U.S. Department of Health and Human Services) have made similar classifications.

For the Diesel HAD, EPA reviewed 22 epidemiologic studies on the subject of the carcinogenicity of workers exposed to diesel exhaust in various occupations, finding increased lung cancer risk, although not always statistically significant, in 8 out of 10 cohort studies and 10 out of 12 case- control studies within several industries, including railroad workers. Relative risk for lung cancer associated with exposure ranged from 1.2 to 1.5, although a few studies show relative risks as high as 2.6. Additionally, the Diesel HAD also relied on two independent meta-analyses, which examined 23 and 30 occupational studies respectively, which found statistically significant increases in smoking-adjusted relative lung cancer risk associated with diesel exhaust, of 1.33 to 1.47. These meta-analyses demonstrate the effect of pooling many studies and in this case show the positive relationship between diesel exhaust exposure and lung cancer across a variety of diesel exhaust- exposed occupations [2, 29].

The EPA Diesel HAD concluded that environmental risks from diesel exhaust exposure could range from a low of 10^{-4} to 10^{-5} to as high as 10^{-3}, reflecting the range of occupational exposures that could be associated with the relative and absolute risk levels observed in the occupational studies.

Retrospective health studies of railroad workers have played an important part in determining that diesel exhaust is a likely human carcinogen. Key evidence of the diesel exhaust exposure linkage to lung cancer comes from two retrospective case-control studies of railroad workers.

(2) Diesel exhaust: other health effects

Noncancerous health effects of acute and chronic exposure to diesel exhaust emissions are also of concern. EPA derived an RfC from consideration of four well-conducted chronic rat inhalation studies showing adverse pulmonary effects [18, 25, 30, 31]. The RfC is 5 μ/m³ for diesel exhaust as measured by diesel PM. This RfC does not consider allergenic effects such as those associated with asthma or immunologic effects even though there is growing evidence that exposure to diesel exhaust can exacerbate these effects.

Other Air Toxics

Vehicles contribute to ambient levels of other air toxics known or suspected as human or animal carcinogens, or that have non-cancer health effects. These other compounds include benzene, 1,3-butadiene, formaldehyde, acetaldehyde, acrolein, polycyclic organic matter (POM), and naphthalene. All of these compounds, except acetaldehyde, were identified as national or regional risk drivers in the 1999 National-Scale Air Toxics Assessment (NATA). For a significant portion of the population, these compounds pose a significant portion of the total cancer and noncancerous risk from breathing outdoor air toxics.

Noncancerous health effects resulting from inhalation exposures include neurological, cardiovascular, liver, kidney, and respiratory effects as well as effects on the immune and reproductive systems.

A major new comprehensive study of air pollution and health in Asia, issued by the Health Effects Institute (HEI) [37], seems to capture well the health risks associated with air pollution in developing countries. It found that while developing Asia has made many promising strides in improving air quality in its cities, susceptibility to the effects of air pollution can be expected to rise as rates of chronic cardiovascular and respiratory disease increase in an aging population. With rapid urbanization, industrialization and vehicle growth, the number of cases of air-pollution related illness is likely to grow.

The study, conducted by an international expert panel of HEI, found that the effects of short term exposure to air pollution in Asian cities is on a par with those in hundreds of cities worldwide…and that further improvements in air quality in Asia would be expected to improve health as they have elsewhere. **With over 530,000 premature deaths occurring each year in Asian cities** due to air pollution levels exceeding World Health Organization (WHO)'s guidelines, interventions to improve air quality can be expected to mirror the health benefits realized in other cities around the world.

Even in Europe serious health concerns related to urban air pollution remain. For example, using traditional health impact assessment methods, APHEKOM (Improving

Knowledge and Communication for Decision Making on Air Pollution and Health in Europe) has shown that a decrease to WHO's annual air-quality guideline on $PM_{2.5}$ fine particles (10 micrograms/cubic meter) in 25 large European cities could add up to 22 months of life expectancy for persons 30 years of age and older, depending on the city and its average level of $PM_{2.5}$.

