How can land and urban development make houses healthier?

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ABSTRACT

Traditionally, the main focus of the professional community involved with indoor air quality has been indoor pollution sources, preventing or reducing their emissions, as well as lowering the impact of the sources by replacing the polluted indoor air with 'fresh' outdoor air. However, urban outdoor air cannot often be considered 'fresh', as it contains high concentrations of pollutants emitted from motor vehicles—the main outdoor pollution sources in cities. Evidence from epidemiological studies conducted worldwide demonstrates that outdoor air quality has considerable effects on human health, despite the fact that people spend the majority of their time indoors. This is because pollution from outdoors penetrates indoors and becomes a major constituent of indoor pollution. Urban land and transport development has significant impact on the overall air quality of the urban airshed as well as the pollution concentration in the vicinity of high-density traffic areas. Therefore, an overall improvement in indoor air quality would be achieved by lowering urban airshed pollution, as well as by lowering the impact of the hot spots on indoor air. This paper explores the elements of urban land and vehicle transport developments, their impact on global and local air quality, and how the science of outdoor pollution generation and transport in the air could be utilized in urban development towards lowering indoor air pollution.

INDEX TERMS

Indoor air; Vehicle emissions; Transport pollution; Urban development; Pollution dispersion

WHY IS THE QUALITY OF OUTDOOR AIR A CONCERN IN THE CONTEXT OF INDOOR AIR?

The significance of good indoor air quality is unquestionable. It is indoor air that people inhale for up to and above 90% of time, in various types of indoor environments including residences, schools, offices, workplace, shopping centres or entertainment facilities. Therefore, it is the quality of indoor air that could be expected to have the highest impact on human health. This is certainly true; however, often underestimated or not realized is the degree of the impact of outdoor air on what we breathe indoors. Under most conditions outdoor air is a significant source of indoor pollutants and, in fact, quite frequently the majority of pollutants in indoor air come from outdoors.

There is a significant difference in the role of outdoor air as a source of indoor pollutants, compared to the role of indoor sources. The indoor sources have a direct effect only on the house in which they operate. Since the characteristics of the sources and pattern of their usage differ from house to house (or from one public building to another), the resulting pollutant concentration levels and other characteristics differ from house to house as well. Outdoor air, however, provides the same background for all houses in the area, and even if the fraction of outdoor pollutants penetrating the buildings differs due to the differences in air exchange rate between the buildings or filters used, the time variation of this background remains the same (provided that the building operation parameters remain constant). Indoor sources operate independently of the outdoor pollutant concentrations, so their effect on human exposure and thus health effects must be independent of the effects of the outdoor exposures to airborne pollutants (Wilson *et al.*, 2000).

Fractional contribution of an outdoor air pollutant to the concentration of this pollutant in indoor air varies and depends on many factors including the type of pollutant, air exchange rate in the building, presence of indoor sources of this pollutant, etc. For example, for PM_{10} and $PM_{2.5}$ the reported range of indoor to outdoor concentration ratios in the absence of known indoor sources has been from 0.50 to 0.98 (with a median value of 0.70) and from 0.54 to 1.08 (with a median value of 0.91, respectively (Morawska and He, 2003). These numbers indicate how significant the impact is of outdoor particle mass concentration on the concentration in indoor air, reaching 100% contribution in the absence of indoor particle mass sources. The outdoor contribution is also very high even in the presence of indoor particle mass sources. In particular, for PM_{10} the reported range of indoor to outdoor concentration ratios in the presence of indoor sources has been from 1.14 to 3.91 (with median value of 1.4) and for $PM_{2.5}$ the range has been from 1.00 to 2.40 (with median value 1.21). These numbers show that the outdoor contribution is still high in the presence of indoor sources, often dominant over the contribution from the indoor sources.

Is this indoor background resulting from penetration of pollutants from outdoor significant in terms of human health? Evidence from population epidemiological studies shows that it is.

EPIDEMIOLOGICAL EVIDENCE OF THE ROLE OF OUTDOOR AIR ON HUMAN HEALTH

There is usually much more information available on concentration and time series of outdoor than indoor pollutants, since air quality is regularly monitored by outdoor monitoring stations for compliance with local air quality standards. In the absence of personal exposure data, or data on pollutant concentration levels in various indoor microenvironments, the large databases on outdoor pollutants have been used for numerous prospective and retrospective epidemiological studies. Such studies have been conducted to identify possible associations between the concentration levels of individual pollutants in outdoor air and a range of health effects including mortality and morbidity. The associations have been investigated for many outdoor pollutants, including particles [measured mainly as TSP (total suspended particles), PM_{10}, or $PM_{2.5}$, less frequently particle number], ozone, SO_2, or NO_2. A general conclusion from these studies is that there is a clear link between outdoor pollutants concentration and health effects. This is despite the fact that people spend the majority of time indoors.

