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Commuter exposure to air pollution in two cities: Newcastle, UK and Mumbai, India

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Abstract

Results of a study on commuter exposure to carbon monoxide (CO) and PM₁₀ during transit in the several commonly popular modes of transport in Mumbai, India and Newcastle, UK are presented in this paper. In Mumbai, real-time exposure concentrations were measured whilst commuting along a route by bus, train, air conditioned taxi and a non-air-conditioned private car. In Newcastle, real-time exposure concentrations were measured whilst travelling by electric vehicle, public bus and bicycle along a route. Average heart rate whilst commuting was monitored and subsequently simulated in a submaximal exercise test to give minute ventilation (VE) associated with each transport mode. The study in Mumbai has indicated that commuters travelling on buses and private non-air-conditioned cars are exposed to very high levels of air pollution compared with the train commuters. In Newcastle, electric vehicle and bicycle displayed lowest exposure concentrations relative to buses. Higher exposure concentrations were observed for all travel modes in Mumbai as compared to Newcastle. When inhaled amount and the lung deposition of pollutants are considered, cyclists are exposed to higher amount of exposure dose in Newcastle due to the considerable increase in VE induced by the physical exertion of cycling. Thus, inhaled quantity and pollutant dosage give a better indication of the possible health risks and should be considered in future studies and in designing the cycle routes in cities.

Key Words

Personal exposure, air pollution, transport modes, Mumbai, Newcastle, exposure dose

Introduction

Morbidity, mortality and reduction in life expectancy have been shown in past studies to be associated with air pollution (Laden *et al.*, 2000; Hoek *et al.*, 2002; Spengler and Ferris, 1985; Peters *et al.*, 2004). The International Agency for Research on Cancer

(IARC), part of the World Health Organization, has classified outdoor air pollution as a cancer-causing agent (WHO; 2013). Studies in past have also identified the serious problem of traffic related particulate emissions (both from exhaust and abrasion) in rapidly growing cities of the world (Kulkarni and Patil, 1999; Shendell and Naeher, 2002; Wang *et al.*, 2003). The transportation sector is also the greatest source of anthropogenic carbon monoxide (Flachsbart, 1999). A significant proportion of daily exposure of commuters is due to the exposure to pollutants in the traffic microenvironment, when commuting in traffic (Kaur *et al.*, 2007; de Harto *et al.*, 2010).

Various studies have linked the exposure to elevated concentrations of particulate matter (PM) to cardiovascular problems (Pope *et al.*, 2004), respiratory illness, including lung cancer (Pope *et al.*, 2002), congenital and neurodegenerative disorders (McCreanore *et al.*, 2007; Power *et al.*, 2011). Elevated levels of carbon monoxide (CO) have reportedly led to an increase in mortality, exacerbate cardiovascular disease, and cause other health problems (Riojas-Rodríguez *et al.*, 2006; Min *et al.*, 2009).

Understanding the variation in exposure is of major importance when trying to define the health effects of pollutants that are highly variable in time and space, like e.g. traffic-related air pollutants (Van Roosbroeck *et al.*, 2008; Setton *et al.*, 2011; Strickland *et al.*, 2011; Zuurbier, 2011; Ekpenyong *et al.*, 2012). The work of Dons *et al.* (2012) shows that 6% of the daily time spent in transport microenvironments (car and bus) can contribute to as high as 21% of total daily exposure. Various studies have confirmed the relationship between activities and air pollution that suggested a possibly important role for the traffic microenvironment, in contrast with the limited time spent in an outdoor or

a traffic environment (Beckx *et al.*, 2009b; Fruinet *et al.*, 2004; Dons *et al.*, 2011; Nyhan *et al.*, 2014).

Exposure studies in the past have relied upon the mean concentration data available from the fixed monitoring stations near traffic areas to study the personal exposure to various air pollutants (Knibbs and de Dear, 2010; Wang and Gao, 2011). However, it has been revealed by subsequent studies that the fixed monitoring stations significantly underestimate the exposure of population sub groups, thus advocating the need for personal exposure measurements (Fernandez-Bremauntz *et al.*, 1993; Adams *et al.*, 2001; Gulliver and Briggs, 2004). For an individual, their daily activity, the time spent completing it and what and where the activity is, are determinants of their daily personal exposure. Thus, real-time personal exposure measurements should be carried out with due consideration given to the activity performed and the commute time (Dons *et al.*, 2011; von Klotet *et al.*, 2011).