In addition, the monetary health benefits from complying with the WHO guideline would total some €31.5 billion annually, including savings on health expenditures, absenteeism and intangible costs such as well-being, life expectancy and quality of life.

There are a number of public welfare effects associated with the presence of ozone and $PM_{2.5}$ in the ambient air including the impact of $PM_{2.5}$ on visibility and materials and the

Fig. 4. Predicted average gain in life expectancy (months) for person 30 years of age and older in 25 Aphekom cities for a decrease in average annual level of $PM_{2.5}$ to 10 ug/m³ (WHO's Air Quality Guideline)

impact of ozone on plants, including trees, agronomic crops and urban ornamentals. These are summarized below.

Visibility

Visibility can be defined as the degree to which the atmosphere is transparent to visible light. Visibility impairment manifests in two principal ways: as local visibility impairment and as regional haze[8]. Local visibility impairment may take the form of a localized plume, a band or layer of discoloration appearing well above the terrain as a result of complex local meteorological conditions. Alternatively, local visibility impairment may manifest as an urban haze, sometimes referred to as a "brown cloud." This urban haze is largely caused by emissions from multiple sources in the urban areas and is not typically attributable to only one nearby source or to long-range transport. The second type of visibility impairment, regional haze, usually results from multiple pollution sources spread over a large geographic

region. Regional haze can impair visibility in large regions and across states.

Visibility is important because it has direct significance to people's enjoyment of daily activities. Individuals value good visibility for the well-being it provides them directly, where they live and work, and in places where they enjoy recreational opportunities. Visibility is also highly valued in significant natural areas such as national parks and wilderness areas and special emphasis is given to protecting visibility in these areas [39, 40].

Plant and ecosystem effects of ozone

Ozone can produce both acute and chronic injury in sensitive species depending on the concentration level and the duration of the exposure [42]. Ozone effects also tend to accumulate over the growing season of the plant, so that even lower concentrations experienced for a longer duration have the potential to create chronic stress on vegetation. Ozone damage to plants includes visible injury to leaves and a reduction in food production through impaired photosynthesis, both of which can lead to reduced crop yields, forestry production, and use of sensitive ornamentals in landscaping. In addition, the reduced food production in plants and subsequent reduced root growth and storage below ground, can result in other, more subtle plant and ecosystems impacts. These include increased susceptibility of plants to insect attack, disease, harsh weather, interspecies competition and overall decreased plant vigor. The adverse effects of ozone on forest and other natural vegetation can potentially lead to species shifts and loss from the affected ecosystems, resulting in a loss or reduction in associated ecosystem goods and services. Lastly, visible ozone injury to leaves can result in a loss of aesthetic value in areas of special scenic significance like national parks and wilderness areas.
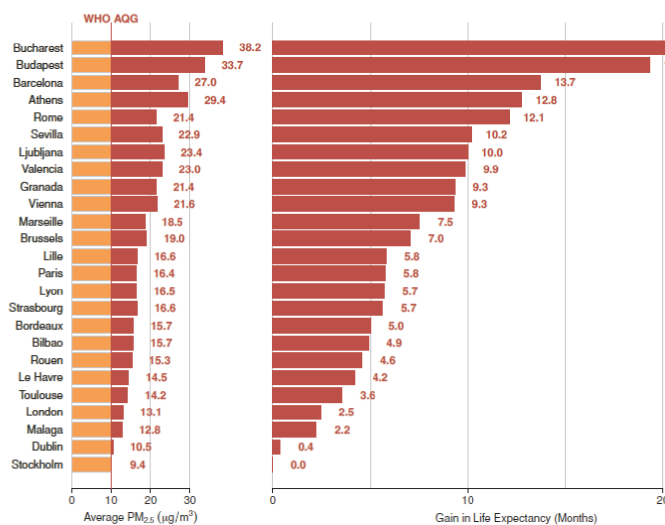
Acid deposition

Acid deposition, or acid rain as it is commonly known, occurs when NO_x and SO_2 react in the atmosphere with water, oxygen and oxidants to form various acidic compounds that later fall to earth in the form of precipitation or dry deposition of acidic particles. It contributes to damage of trees at high elevations and in extreme cases may cause lakes and streams to become so acidic that they cannot support aquatic life. In addition, acid deposition accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of a nation's cultural heritage.