It was concluded, for example, in the review conducted by Wallace (2000) that a large number of epidemiological studies conducted in cities in different parts of the world have linked daily mortality statistics with increased particle concentrations measured outdoors, despite significant variation in indoor particle concentration levels. An increase of 1–8% in deaths per 50 $\mu g\ m^{-3}$ increases in outdoor air particle mass concentrations has been a common conclusion from these studies. In relation to gaseous pollutants, epidemiological data show, for example, relationships between changes in various health outcomes and changes in the peak daily ambient O_3

concentrations. Short-term increases in levels of ambient O_3 have been associated with increased hospital admissions, with a respiratory diagnosis, and with respiratory symptom exacerbation in healthy people and asthmatics. The relationship between ambient O_3 and health effects was shown to be linear for a typical range of outdoor ozone concentrations (with some question marks remaining about the relationship outside this range—for very low and very high concentrations). For example, increase in 8-h mean ambient concentration of O_3 by 10 μg m^{-3} results in increase in hospital admissions of the order of 1% and in the change in symptom exacerbation among asthmatic adults of the order of 4% (WHO, 2000).

The findings discussed above do not imply that indoor sources do not play a role in affecting human exposures. They indicate the importance of the outdoor air as a source of indoor pollutants, and the importance of understanding outdoor pollution characteristics and their penetration to the buildings, in attempting to develop a general understanding of human exposure and health effects. The role of indoor sources should not obviously be disregarded: in relation to particulate matter, for example, there have also been studies showing the link between concentrations elevated by indoor sources and health effects (Quackenboss *et al.*, 1989; Naeher *et al.*, 2000; Patterson and Eatough, 2000; Long *et al.*, 2001; Jetter *et al.*, 2002).

THE IMPACT OF MOTOR VEHICLE EMISSIONS ON THE QUALITY OF URBAN AIR

Outdoor pollution comprises a mixture of pollutants originating from all natural and heterogeneous outdoor sources. But in most urban environments vehicle emissions are a dominating source of particle and gaseous pollutants, of complex chemistry including trace metals and other inorganic elements, as well as organic compounds. Many of these pollutants have been shown to be detrimental to human heath due to their toxic or carcinogenic properties, but also as irritants, causing discomfort and affecting general human well-being.

For many decades now vehicles have been an intrinsic part of modern life and people's dependency on vehicles continues to grow. In most parts of the world ownership and usage of motor vehicles has been steadily increasing. In many developed countries, the number of vehicles per family exceeds one. The number of vehicles is also rapidly increasing in developing countries, where a vehicle is not only a means for transport but also a symbol of economic status. As an example, Figure 1 presents the trends in the number of passenger cars and motorcycles per capita in Asian countries (and for comparison in the UK) (ADB, 2003). It can be seen that there has been an increase in vehicle ownership per capita in almost all of the Asian countries over the last 20 years. The exceptions are Singapore where there has been little change over this period of time, and Hong Kong where there has been little change over the last few years. There are number of reasons for this, including provision of good public transport, and pricing for driving private vehicles to, and parking them in the CBD area, the discussion of which is outside the scope of this paper. Interestingly, these are the two urban areas where limited space is a factor which cannot be neglected.

Thus, number of vehicles on the roads, the prime pollution source in most urban agglomeration, is growing. Is, however, pollution caused by the vehicles growing as well, taking into account the advancement in engine and exhaust after-treatment devices technology as well as increasing cleanliness of the fuels? It is changing, but overall it is not necessarily decreasing. Modern vehicles emit significantly less particle mass, thus less soot, which is due to more complete combustion. This results in the decrease in TSP, PM_{10} and $PM_{2.5}$ emissions. There is also a decrease or complete cessation of emissions of some other pollutants. An example of this is lead, an element that upon intake by human body tends to settle in the brain and cause mental retardation. Over the last decade lead has been gradually phased-out from petrol in developed and in many developing countries, and as a result, concentration of lead in the air has been rapidly decreasing. As an example, Figures 2 and 3 present the decreasing trends in concentration of PM_{10} and lead, respectively, in the air in Bangkok, Thailand (ENVIRONMENT, 2002).

Figure 1 Selected motorization trends (ADB, 2003).

But the changes in technology, while resulting in decrease of emissions of certain pollutants, often lead to an increase of emissions of other pollutants. An example of this is an increase in emissions of nanoparticles (<0.05 μm) from diesel vehicles. In the presence of an abundance of larger soot particles of extensive total surface area, which is the case of older diesel engine technologies with less complete combustion, the semi-volatile compounds and sulphuric acid present in emissions condense on the soot particles. However, newer engines, characterized by more complete combustion, generate fewer and smaller soot particles. In the absence of sufficient surface for condensation, the semi-volatile compounds and very importantly sulphuric acid form through the process of nucleation of large amounts of particles of nanometre size. As a consequence, unless there is a significant reduction in sulphur content of the fuel, the increase in nanoparticle number concentration could be over an order of magnitude.