Int Panis *et al.* (2010) suggested that assessing the health impact of transport modes by only considering the pollutant concentrations is not entirely representative of the actual personal exposure. Instead, they advocated the use of the pollutant dosage, inhaled pollutants and the associated health risk. Variance in physiological behaviour on different transport modes, fundamental changes in breathing rates, logically suggest that there is a clear difference in exposure between active transport modes (cycling, running, walking) and passive modes such as (driving, bus/train usage). The difference is the increase in minute ventilation (VE) (breathing frequency x tidal volume) induced by physical exertion. Additionally the deposition of pollutants into respiratory systems increases during exercise due to increased air velocity and breathing depth.

Han and Naeher (2006) surveyed a number of studies for exposure to traffic-related air pollution in developing countries, but found that most studies did not focus

on comparing the exposure between different travel-modes in the same city. The main objective of this study was to quantify PM₁₀ and CO personal exposure of commuters (in different popular transport modes) to air pollutants in two cities, namely, Mumbai, India and Newcastle, UK. By monitoring air pollutants on a multi-modal commuter route in two different cities an inter-modal comparison completed to establish the relative health risk associated with modal choice. In order to provide more realistic estimates of relative air pollution dose received while commuting, the focus was on the commute time and the average pollutant concentration to which the commuter is exposed during their journey.

Methodology

Case Cities

Mumbai

Mumbai is the commercial capital of India and the most populous city in India, with the metropolitan area population of approximately 20.5 million in an area of 468 km² (Indian Government Census, 2011). The city generates 5% of India's GDP and accounts for 25% of industrial output, 40% of income tax collections, 40% of foreign trade, 70% of maritime trade in India and 70% of capital transactions to India's economy (Swaminathan *et al.*, 2006). The average per-capita income in the city is 141,000 Indian Rupees (INR), which is three times that of the national per-capita income (Department of Economics and Statistic, Government of Maharashtra, 2012).).

A little under half, or 43.7% of the population was categorised as migrants in the 2001 census as they reported a different place of birth (Mumbai HDR, 2009). Being surrounded by sea on three sides, the city had an average density of over 27000 persons living per sq. km. in 2001 (Mumbai HDR, 2009), making it one of the most dense cities

in the world. There is a major reliance by most of the Mumbai's inhabitants on public transport to make the daily commute to their workplace. Public transport systems in Mumbai comprises of the Mumbai Suburban Railway, Brihanmumbai Electric Supply and Transport (BEST) buses, black-and-yellow metered taxis, blue and grey air-conditioned taxis, auto-rickshaws and ferries. The major section of the passenger traffic is handled by the Mumbai Suburban Railway, which comprises of three separate networks running along the length of the city, in a north-south direction. Public bus services cover almost all parts of the city with decent frequencies. The current BEST bus fleet consists of single-decker non air-conditioned and air-conditioned buses, running on compressed natural gas (CNG). Taxis operate throughout the city and are restricted to four passengers. Auto rickshaws (3-seaters) are the main form of hired transport but operate only in the suburban areas for short distances especially to connect to another transport mode. In the last few years the Government has made it mandatory for taxis and rickshaws in Mumbai to run on compressed natural gas (CNG). There are a large number of long distance train services to and from Mumbai daily bringing thousands of people into the city. The Chhatrapati Shivaji International Airport in Mumbai is the busiest in India and catered to 29.1 million passengers in 2010-11. The city has seen an exponential increase in car ownership which has resulted in heavy congestion, severe delays and increased air pollution.

The sub-urban trains are considered to be the lifeline of Mumbai, carrying more than 7.24 million passengers per day. However, during the morning and evening peak hours more than 4,500 passengers are packed into a compartment designed for 1,700 passengers (Railway Gazette, 2010). The trains are powered by overhead electric cables(Mumbai Rail Vikas Corporation, 2008). The BEST buses in Mumbai numbering around 3000 provide a complementary service to the trains. With the growth of

economy and increased availability of cheaper models, there has been a steady increase in the number of cars purchased every year. Diesel models are favoured compared to petrol vehicles, but increasingly the car companies are offering models fitted with CNG kit. There are around 10,000 blue and grey air-conditioned taxis of various models running on CNG. More than 65% of the cars are petrol driven, whereas approximately 24.5% are diesel fuelled with less than 6% running on CNG (Motor Vehicles Department, India 2012).