Nitrogen oxides have also been found to contribute to ocean acidification, thereby amplifying one of the many deleterious impacts of climate change [12]. Approximately one third of all nitrogen oxide emissions end up in the oceans. The impact of these emissions on acidification is intensely felt in specific, vulnerable areas; in some areas it can be as high as 10 to 50 percent of the impact of carbon dioxide.

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[8] See discussion in U.S. EPA, National Ambient Air Quality Standards for Particulate Matter; Proposed Rule; January 17, 2006, Vol. 71 p. 2676.

The hardest hit areas are likely to be those directly around the release site, so these emissions are especially significant in and around coastal waters.

Eutrophication and nitrification

Eutrophication is the accelerated production of organic matter, particularly algae, in a water body. Nitrogen deposition contributes to eutrophication of watersheds, particularly in aquatic systems where atmospheric deposition of nitrogen represents a significant portion of total nitrogen loadings. This increased growth can cause numerous adverse ecological effects and economic impacts, including nuisance algal blooms, dieback of underwater plants due to reduced light penetration, and toxic plankton blooms. Algal and plankton blooms can also reduce the level of dissolved oxygen, which can adversely affect fish and shellfish populations. In recent decades, human activities have greatly accelerated nutrient impacts, such as nitrogen and phosphorus, causing excessive growth of algae and leading to degraded water quality and associated impairment of freshwater and estuarine resources for human uses [9].

Severe and persistent eutrophication often directly impacts human activities. For example, losses in the nation's fishery resources may be directly caused by fish kills associated with low dissolved oxygen and toxic blooms. Declines in tourism occur when low dissolved oxygen causes noxious smells and floating mats of algal blooms create unfavorable aesthetic conditions. Risks to human health increase when the toxins from algal blooms accumulate in edible fish and shellfish, and when toxins become airborne, causing respiratory problems due to inhalation.

Materials damage and soiling

The deposition of airborne particles can reduce the aesthetic appeal of buildings and culturally important structures through soiling, and can contribute directly (or in conjunction with other pollutants) to structural damage by means of corrosion or erosion [40]. Particles affect materials principally by promoting and accelerating the corrosion of metals, by degrading paints, and by deteriorating building materials such as concrete and limestone. Particles contribute to these effects because of their electrolytic, hygroscopic, and acidic properties, and their ability to adsorb corrosive gases (principally sulfur dioxide). The rate of metal corrosion depends on a number of factors, including the deposition rate and nature of the pollutant; the influence of the metal protective corrosion film; the amount of moisture present; variability in the electrochemical reactions; the presence and concentration of other surface electrolytes; and the orientation of the metal surface.

Climate change

Finally, there is no longer any scientific dispute that human production of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are responsible for the unprecedented rate of warming observed over the past century. According to the Intergovernmental Panel on Climate Change ("IPCC"), "[w]arming of the climate system is unequivocal, as is now evident from observations of increases in global air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" [24] Moreover, "[m]ost of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." Thus, the world's leading scientific body on the subject has now concluded, with greater than 90 percent certainty, that emissions of greenhouse gases are responsible for climate change.