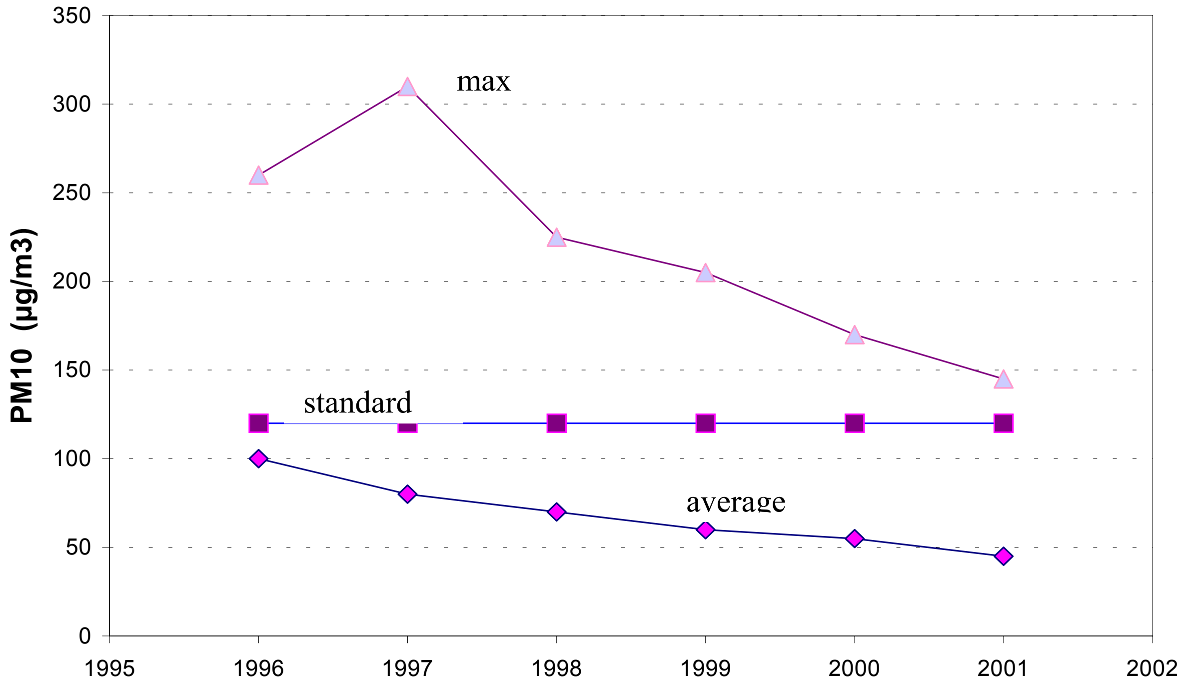

Figure 2 Annual trends of PM_{10} concentrations (24 h average) in Bangkok (ENVIRONMENT, 2002).

Changes in engine technology often require reformulation of fuel content, with different additives, which lead to emission of new organic and inorganic compounds to the air, such as, for example, aldehydes or trace metals present in catalytic converters. While the resulting increase in concentrations of many of these new substances has not necessarily been investigated, nor their effect on health, yet they are anthropogenic pollutants, undesirable in the air.

The progress in vehicle technology has been extraordinary, and it can be expected that future vehicles will emit very little. In fact, vehicles acting as air cleaners, with lower concentration of pollutants at the exhaust rather than at the air intake, have already been developed (Kasper, 2001). But it is still quite some time, before such vehicles would become a reality on the roads in developed counties and even longer in developing countries.

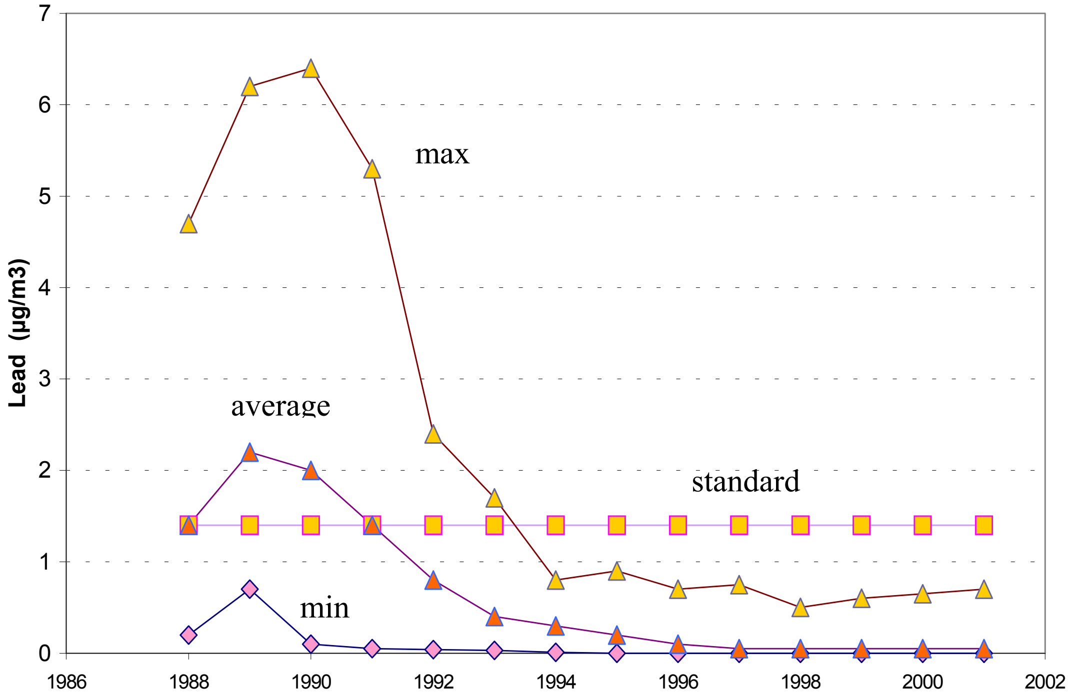

Figure 3 Roadside lead (24 h average) in Bangkok (ENVIRONMENT, 2002).