43.8% of people still walk to work in Mumbai daily, whereas 3.1% make use of bicycles. Trains account for 22.7%, buses for 16.1 %, auto-rickshaws and taxi's for 1.9% and cars for the remaining 12.3% (Mumbai HDR, 2009). In 2009, 'Residential' air quality monitoring site (Worli) in Mumbai recorded annual average concentrations of 230 $\mu\text{g}/\text{m}^3$ for PM_{10} and 39 $\mu\text{g}/\text{m}^3$ for NO_2 . The CO monitoring is not carried out at this location in Mumbai (NEERI, 2010)

Newcastle upon Tyne

The city of Newcastle upon Tyne has a population of 292,179 (NESMP, 2011) and it is estimated that 100,000 commuters travel to urban core on a daily basis (TWITA, 2008). The Tyne and Wear Metro serves 60 stations along 78 kilometres of track and it carried 41 million passengers in 2009/10 (TWITA, 2011). The Metro system underpins transport provision in the region serving 25% of households in the region (Local Transport Plan, 2011). The trunk road network around Tyne and Wear is usually congested (TWITA, 2011). Rising costs of bus by travel relative to alternatives has resulted in a decline in usage. However subsidies and investment has been successful in slowing this. Excluding taxi trips, 78% of public transport journeys are by bus (TWITA, 2011); this reflects the importance of this mode to transport in the area. Bicycle infrastructure in the city is fairly sparse when compared to cities such as London and

Paris. The private enterprise Scratch Bikes, a spin off from a Newcastle University project, has attempted to emulate the success of bicycle hire schemes like Barclays bikes (London) and Velib (Paris) in Newcastle. Over 150 bikes are available to rent from 22 stations in the city.

In 2012, Newcastle Centre air quality monitoring station recorded annual average concentrations of $15.63 \mu\text{g}/\text{m}^3$ for PM_{10} , $29.52 \mu\text{g}/\text{m}^3$ for NO_2 and $0.24 \text{ mg}/\text{m}^3$ for CO (DEFRA, 2013).

Monitoring Equipment

Langan T15n monitors (Langan Products, Inc., San Francisco, CA, USA) were used to monitor CO in this study. This monitor has been widely used in similar studies and is known to operate well at the low levels of CO expected within this study. The unit has an electrochemical sensor which is calibrated to observe CO levels between 0-200 parts per million (ppm) with a resolution of 0.05ppm. Sampling frequency can be adjusted to suit the study with options to record from one second to longer with a storage capacity of 43,000 records. With a battery life of 1 year, the length of each data collection is dictated by the sampling frequency and subsequent storage capacity. Zeroing and calibration of each monitor was done each monitoring day. The monitor was subjected to a two point, zero/span check. The observed zero value should be in the range of 0.0 to 1.5 ppm. If the zero value fell outside this range, the zero response of the monitor was calibrated to a nominal level of 0.5 ppm. This nominal zero level was used to avoid the likelihood of negative responses to near zero concentrations due to monitor drift. Other guidelines details provided by the manufacturer were followed closely to ensure quality controlled data gathering.

The DustTrak™ DRX Aerosol Monitor 8534 employed in this study has been previously used by others (Chan *et al.*, 2002; Braniš, 2006; Int Panis *et al.*, 2010) to

record PM_{1.0}, PM_{2.5} and PM₁₀ concentrations. The unit works by isolating the aerosol in an optics chamber and then monitoring its mass and size using light-scattering laser photometers. It operates best in an aerosol concentration range of 0.001 – 150 mg/m³. The sampling frequency can be set to one-second or longer allowing the DustTrak™ to be synced with the Langan monitors. The DustTrak was factory calibrated to the standard ISO 12103-1 Arizona test dust by the supplier. The flow rate was set at the factory flow rate of 1.7 L min⁻¹ and checked before field monitoring. Additionally, the unit was calibrated daily to a zero filter, used to re-zero the unit and ensure reading accuracy.