Concentrations of the main greenhouse gases in the atmosphere have reached their highest level since pre-industrial times, the World Meteorological Organization (WMO) announced recently [48]. Concentrations of the gases continued to build up in 2009 – the latest year of observations – despite the economic slowdown, the U.N. agency said in its latest Greenhouse Gas Bulletin. Total radiative forcing of all long-lived greenhouse gases – the balance between radiation coming into the atmosphere and radiation going out – increased by 1.0 percent in 2009 compared to 2008 and rose by 27.5 percent from 1990 to 2009, the WMO said.

Carbon dioxide is the single most important greenhouse gas caused by human activity, contributing 63.5 percent of total radiative forcing. Its concentration has increased by 38 percent since 1750, mainly because of emissions from burning fossil fuels, deforestation and changes in land use, the WMO said. Figure 5 shows the recent global trend in CO2 emissions from the transportation sector, illustrating the rapid rise in recent decades.

Natural emissions of methane due for example to the melting of the Arctic icecap or increased rainfall on wetlands – themselves caused by global warming – are also becoming more significant, according to the Bulletin. This could create a "feedback loop" in which global warming releases large quantities of methane into the atmosphere which then contributes to further global warming. These natural emissions could be the reason why methane has increased in the atmosphere over the past three years after nearly a decade of no growth, the WMO said.

The average concentration for carbon dioxide was measured at 386.8 parts per million (ppm), the average for methane at 1,803 parts per billion (ppb), and the average for nitrous oxide at 322.5 ppb. "These values are greater than those in pre-industrial times (before 1750) by 38 percent, 158 percent, and 19 percent respectively," the WMO said. The U.N. agency noted that atmospheric growth rates for carbon dioxide – the main contributor to global warming – and nitrous oxide in 2009 were consistent with recent years but lower than in 2008.

To highlight the most recent developments, cutting emissions of black carbon and concentrations of ozone in the atmosphere's lowest level, the troposphere, would have significant effects on climate change and health, a multiyear study by the United Nations Environment Program of black carbon and other short-lived pollutants recently concluded. Black carbon, also known as soot and tropospheric ozone have a wide range of harmful effects on the environment and human health. Those effects include contributing to climate
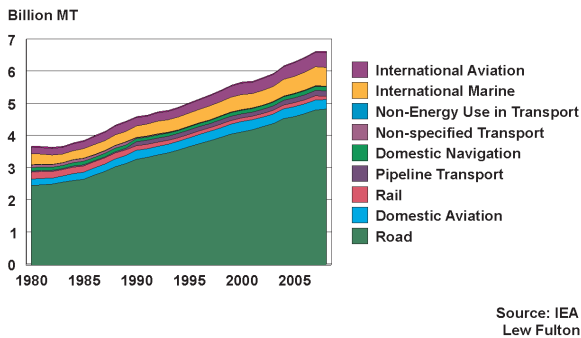
Billion MT

Source: IEA
Lew Fulton

Fig. 5. Global trends in CO_2 emissions from transportation

change, as black carbon limits the ability of snow cover and ice to reflect heat back into the atmosphere; changes in tropical rainfall patterns; respiratory disease and premature deaths; and ozone-caused reductions in crop yield and food security.

The report[9] highlighted several efforts that could reduce the short-lived pollutants, such as recovering methane from transport, which would reduce ozone concentrations because methane is an integral part of the chemical reaction that creates ozone in the troposphere. Black carbon could be significantly reduced by requiring the use of "particulate filters" on vehicles, the report said.

If the recommended measures are fully implemented, the authors predicted that future warming could be reduced by about 0.5 degrees Celsius (0.9 degrees Fahrenheit). The measures could also help to avoid about 2.4 million premature deaths and prevent the loss of about 52 million tons of corn, soybeans, and wheat.

The principle motor vehicle related pollutants of concern with regard to climate change are summarized below.

Carbon dioxide

According to the IPCC, carbon dioxide is the most important anthropogenic greenhouse gas. The primary source of carbon dioxide emissions since the pre-industrial period has been the combustion of fossil fuels, with land-use changes also contributing. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial level of about 280 parts per million ("ppm") to 379 ppm in 2005, by far exceeding the natural range over the last 650,000 years (180 to 300 ppm), as estimated by ice core samples[10].