Obviously, motor vehicles are not the only sources of ambient pollution, causing decrease of air quality and health effects to the exposed population. For example, in January 2001, the Premier of Queensland, Australia, committed the Government to undertake an independent technical review of the Stuart Oil Shale project, in response to community health concerns associated with the operation of the Stuart oil shale facility. The operation of the facility located north-west of Gladstone, Queensland, and surrounded by residential areas, has been linked by the community with an increasing rate of respiratory symptoms, eye irritation and general un-well feeling. This is not a unique case and examples of impacts of industrial emissions on health of local residents could be quoted from many parts of the world.

Industrial sources, as well as other anthropogenic sources are undoubtedly still a considerable source of global pollution, contributing to local and global environmental effects, such as, for example, greenhouse effects. Overall, however, motor vehicle emissions are closer to where the exposed population is, and therefore they constitute a more serious threat to human health than other outdoor sources. The significance of this threat compared to, for example, one of the important sources of premature mortality—vehicle accidents—is presented in Figure 4, which compares figures for death from road accidents with premature death attributed to vehicle related air pollution in three countries including France, Switzerland and Austria (Seethaler *et al.*, 2003). It can be seen from this figure that in all three countries, mortality due to vehicle related air pollution is higher than mortality due to road accidents.

THE ROLE OF URBAN DEVELOPMENT ON TRAFFIC RELATED AIR POLLUTION

Urban development and transport are two closely related factors of the same formula. The trends in urban development depend on the available transportation means, but vice versa, the type of development itself results in certain transportation means being more favoured over others. There is usually a close relationship in urban environments between public transport systems and land use in relation to various human activities, needs and requirements. Thus, developments in one of these two areas, which are public transport and land use, inevitably affect the other one as well.

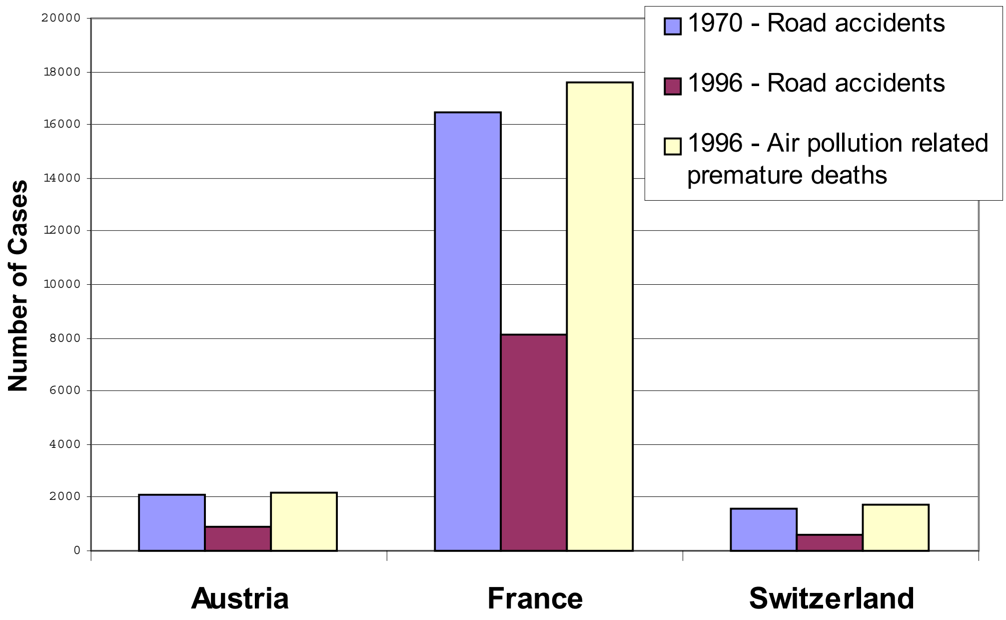

Figure 4 Fatal road accidents and air pollution related mortality (Seethaler *et al.*, 2003).

The two important characteristics of urban development are urban density and urban consolidation. Density is the number of houses or units on a given area of land, and, for example, a high-rise apartment block would be regarded as high density, a townhouse complex as medium density and a single house with a back yard as low density. Urban consolidation means increasing the number of houses or units in an existing area so they can have more efficient use of services and thus reducing the amount of land utilized to house the population. Higher consolidation means higher urban density. This is opposite to urban sprawl, which stems from the desire for a large, new detached house with a big backyard. Figure 5 presents the general urban form models, which include (SEQ2021, 2003):

- corridor (or linear) development,
- satellite (or self-contained) development,
- urban consolidation.