The portable A-411M (MTK) Bluetooth GPS Data Logger which has an accuracy of 3m and 50 nanoseconds was used to record location of the observer carrying DustTrak™ and Langan monitors along the selected routes. The storage capacity of the device is up to 400,000 way points and allows a sampling frequency of one-second or longer – it can therefore be synced with other devices. The instrument was calibrated and certified by supplier prior to the monitoring.

The device to monitor and log heart rate was Polar RS400 heart rate watch which was used in conjunction with a Wearlink chest strap. Heart rates are then used in the sub-maximal tests in the medical lab to determine corresponding inhalation rates (minute ventilation, VE). The instrument was calibrated and certified by supplier prior to the monitoring.

DustTrak™ and Langan monitors were carried in a rucksack by the observer. The Langan monitor was fixed to the straps by cable ties. The DustTrak™ monitor was held in a casing within the bag to prevent movement whilst in transit with a pipe extruding from the nozzle to head-height. The GPS logger was attached to the rucksack strap. The heart rate monitor was worn on the wrist and chest. During trips, the bag was

held on the researcher's lap when he was seated in the bus and train, whilst it was kept near the breathing zone in the cars and while cycling.

Factors affecting the performance of the monitors were considered in this study design. An unpublished study developed a similar testing rig for a bicycle which was tested in a wind tunnel to define the best angle for the PM inlet tube (Pattinson, 2009). It concluded that for the most consistent performance the tube should be angled horizontally.

The 'commuter dose rate' for this study was defined using the following equations:

$$\text{Inhaled Air Volume, IAV (m}^3\text{)} = [\text{VE (litres per min)} / 1000] \times \text{Journey duration (min)}$$

$$\text{Inhaled Pollutant Amount PM}_{10} (\mu\text{g}) = \text{IAV (m}^3\text{)} \times \text{Pollutant concentration (}\mu\text{g/m}^3\text{)}$$

$$\text{Inhaled Dose PM}_{10}\text{Rate (}\mu\text{g/km)} = \text{Inhaled Pollutant Amount (}\mu\text{g)} \times \text{DF} / \text{Distance travelled (km)}$$

$$\text{Inhaled Pollutant amount CO (mg)} = \text{IAV (m}^3\text{)} \times \text{Pollutant concentration (mg/m}^3\text{)}$$

$$\text{Inhaled Dose CO Rate (mg/km)} = \text{Inhaled Pollutant Amount (mg)} \times \text{DF} / \text{Distance travelled (km)}$$

Where, DF is the Deposition Fraction factor.

Commonly to investigate air pollutant dosage a deposition factor (DF) is used. This method applies a factor (<1) to the mass of inhaled particulates for a given trip resulting in an indicative value of mass of pollutant deposited in the bodies systems. Work by Londahlet *al.* (2010) has suggested a deposition fraction for PM₁, PM₁₀ that has been used in similar assessments of the health risk of air pollution in transport microenvironments (namely Int Panis *et al.*, 2010). Whilst deposition factors are useful they simplify a vast range of possible complex responses from the body and hence they are fairly crude estimations. As research in this area is still in its infancy many pollutants do not have deposition factors. Furthermore the effect of age/health condition

and, increased ventilation has not yet been considered (Londahlet *et al.*, 2009; Int Panis *et al.*, 2010).

To account for the variations in breathing behaviour between modes the observed heart rates levels were simulated in a lab by submaximal exercise test with gas exchange and ventilation levels monitored. Following this, published deposition factors were multiplied to inhaled volumes of pollutant to calculate the dosage of both PM and CO.

To calculate the dose of PM₁₀, the inhaled quantity (calculated by multiplying the volume of air by the concentration of the pollutants) was reduced by deposition fractions (DF) of 0.23 for PM₁₀ which was recommended by Londahlet *et al.* (2009) and later used by Int Panis *et al.* (2010). For CO, there are no published deposition factors, thus considering this, the inhaled quantity was assumed to be fully absorbed (DF=1.0).