Carbon dioxide's behavior in the atmosphere is well understood. Carbon dioxide is a "radiative forcing" gas, meaning that it alters the balance of incoming and outgoing energy in Earth's atmosphere[11]. Carbon dioxide absorbs radiation leaving the Earth's surface, trapping this heat in the atmosphere. As levels of carbon dioxide increase less and less heat escapes the atmosphere, and the planet warms.

Because CO_2 concentrations are relatively well-mixed the radiative forcing that is exerted is relatively homogeneously distributed across the globe, although it is slightly larger in the tropics and slightly smaller at high latitudes. The radiative forcing in 2005 (i.e. the change owing to the increase in the CO_2 concentration since 1750) is estimated to be 1 .66 $W \cdot m^{-2}$, which is an increase of 0.2 $W \cdot m^{-2}$ on its value for the year 2000 [34], an increase that is mainly due to the continued rise in atmospheric CO_2 concentrations in the intervening time period. The GWP of CO_2 is necessarily 1 whatever the timescale given, because it is the reference trace gas.

Methane

The mixing ratio of CH_4 (1778 ppb (1191 $\mu g/m^3$) in 2004 according to a global network of measurements performed by NOAA Climate Monitoring and Diagnostics Laboratory (C MDL)) is also increasing, although the rate has slowed in recent years. Methane has a range of sources, both natural and anthropogenic. The change from the pre-industrial concentration of 715 ppb (479 $\mu g/m^3$) to the 2004 value of 1778 ppb (1191 $\mu g/m^3$) gives a radiative forcing of 0.48 $W \cdot m^{-2}$. The GWP is stronger than that for CO_2 owing to the stronger radiative efficiency, but the GWP decreases as longer time horizons are considered because its atmospheric residence time is shorter than that of CO_2. Methane has a shorter atmospheric lifetime than CO_2 and, although still quite well-mixed, its concentration shows greater variation between monitoring sites.

Methane is removed from the atmosphere mainly by reaction with the hydroxyl radical (OH), whose concentration is affected by emissions of CO, VOCs and NO_x. Thus, in addition to direct emissions of CH_4, anthropogenic emissions of CO, VOCs and NO_x can respectively increase and decrease the atmospheric CH_4 burden. Positive and negative indirect GWPs can therefore be ascribed to VOCs and NO_x [7, 10]. Similarly CH_4 itself has an indirect GWP through its effect on its own removal rate and on tropospheric O_3 production.

According to new calculations, methane's effect on warming the world's climate may be double what is currently thought. The new interpretations reveal methane emissions may account for a third of the climate warming from well-mixed greenhouse gases between the 1750s and today. The IPCC report states that methane increases in our atmosphere account for only about one sixth of the total effect of well-mixed greenhouse gases on warming.

Part of the reason the new calculations give a larger effect is that they include the effect methane has on air pollution. A major component of air pollution is near-surface-level or tropospheric ozone, which is not directly emitted, but is instead formed chemically from methane other hydrocarbons, carbon monoxide and nitrogen oxides. The IPCC report includes the effects of tropospheric ozone increases on climate, but it is not attributed to particular sources. By categorizing the climate effects according to emissions, Shindell and colleagues found the total effects of methane emissions are substantially larger. In other words, the true source of some of the warming that is normally attributed to smog is really due to methane that leads to increased smog.

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[9] Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers.
[10] Working Group I Summary at 2.
[11] See Solomon, S., et al., Technical Summary, Working Group I, (2007), at 21 n.1, [hereinafter "Technical Summary"].