Linked to urban development and different urban forms is the development of transport and traffic modes. Transportation priorities give rise to three types of cities (Newman and Kenworthy, 1999):

- Walking cities: mixed land use and higher urban densities where walking constitutes the principle mode of transportation.
- Transit cities: invention of steam train and electric car resulted in creation of urban sub-centres around railway stations, characterized by 'walkable' distances. Electric cars facilitated linear urban growth owing to their more frequent stops.

a)

b)

c)

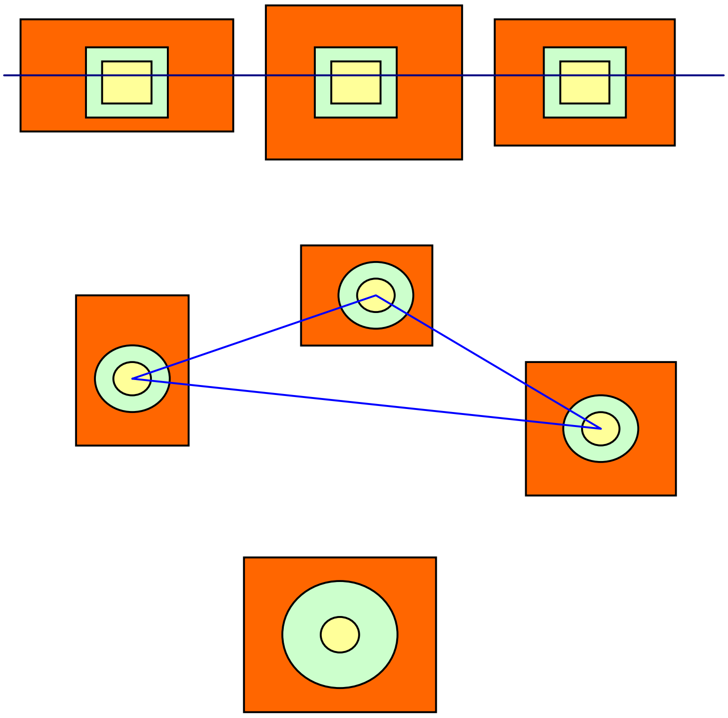

Figure 5 Urban form models: (a) corridor; (b) satellite; (c) urban consolidation (SEQ2021, 2003).

- Automobile cities: private automobiles and bus contributed to the new shape of cities in post World War II era. North American and likewise Australian cities are primary examples of development based on the accessibility of the private motor vehicle. A major contributing factor is the convenience in undertaking daily routines by using the private vehicle compared to reliance on public transport network, particularly if it is poor. Urban sprawl leads to urbanization of land, and as urban areas have expanded outwards so too has the dependency on vehicles and the need to travel longer distances. With the sprawl normally comes lower density and more dispersed settlement patterns that encourage car accessibility out of perceived need, and discourages large-scale public transport operations from servicing these new areas, along but a few defined corridors. Vehicle dependency consists of high levels of private vehicle use, automobile oriented land use patterns and usually a lack of alternatives. Current global trends point towards continual growth in vehicular movement with a relative decline in public transport usage and potentially dire environmental consequences. For example, in China an annual increase in automobile use is greater than 20%. Since the 1990s the proportion of public transport across China has dropped from 30% to less than

10% due to failure of government policy to give priority to public transport (Wong, 1997). 'Asia is undergoing a rapid increase in urbanization. The region's mega cities are getting larger and rapidly suburbanizing. Its small- and medium-sized cities are also growing quickly. Urban growth is largely unplanned in many cities due partly to the speed at which such growth is occurring, and also because of the lack of technical capacity to direct and manage growth' (ADB, 2003). In general, in developing countries infrastructure continues to be planned for projected vehicle ownership that equals that in Europe or even North America, instead of focusing on the development of a more efficient public transport system (du Plessis, 2002).

The increasing trend in urban sprawl, dependency on vehicles and kilometres travelled have been recognized as detrimental to the environment, human health and the economy, and thus not sustainable. In particular, the increase in kilometres travelled and increase in congestion lead to the increase of airborne pollution generated from vehicle exhaust. It has been recognized that a comprehensive approach to sustainability requires reduction in total travel. The three mechanisms, which have been identified to achieve this, include planning, economic instruments and technological improvements. In particular, planning mechanisms include *land use*, which involves changing land-use patterns to reduce travel distances and increase mode choice by locating services and jobs near residential neighbourhoods. It also includes *alternative modes of transport* (including heavy rail, tram, express bus, conventional fixed route bus, mini bus, taxi and others—ridesharing, non-motorized transport and telecommuting) and *demand management* considers the need to change travel behaviour such as travel times, routes, modes and destinations and seeks to maintain a favourable volume-to-capacity ratio through actions that *reduce traffic volume*, rather than those that *expand road capacity.* Reduction in total travel relates not only to passenger vehicles, but very importantly also to freight. In particular, moving freight from road to rail would result in significant decrease in total kilometres travel by heavy vehicles.

Implementation of these mechanisms will undoubtedly result in lowering in total motor vehicle related emissions and thus in the decrease in overall urban airshed pollution. It will thus result in the decrease in the concentration of pollutants penetrating from outdoor to indoor. Therefore, this constitutes one of the most important aspects of urban planning, towards reduction of outdoor and thus indoor air pollution.

Is, however, the reduction of total emissions to the airshed the only factor necessary to reduce the outdoor originating indoor pollution? The answer is no, as the reduction in overall airshed concentration does not mean that there would not be so called 'hot spots', which are local areas of increased concentration of pollution due to high concentration of traffic.