Personal Exposure Monitoring

Mumbai

The following four popular modes of transport: bus, train, non-air-conditioned private car and air-conditioned taxi were selected. A road route (shown as a solid line in Figure 1), approximately 8km long, linking Chembur and Dadar was selected. The route starts from Chembur as part of the 3-lane National Highway No. 3 (Mumbai – Pune) and merges into the National Highway No. 4 (Mumbai-Nasik) at Suman Nagar junction with the number of lanes remaining same and continues onwards till Dadar. Chembur is predominantly a residential area with dense housing along the route. From Suman Nagar junction to Sion, there is open ground on both sides of the road. From Sion onwards, it passes through mainly residential area until Dadar which is a mixed use commercial/residential area. The BEST bus has sliding windows and opening which

serve as doors, providing circulation of air inside the bus.

The rail route (shown as a dotted line in Figure 1), starts from the Chembur station, which is very close to the road-route starting point and ends at Wadala Road station, which is one of the suburban railways stations serving Dadar area. This route is approximately 11 km long and was selected as it involved no switchover between trains to reach the destination and thus avoiding a gap in data collection.

The same make and model of the vehicle (2010 Hyundai Santro) was used for the non-air-conditioned private car and air-conditioned taxi trips. Car with taxi permit was powered by CNG while the private car was powered by petrol. The same automobile was used to eliminate the differences which might arise by the change of vehicle make. In the non-air-conditioned private car mode, the windows were kept fully open and the ventilation system (fan) was set to the maximum level. Under the air-conditioned taxi mode, windows were kept fully closed and the air conditioning system set to the maximum level. The exposure monitoring for bus and train was done from 8th August to 11th August, 2011 while for non-air-conditioned private car and air-conditioned taxi, it was carried out from 24th August to 27th August, 2011. The trips were conducted on four consecutive days with clear weather with a trip each in the morning (09:00-11:00) and evening (16:30-19:00) rush hours, thus leading to 8 trips per mode. Measurements were taken only whilst aboard each transport mode.

Newcastle upon Tyne

Personal exposure monitoring was undertaken in the morning (8-10am) and evening (4-6pm) rush hours to best simulate the experience of a commuter over a three day period along a fixed route in Newcastle. To give an accurate representation of pollutant levels that is sensitive to the variations in congestion associated with different travel times, modes were used on a rotational pattern. The transport modes investigated include

bicycle, public bus and electric vehicle.

The Newcastle route (Figure 2) is 4.183 km long, offers multimodal services and is widely used by commuters. The trip ends are both transport hubs from which metro and buses operate. By road, they are well connected by the main trunk road to the north of the city, the Great North road with parking facilities at either end. The route goes through two Air Quality Management Areas which Newcastle City Council has declared for breaching the UK National Air Quality Objectives.

The spatial layout of adjacent structures along the route is also of interest to this study due to its considerable variation. South Gosforth High Street is effectively an urban canyon with two to three storey buildings along its length thus restricting dispersion of pollutants. Whereas the Great North Road, despite its busy nature is very well ventilated with the flat land of the Town Moor to its west; the dispersion by wind is likely to be prominent. Public health is of importance in the areas dissected by the route due to high number of workplaces and schools. The equipment was carried in a rucksack following the similar protocol adopted in the Mumbai study. The car used for personal exposure monitoring was a stock issue 100% electric powered Peugeot Ion 2010. The monitors were positioned in the ruck sack on the front passenger seat with inlet tube at a height similar to the likely position of a human receptor. For consistency and to allow comparison to other studies of private cars the windows were kept closed and the ventilation settings set to a moderate half level, this represents typical urban driver behaviour (Briggs *et al.*, 2008). No doors were opened during the investigation.

The public buses operating along the selected route vary considerably in age, model and state of maintenance. The buses are commonly rotated to work different routes making it impossible to use the same bus throughout the duration of the study. Considering this, it was difficult to conclude on the impact the type and condition of the

individual buses has on the composition and levels of air pollutants. All the buses travelled on as part of the study were diesel fuelled.

The exposure monitoring for Newcastle was done from 23rd March to 25th March, 2012. The trips were conducted on days with clear weather with a trip each in the morning and evening, for all the three transport modes.