Nitrogen oxides and nitrous oxide

Nitrogen oxides consist of a family of several compounds containing nitrogen and oxygen in varying amounts. Nitrogen oxides play a role in climate change through two primary means: (1) nitrogen oxides react with other substances to form the greenhouse gas ozone, and (2) nitrous oxide is itself a highly potent and long-lived greenhouse gas. Moreover, nitrogen oxide pollution represents an additional burden on oceanic pH levels by lowering pH and increasing acidity.

Emissions of nitrogen oxides contribute to the atmospheric concentration of ozone, which the IPCC has determined is the third most damaging greenhouse gas, after carbon dioxide and methane [8]. As nitrogen oxides react with volatile organic compounds, they create ozone in the lower layer of the atmosphere, the troposphere. Through the production of tropospheric ozone, nitrogen oxide emissions contribute to the warming of the surface-troposphere system.

Nitrous oxide behaves very similarly to carbon dioxide in that it both directly traps heat in the atmosphere and remains in existence for many decades once emitted[12]. However, nitrous oxide is far more potent, with a global warming potential 298 times that of carbon dioxide over 100 years. According to the IPCC, the concentration of nitrous oxide in the atmosphere in 2005 was 319 parts per billion (ppb), approximately 18 percent higher than its pre-industrial level. Moreover, data from ice cores indicate that in the 11,500 years before the Industrial Revolution, the level of nitrous oxide in the atmosphere varied by less than about ten ppb.

Black carbon

A product of inefficient combustion, black carbon, also known as soot, consists of microscopic solid particles of incompletely burned organic matter[13]. Black carbon is a potent warmer, exerting effects on the global climate both while suspended in the atmosphere and when deposited on snow and ice. In fact, one study estimates that a given mass of black carbon will warm the air between 360,000 and 840,000 times more than an equal mass of carbon dioxide [26]. While the quantification is quite variable, a large number of recent studies have raised serious concerns regarding the climate impacts of black carbon[14]. The most pernicious characteristic of black carbon from a climatic perspective is its dark color and correspondingly low albedo, or reflectivity. Because of this dark coloring, black carbon absorbs heat from sunlight.

When suspended in the air, black carbon warms by trapping heat in the top of the atmosphere. The IPCC estimates that atmospheric black carbon exerts a positive radiative forcing effect of +0.2 W/m^2 [15]. This direct warming leads to feedback effects which magnify the global warming contribution of black carbon [26]. For example, as black carbon particles absorb sunlight, they warm the air around them, decreasing the relative humidity of the air and thus the liquid water content of other particles suspended in the air. The drying out of these other particles reduces their reflectivity, and as they absorb more sunlight the air warms even more. Further, the water evaporated from such particles remains in the air as water vapor, which is itself a greenhouse gas.

When deposited out of the air onto a lighter surface, the darker black carbon causes the surface to absorb more of the sun's energy. Thus, when deposited on snow or ice, black carbon can reduce the snow's reflectivity and accelerate the melting process [35]. As when suspended in the atmosphere, black carbon's deposition onto ice and snow creates positive feedback effects that lead to even greater warming. For example, as snow and ice around them melt away, the deposited black carbon particles can become even more concentrated on and near the surface, further reducing the reflectivity of the remaining snow and ice [16]. Thus, although the IPCC estimates the radiative forcing effect of black carbon deposition on snow and ice to be +0.1 W/m^2, it acknowledges that the radiative forcing metric may not accurately capture the climatic impacts of black carbon deposition on snow and ice. In the words of the IPCC, "the 'efficacy' may be higher" for black carbon radiative forcing, as it produces a temperature response 1.7 times greater than an equivalent radiative forcing due to carbon dioxide [21]. Because the Arctic has warmed at around twice the rate of the rest of the world over the last 100 years, controlling and reducing black carbon emissions is particularly important [22]. The impacts of black carbon are not limited to the Arctic, however. Black carbon may be responsible for as much as 25 percent of observed global warming [19]. Thus, the overall contribution of black

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[12] E.g., Technical Summary at 27 (discussing the radiative forcing effect of N_2O); at 23-24 (discussing the long atmospheric lifetimes of CO_2, CH_4, and N_2O).