GLOBAL VERSUS LOCAL AIR POLLUTION AND HUMAN EXPOSURE

It is important to distinguish between local air pollution, its magnitudes and impacts it causes, and global air pollution and its impacts. Global air pollution impacts are related to the total emissions on a continental scale or worldwide and include greenhouse effect, effects on climate or ozone depletion. The effects of local air pollution are local environmental problems (e.g. visibility reduction), but most importantly the impacts on human health. Although many traditional polluters such as heavy industry have had their practices regulated by environmental authorities under pressure to reduce global effects, yet vehicle emissions continue contributing to local air pollution (as well as global) and thus to health effects.

The problem with urban agglomerations is that a large proportion of pollution is emitted in a relatively small area. In the close proximity to transportation routes, intersections or interchanges (bus or train stations)—urban 'hot spots'—concentration of pollutants is often significantly higher than in the urban airshed. For the purpose of compliance with the standards air-monitoring stations are normally located such that they are not directly influenced by local air pollution sources. Therefore, concentrations of pollutants measured by such stations are representative of reasonably mixed air, where pollutants coming from the sources are already diluted, and therefore much lower than the concentrations in the vicinity of 'hot spots'. However, a large fraction of the population in urban environments live, work or study in such areas. Yet, air quality is expressed not in relation to such local areas, but as prescribed by the formulation of air quality regulations, to the airshed. Therefore, the exposures of a large fraction of population are significantly elevated above what is assumed to be the exposure based on pollutant concentrations reported by the monitoring stations.

As explained above it is important to decrease the total kilometres travelled to reduce the total emissions. To achieve this, urban density should be increased, urban consolidation should be an encouraged practice and urban sprawl prevented. In particular, services and facilities such as schools, hospitals or shopping outlets should be located next to urban arterial routes, bus corridors or traffic interchanges. However, this practice, while advantageous in decreasing total emissions, leads to high human exposures in high-density local areas. A significant fraction of this exposure occurs in indoor environments where outdoor pollutants penetrate. This factor is normally not considered in urban planning or environmental health considerations. For example, in Stockholm, high density urban development was concentrated under the 1972 city plan around rail stations radiating out of the city (Newman and Kenworthy, 1992). One of the aims of the plan was to create urban villages of residential and mixed activity and traffic free centres. This model was successful in reducing the absolute car use in the 1980s and increasing usage of public transport system, thus decreasing the total kilometre travelled. It is not, however, clear, what are the concentration levels of pollutant in this high-density local area, particularly those located close to bus–rail interchanges. Another example from Australia was the announcement in August 2003 of a Federal Inquiry into urban sprawl and environmental pressures. The focus of the inquiry is on 'how cities can meet social, environmental and economic needs of Australia within the context of the Australian landscape'. However, health has not been specifically mentioned in this context.

Therefore, in order to achieve sustainability in relation to the environment and to human health, both global and local pollution needs to be considered. Thus, urban development should incorporate into land use and transport planning not only the decrease in total kilometres travelled, and thus the decrease in total transport related emissions (in addition to the whole range of other environmental gains), but also minimization of human exposure in the vicinity of 'hot spots' in a denser and consolidated urban development. To achieve this, the science of pollution generation from vehicle emissions and the subsequent transport in the air as well as penetration to the building should be utilized in future land and transport planning and in developing future air quality regulations.

DISPERSION AND SPATIAL DISTRIBUTION OF POLLUTANTS

Below is a brief discussion on dispersion of pollutants from roads and their spatial distribution in urban environments. Normally an assessment of absolute concentrations of emission products in the air requires in the first instance knowledge of source strengths, and thus in this case, vehicle emission factors or rates. Discussion of this, however, is outside the scope of this paper.

In general, the impact of the outdoor pollution sources on indoor environments depends significantly on the distance from the sources and thus dispersion and dilution of pollutants. Following emission from outdoor combustion sources, such as, for example, vehicles on the roads, emitted pollutants undergo dilution with ambient air, and then various types of changes and transformation during the transport process. Larger particles are gravitationally deposited on the ground soon after emission, while gases and smaller particles travel larger distances and remain present in the air for hours and days after emission. Of importance for indoor air quality are horizontal and vertical concentration profiles of pollutants as a function of distance from the road.

There have been a number of experimental studies investigating concentration levels of gaseous emissions as a function of distance from the road and height above the ground. Some studies have also investigated particle mass concentrations (PM_{10} or $PM_{2.5}$); however, very few studies have attempted to quantify the relationship between particle number concentration and the distance from the road.

A recently conducted review of studies investigating the relationship between particle mass concentrations (PM_{10} or $PM_{2.5}$) and the distance from the road (Morawska and He, 2003) identified studies conducted in several places in the world, such as: Houston, Texas (Bullin *et al.*, 1985), Tokyo, Japan (Nitta *et al.*, 1993), Zurich, Switzerland (Monn *et al.*, 1997), Delft, Netherlands (Roorda-Knape *et al.*, 1998), Brisbane, Australia (Hitchins *et al.*, 2000), Kuopio, Finland (Tiitta *et al.*, 2002). The review revealed that despite significant differences between the studies all the studies showed that there is very little or no gradient in TSP, PM_{10} and $PM_{2.5}$ concentrations with the distance from the road. The decrease in mass concentration between these at the minimum distance from the road, and the background levels was reported to range from 0 to about 25–30%.