Results

Tables 3 and 4 show overall mean concentrations of PM₁₀ and CO for each transport mode in Mumbai. As seen from Table 3, commuters travelling in bus were exposed to the highest levels of concentration of PM₁₀ (502.78 µg/m³), followed by non-air-conditioned private car (310.76 µg/m³), train (156.18 µg/m³) and air conditioned taxi (68.78 µg/m³). From Table 4, we can observe that passengers travelling in non-air-conditioned private car were exposed to highest concentrations of carbon monoxide (6.41 ppm). This was followed by the air-conditioned taxi (6.11 ppm), bus (5.65 ppm) and train (1.30 ppm).

Tables 3 and 4 also show the final commuter dosage rate for particulate matter and carbon monoxide using the formula described in the methodology section. As we can see from the Table 3, the air-conditioned taxi had the lowest commuter dosage rate for PM₁₀ (0.99 µg/km). This was followed by train (1.11 µg/km), non-air-conditioned private car (4.16 µg/km) and bus (7.32 µg/km). For commuter dosage rate of CO, the mode of transport with lowest concentration was the train (0.04 mg/km), followed by other three modes which approximately have similar commuter dosage rate for CO, viz. bus (0.36 mg/km), non-air-conditioned private car (0.37 mg/km) and air-conditioned taxi (0.38 mg/km).

Tables 5 and 6 show overall concentrations of PM₁₀ and CO for each transport mode in Newcastle. As seen from Table 5, commuters travelling in bus were exposed to

the highest levels of concentration of PM_{10} ($72.5 \mu\text{g}/\text{m}^3$), followed by bicycle ($41.2 \mu\text{g}/\text{m}^3$) and electric vehicle ($39.5 \mu\text{g}/\text{m}^3$). From Table 6, we can observe that passengers travelling in the electric vehicle were exposed to highest concentrations of carbon monoxide ($1.523 \text{ mg}/\text{m}^3$). This was followed by the bus ($1.511 \text{ mg}/\text{m}^3$) and bicycle ($1.328 \text{ mg}/\text{m}^3$). Tables 5 and 6 also show the average commuter dosage rates for particulate matter and carbon monoxide. The electric vehicle has the lowest commuter dosage rate for PM_{10} ($0.35 \mu\text{g}/\text{km}$). This is followed by bus ($0.89 \mu\text{g}/\text{km}$) and bicycle ($2.20 \mu\text{g}/\text{km}$). For commuter dosage of CO, the mode of transport with lowest concentration is the electric vehicle ($0.06 \text{ mg}/\text{km}$), followed by bus ($0.08 \text{ mg}/\text{km}$) and bicycle ($0.31 \text{ mg}/\text{km}$).

Inhaled quantities of PM_{10} and CO were calculated for each mode by multiplying pollutant concentrations by minute ventilation (derived from the submaximal test) and average trip length. It is interesting to note that despite the low concentrations of both PM_{10} and CO observed whilst cycling the mass inhaled is greater by this mode relative to the alternatives when ventilation is factored. A fixed deposition fraction factor was applied for this study as no factors that considered the variations in physiological response caused by exercise were available.

Discussion

The aim of the study was to objectively compare the exposure to air pollution by commuters in popular modes of transport in two different cities; one in a developing country and one in a developed country. The study has found that PM_{10} concentrations and also exposure to it are when travelling on buses and non-AC vehicles are an order of magnitude higher in Mumbai than in Newcastle upon Tyne. CO concentrations while commuting are about five times higher in Mumbai than in Newcastle upon Tyne. This shows the influence of older and poorly maintained vehicles coupled with the presence

of several unregulated industrial sources in Mumbai compared to the new and maintained vehicle fleet and absence of unregulated industrial emissions in Newcastle upon Tyne.

The results for Mumbai suggest that commuting by bus and private non-air-conditioned car may lead to higher exposure to pollution than commuting by train or air-conditioned taxi. The air conditioned taxi is able to act like an enclosed micro-environment with the filtration system preventing the ingress of particles, thus resulting in lower PM₁₀ concentrations. Also with the windows closed, it acts as a direct barrier against the pollutant stream from the tailpipe emissions of other vehicles. The high CO concentrations in the non-air-conditioned private cars may be due to the lower elevation of the cars and also due to the fact that windows were kept open which allowed exhaust from other vehicles in the traffic stream to enter the cabin.