[13] See W. Chameides and M. Bergin, Soot Takes Center Stage, 297 Science 2214 (Sept. 27, 2002), (explaining that "BC is produced through incomplete combustion of biomass, coal, and diesel fuel").

[14] Bond TC, Sun H. 2005. Can Reducing Black Carbon Emissions Counteract Global Warming? Environ. Sci. Technol. 39(16):5921-5926, Delucchi MA. 2003. Appendix D: CO_2 Equivalency Factors. An Appendix to the Report, "A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. Davis, California: Institute of Transportation Studies, Forster P, Ramaswamy V, Artaxo P, Berntsen TK, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myrhe G and others.

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[15] Technical Summary, at 29.

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carbon to global warming may be substantial, perhaps second only to that of carbon dioxide[16].

A very recent study indicates that black carbon has a warming effect in the atmosphere three to four times greater than prevailing estimates, according to scientists in a review article in the journal Nature Geoscience [3]. Scripps Institution of Oceanography at UC San Diego atmospheric scientist V. Ramanathan and University of Iowa chemical engineer Greg Carmichael said that soot and other forms of black carbon could have as much as 60 percent of the current global warming effect of carbon dioxide, more than that of any greenhouse gas besides CO_2. In the paper, Ramanathan and Carmichael integrated observed data from satellites, aircraft and surface instruments about the warming effect of black
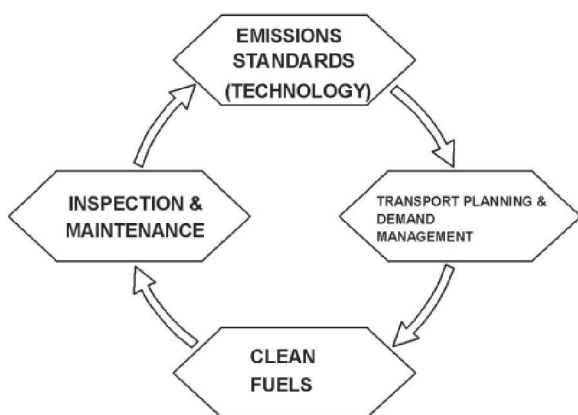

Fig. 6. Elements of a comprehensive vehicle pollution control strategy

carbon and found that it's forcing, or warming effect in the atmosphere, is about 0.9 watts per meter squared.

Ramanathan and Carmichael said the IPCC's conservative estimates are based on widely used computer model simulations that do not take into account the amplification of black carbon's warming effect when mixed with other aerosols such as sulfates. The models also do not adequately represent the full range of altitudes at which the warming effect occurs. The most recent observations, in contrast, have found significant black carbon warming effects at altitudes in the range of 2 kilometers (6,500 feet), levels at which black carbon particles absorb not only sunlight but also solar energy reflected by clouds at lower altitudes.

Water vapor

Aircraft are unique in that they also contribute to climate change by altering cloud cover patterns. They do this by emitting water vapor which forms condensation trails, or "contrails," when released at high altitude. Contrails are visible line clouds that form in cold, humid atmospheres [23]. In addition, the persistent formation of contrails is associated with the spread of cirrus clouds [20]. An increase in cirrus cloud cover tends to warm the surface of the Earth, further contributing to global warming.

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[16] Chameides and Bergin, at 2214.

Great progress in reducing emissions of the urban air pollutants and their precursors from gasoline-fueled cars has occurred in the major industrialized countries and stringent requirements for diesel vehicles are starting to be phased in. However, the vehicle population and vehicle kilometers traveled are expected to continue to grow rapidly in the future especially in developing countries which will offset many of the gains to date [47].

The next section will review the steps necessary to reduce motor vehicle emissions and the current status in many countries.

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