There are a number of studies investigating gradients of gaseous pollutant concentrations in the vicinity of roads (e.g. Nitta *et al.*, 1993; Kuhler *et al.*, 1994; Roorda-Knape *et al.*, 1998). In relation to NO_2 concentrations the three studies showed that the concentrations declined with distance from the road by an estimated 60% after 250 m, ~50% after 600 m and by ~75% after 150 m, respectively. The gradients found were curvilinear, in line with the dispersion models describing an exponential decay in contribution from the road with distance. It needs to be stressed, however, that NO_2 is a secondary pollutant, which is formed in the area immediately downwind of a road; therefore, some differences can be expected between its behaviour in this region and the behaviour of primary gaseous pollutants.

Particle number concentrations, similarly to the concentration of gaseous pollutants, were shown to decrease significantly with distance from the road. Studies on this topic were conducted in Brisbane, Australia (Hitchins *et al.*, 2000), Birmingham, England, (Shi *et al.* (1999), Los Angeles, USA (Zhu *et al.*, 2002). Decay in particle concentration was approximated by exponential curves in a number of studies, and it was shown that the impact of the road on particle number concentration, while significant in the immediate vicinity of the road, is not distinguishable past about 300 m from the road. It was shown that dispersion is the main factor responsible for the decrease in particle concentration with the distance from the road. Modelling of particle concentration using the same approach as that used for modelling of dispersion of gaseous pollutants (CALINE4) showed that in some cases an even better approximation of the decay could be modelled by power law.

As a summary of the findings on pollutant concentration versus distance from the road, Figure 6(a) and (b) presents normalized profiles of particle mass concentration (TSP, PM_{10} or $PM_{2.5}$) and concentrations of gaseous pollutants as well as particle number, respectively. The concentrations are normalized with respect to the background.

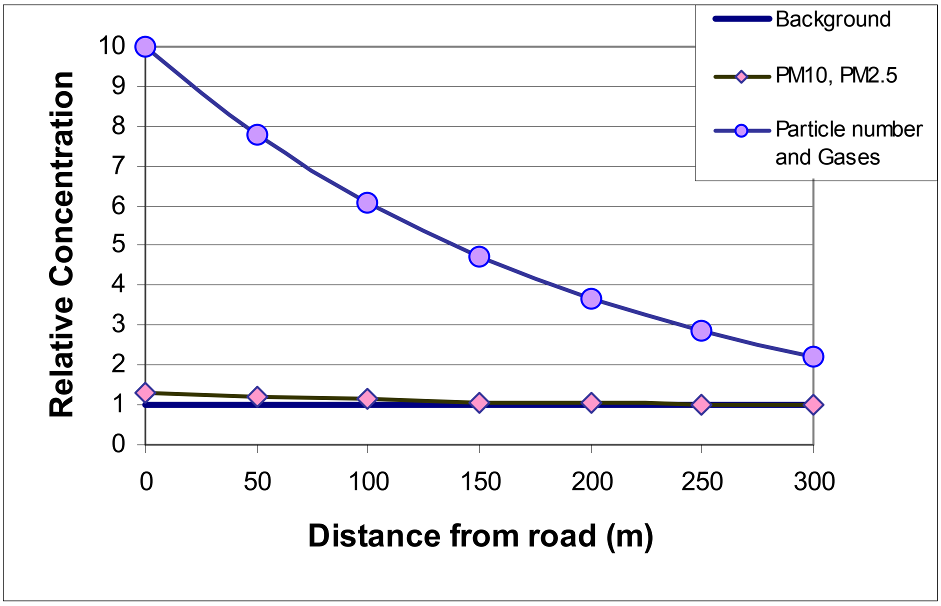

Figure 6 Profiles of particle mass concentration (PM_{10} or $PM_{2.5}$) and concentrations of gaseous pollutants as well as particle number, normalized with respect to the background.

A practical implication from these findings is that the exposure to gaseous pollutants and number concentration of particles emitted by vehicle traffic on the road is significantly increased within the distance of the first 100–200 m from the road, compared to the urban average exposure levels, and reduces to the urban background level at distances larger than about 300–400 m from the road. On this basis, it is reasonable to assume that people living and working in close proximity to an urban arterial road will likely be exposed to these pollutants beyond what could be considered ‘normal’ ambient levels. The situation is somewhat different in relation to particle mass, which is not so strongly elevated at the road compared to the background. The reason for this is that newer vehicle technologies result in lower emissions of particle mass, as explained above. In addition, there is little dust generated from modern, sealed roads.

What is the spatial distribution of pollutants away from the sources? A review of studies conducted worldwide on spatial distribution of particle mass (Morawska and

He, 2003) included studies conducted in: various cities in the US (Spengler *et al.*, 1981; Clayton *et al.*, 1993; Ito *et al.*, 1995; Burton *et al.*, 1996; Wallace, 1996; Bahadori, 1998; Blanchard *et al.*, 1999; Ramachandran *et al.*, 2000; Williams *et al.*, 2000); in Europe in: Basel, Switzerland (Oglesby *et al.*, 2000), Huddersfield, UK (Kingham *et al.*, 2000) and in Brisbane, Australia (Morawska *et al.*, 2002). In summary, the degree of homogeneity in PM_{10} and $PM_{2.5}$ concentrations in the air when using monitoring data from stations not affected by local sources is usually high or very high, with correlation coefficient ranging in general between 0.7 and well over 0.9; nevertheless, complete homogeneity cannot be assumed. However, even in those cases where the reported values of correlation coefficients were considerably below one, most of the correlations were statistically significant, which means that there was still a considerable degree of homogeneity.