In agreement with Int Panis *et al.* (2010), the results of the study in Newcastle indicate that the exposure dose for the cyclists is higher than those travelling by buses and cars when minute ventilation is considered. This is due to the increased minute ventilation while cycling which is caused by increased physical exertion, and coupled with the longer journey times because of the slow nature of the travel mode. Increased minute ventilation and higher inhaled volume of air, results in higher exposure dose for cyclists.

The use of an electric vehicle in this study for Newcastle provides an indication of the level of external pollution alone, as EV's do not use combustion for power and hence do not self-pollute. Changes in the airflow, particularly entrance of air from outside the bus, caused by opening of windows and doors can explain fluctuations of CO and PM₁₀ concentrations as pollutants from surrounding traffic enters the

environment. Finally, fluctuations in particulates are likely to be induced by re-suspension caused by the movement of passengers.

In both cities, the difference in the spatial layout of the adjacent structures as well as the nature of activities along the route can be considered to have had an important impact on the pollutant concentrations observed in each transport mode

Recommendations

This study provides guidance to the transport planners in Mumbai to focus on reducing exposure to prevent unwanted health effects. The authorities in Mumbai should focus on reducing the exposure of passenger in conventional buses where doors and window are mostly kept open. This can be achieved by replacing these buses with air-conditioned buses. The authorities in Mumbai can also focus on changing the current traffic mix to the newer emission standards as soon as possible to reduce the ambient pollutant concentrations. The buses, taxis and auto-rickshaws mainly have an old fleet belonging to pre-Euro 1 emission control standards. These will be easier to replace with newer fleet than the private cars. There is also a need to fast-track the intake of electric and hybrid vehicles by incentivizing their production and adaptation. Also, there is a need to implement traffic management measures like congestion charging, low emission zones and bus rapid transit system.

If society continues to promote cycling, it is necessary that efforts are made to reduce their exposure to air pollutants. This investigation recommends a twin-track solution whereby firstly; cyclists are moved further from pollutant sources (namely traffic), reducing exposure, and secondly, designing cycle routes which do not induce excessive physical exertion thus reducing ventilation rates (VE) and hence the total pollution dosage. By incorporating these design philosophies into the development of cycling infrastructure it may be possible to reduce the health risk of cycling. However,

further studies are needed to estimate the new health impacts of cycling taking into account the 'health loss' due to the extra air pollution dose by way of higher breathing rates and 'health gain' due to physical activity while cycling. This is of particular interest to the developed nations which have seen a significant interest and surge in the number of people cycling to work and for leisure. This research has shown the importance of developing cycling infrastructure; in such a way so that it is cyclist friendly and has lower air pollution exposure dose.

The health risks resulting from air pollution on public buses could be mitigated by improvements to the vehicle fleet. This can be improved by updating, maintaining or replacing engines on public buses. The provision of air conditioning units on public buses may reduce the need to have open windows which would subsequently reduce infiltration of external pollutants.

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Table 1: Weather Conditions, Mumbai

Date	08/08/ 11	09/08/ 11	10/08/ 11	11/08/ 11	24/08/ 11	25/08/ 11	26/08/ 11	27/08/ 11
Wind Speed (km/hr)	16	16	17	15	6	6	11	11
Average Humidity	83	84	81	83	90	90	88	96
Mean Temperature (°C)	28	28	28	28	26	26	27	24
Precipitation (mm)	1.0	1.0	0.0	2.0	15.0	16.0	44	15

Table 2: Weather Conditions, Newcastle upon Tyne

Date	23/03/12	24/03/12	25/03/12
Wind Speed (km/hr)	5	3	4
Average Humidity	90	89	78
Mean Temperature (°C)	7	10	10
Precipitation (mm)	0.0	0.0	0.0

Table 3: PM₁₀ personal exposure level and dose rate, Mumbai

Mode	PM ₁₀ , (µg/m ³) (Mean ±SD)	Average Trip Time (min)	Minute ventilation (lpm)	Total Intake volume, (m ³)	Inhaled amount (µg)	Distance (km)	Inhaled PM ₁₀ (µg /km)	Deposition Fraction	PM ₁₀ Final Dose Rate (µg /km)
Bus	502.78 ± 157. 7	54.45	18.6	1.017	509.20	16	31.82	0.23	7.32
Train	156.18 ±32. 4	36.42	18.6	0.677	105.80	22	4.81	0.23	1.11
AC Taxi	68.78 ±15. 8	53.62	18.6	0.997	68.59	16	4.29	0.23	0.99
Non AC Car	310.76 ±83. 8	50.12	18.6	0.932	289.70	16	18.10	0.23	4.16

Table 4: CO personal exposure level and dose rate, Mumbai

Mode	CO, (mg/m ³) (Mean $\pm$ SD)	Average Trip Time (min)	Minute ventilation (lpm)	Total Intake volume, (m ³)	Inhaled amount (mg)	Distance(km)	Absorption Fraction	CO Final Dose Rate (mg/km)
Bus	5.65 $\pm$ 1. 05	54.45	18.6	1.017	5.72	16	1.00	0.36
Train	1.30 $\pm$ 0. 18	36.42	18.6	0.677	0.88	22	1.00	0.04
AC Taxi	6.11 $\pm$ 0. 78	53.62	18.6	0.997	6.09	16	1.00	0.38
Non AC Car	6.41 $\pm$ 1. 32	50.12	18.6	0.932	5.97	16	1.00	0.37

Table 5: PM₁₀ personal exposure level and dose rate, Newcastle

Mode	PM ₁₀ , (μ g/m ³) (Mean $\pm$ SD)	Average Trip Time (min)	Minute ventilati on (lpm)	Total Intake volume, (m ³)	Inhaled amount (μ g)	Distance (km)	Inhaled PM ₁₀ (μ g /km)	Depositi on Fraction	PM ₁₀ Final Dose Rate (μ g /km)
Bicycle	41.2 $\pm$ 7.68	27.87	60.8	1.694	69.81	7.288	9.58	0.23	2.20
Bus	72.5 $\pm$ 17. 19	20.83	18.6	0.387	28.09	7.256	3.87	0.23	0.89
EV	39.5 $\pm$ 7. 2	19.33	14.1	0.272	10.49	6.926	1.51	0.23	0.35

Table 6: CO personal exposure level and dose rate, Newcastle

Mode	CO, (mg/m ³) (Mean $\pm$ SD)	Average Trip Time (min)	Minute ventilation (lpm)	Total Intake volume, (m ³)	Inhaled amount (mg)	Distance (km)	Absorption Fraction	CO Final Dose Rate (mg/km)
Bicycl e	1.328 $\pm$ 0. 067	27.87	60.8	1.694	2.250	7.288	1.00	0.31
Bus	1.511 $\pm$ 0. 288	20.83	18.6	0.387	0.585	7.256	1.00	0.08
EV	1.523 $\pm$ 0. 223	19.33	14.1	0.272	0.415	6.926	1.00	0.06

Figure captions

Figure 1: Routes selected for the different modes of transport in Mumbai (Source : Google Maps)

Figure 2: Route selected for the different modes of transport in Newcastle upon Tyne (Source : Google Maps)

Figure 3: Spatial distribution of PM₁₀ in bus (Mumbai)

Figure 4: Spatial distribution of PM₁₀ in train (Mumbai)

Figure 5: Spatial distribution of PM₁₀ in car (Mumbai)

Figure 6: Spatial distribution of PM₁₀ in air-conditioned taxi (Mumbai)

Figure 7: Spatial distribution of CO in bus (Mumbai)

Figure 8: Spatial distribution of CO in train (Mumbai)

Figure 9: Spatial distribution of CO in car (Mumbai)

Figure 10: Spatial distribution of CO in air-conditioned taxi (Mumbai)

Figure 11: Spatial distribution of PM₁₀ on bicycle (Newcastle upon Tyne)

Figure 12: Spatial distribution of PM₁₀ on bus (Newcastle upon Tyne)

Figure 13: Spatial distribution of PM₁₀ in Electric Vehicle (Newcastle upon Tyne)

Figure 14: Spatial distribution of CO on bicycle (Newcastle upon Tyne)

Figure 15: Spatial distribution of CO in bus (Newcastle upon Tyne)

Figure 16: Spatial distribution of CO in Electric Vehicle (Newcastle upon Tyne)