Spatial distribution of other pollutants is usually also high. For example, spatial distribution of NO_x and ozone between three stations of the urban monitoring network of Brisbane, Australia, showed that spatial distribution was very high for ozone (0.79–0.89) and high for NO_x (0.61 and 0.77) (Morawska *et al.*, 2002).

In summary, while spatial distribution of pollutants in the urban environment appears to be highly homogenous based on the data from air quality monitoring stations, closer analyses of pollutants dispersion and transport reveals that for gaseous and particle number concentration there is a high level of heterogeneity displayed, with significantly elevated concentration within the first 100–200 m from the road (dependently on the traffic flow on the road). This is the aspect that needs to be taken into consideration in future urban land and transport planning.

Another factor that needs to be taken into account when considering the impact of outdoor generated air pollution on indoor air is the street canyon effect and vertical profiles of pollutant concentrations. Dense street development creates conditions for slowing down dispersion and accumulation of pollutants in between the buildings—in street canyons. Flow patterns around building envelopes and in street canyons are very complex, and the results reported by various studies on this subject are often contradictory, as shown in a recent review by Morawska and He (2003). Vehicle movement and wind induced turbulence and thus efficient mixing may result in no change in concentrations up to a certain height, followed by a decrease of concentration with height. In simpler cases the expected vertical trend above this initial height in concentration is most likely to take an exponential form. However, under certain flow patterns around the building envelope related to building location in a street canyon, to other buildings or to its orientation to air flow, pollutant concentrations at certain heights could be elevated compared to the concentrations at ground level. The implication of this complexity in relation to vertical profiles of pollutant concentration is not only that careful consideration should be given when deciding on the location of air inlets for the building, but also that consideration should be given at the planning stage of the effect of the street canyon development on pollutant concentration within the canyon and thus on indoor air quality in the buildings constituting the canyon.

SUMMARY

It has been shown in this paper that the effect of outdoor pollutants on human health and well-being is significant, despite the relatively small fraction of time that on average people spend outdoors. This is because outdoor pollutants penetrate indoors very efficiently and thus become a major source of indoor air pollution. Therefore, it is of critical importance for indoor air quality to seriously consider the impact of the pollution penetrating from outdoors and to minimize it. Reduction of emissions or even removal of all the indoor sources is not sufficient to ensure good indoor air quality since a large fraction of the outdoor cocktail of pollutants enters the indoor environment without even opening the window. The importance of considering the indoor environment as part of a system including the outdoor environment has been derived not only from knowledge and understanding of the mechanisms of pollutant transport between these two environments, but also, most importantly, from epidemiological and health studies.

It has also been shown that in urban environments motor vehicle emissions constitute the most significant source of air pollution. Vehicle emissions contribute to increased pollution of urban airsheds, and even more so, to significantly increased concentration of pollutants in urban hot spots. Both the airshed and the local pollution are of significance in terms of their contribution to the overall exposure of urban populations, yet the latter has not attracted the same level of attention and efforts to reduce it.

Urban land and transport developments are closely related to each other: the transportation modes available to the community impact on the directions of urban land development and vice versa, the development of urban land makes certain transportation modes more preferred over others. Globally, there has been an increase in urban sprawl, and related dependency on vehicle use. Worldwide vehicle ownership per capita is increasing. The challenge facing developing cities is now to manage the demand for travel as urban growth promotes urban sprawl and the resultant car use. An important aspect of urban and transport developments from the point of their impact on outdoor and thus indoor air quality is the reduction of kilometres travelled, which would lead to decreases in total emission to the urban airsheds and decreases in urban background concentration of pollutants. However, high consolidation of urban development may lead to high density of traffic in certain areas and thus to hot spots where concentration of pollutants is significantly elevated over the urban background levels. As a consequence, indoor air pollution in buildings located in the proximity of hot spots will be significantly elevated as well. In a dense urban environment, a large fraction of the population may live, work or study in the proximity to such hot spots. Therefore, an overall improvement in indoor air quality would be achieved by lowering urban airshed pollution as well as by lowering the impact of the hot spots on indoor air.

But whose role is it to oversee the directions in urban land development with a view to consider its impact on indoor air quality? Is this the role of the professionals involved and responsible for outdoor air quality or those involved with indoor air quality?

The main focus of those responsible for outdoor air quality is lowering the overall pollution of urban airsheds and ensure its compliance with the air quality standards. Monitoring for compliance with the standards is conducted at the monitoring stations, which by definition should not be affected by local pollution sources. Our houses and all other types of indoor environments are affected by local sources; therefore, it is the responsibility of the indoor air professional community to take an interest in and to ensure their role in urban land development to minimize the impact of outdoor air pollution on what we breathe indoors.

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