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In-vehicle exposure to traffic and road-generated air pollution

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1 Executive Summary

There is widespread scientific consensus that both short- and long-term exposures to air pollution, at levels still commonly experienced throughout London are associated with significant health burdens for the population. This evidence continues to strengthen and evolve as air pollution is associated with a wider range of adverse health outcomes across the life course.

One area of key focus has been emissions from road transport and its impact on the health of vulnerable urban populations. To date the major focus has been on tailpipe emissions, particularly from diesel vehicles, but as combustion powered vehicles are phased out as the UK transitions toward its environmental and net zero targets, greater emphasis is being placed on understanding potential health impacts associated with non-exhaust emissions from motor vehicles – tyre and brake wear, and the resuspension of road dust. Collectively these traffic derived contributions, both pollutant gases and particles comprise what is referred to as traffic-related air pollution, or TRAP.

In this report we will provide a summary of the evidence that TRAP impacts on health, but with an emphasis on the group who are often excluded from discussions of potential exposures, health impacts and mitigation – the wider road users, including drivers themselves. As TRAP concentrations fall off rapidly from the centre of the road, drivers, bus passengers and cyclists are technically at most risk with regard to exposure and are thus the groups who will most immediately benefit from actions to reduce pollutant emissions from vehicles.

This report will provide evidence on the exposures across these groups, and for cyclists and pedestrians contextualise exposures against the health benefits associated with increased physical exercise. This is an emerging area, and the evidence base is not always complete, or entirely consistent, but overall, there are several key messages that emerge:

1. that driver's exposure to TRAP in traffic is often underestimated, and that this is particularly an issue for individuals for whom driving is a major component of their work,
2. that active transport modes, remain beneficial even with high exposure doses, but would clearly further benefit from better segregation from highly polluted road environments,
3. that all road users benefit from actions that reduce vehicle emissions, and
4. with an eye to the future, more consideration will have to shift to tyre and brake wear contributions, for which technological mitigation measures already exist, or are in development.

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3 Introduction

Air pollution from road transport is ubiquitous in our urban areas affecting both our health and the wider environment. It is therefore an important focus of abatement polices in London and in other cities around the world.

Travelling along a road, as a pedestrian or cyclist, or as passenger or driver within a vehicle, results in exposure to a complex mixture of air pollutants. Each breath that you take will include a mix of gaseous and particulate pollutants from the vehicle exhausts around you, as well as particles produced from the wear of road surfaces, tyres, and brakes. This mixture is termed traffic-related air pollution (TRAP), and there is ever-growing scientific literature demonstrating its impact on human health.

Since the 1990s, numerous studies have reported harmful health effects from air pollution exposures in populations living or working close to busy roads. This is a very mature evidence base largely focused on exhaust emissions from road transport but has often excluded consideration of the travelling public, including cyclists and drivers themselves. As the concentration of TRAP falls rapidly as you move away from the roadside, it is the road users themselves who occupy the highest pollutant microenvironment and are therefore disproportionally exposed to these pollutants. They are therefore also the most likely to benefit from policies and technological innovations that reduce TRAP.

In the last 13 years, both the US Health Effects Institute and the World Health Organization have convened expert panels to review the growing body of evidence on the sources of TRAP and its impact on our health. These reviews form the basis of a strong scientific consensus demonstrating that both short and the long-term exposures to TRAP have multiple adverse impacts on human health.

This highlight note will focus on the pollutants associated with road transport, their sources and the potential exposures and health impacts of individuals living and working near roads, including drivers themselves. It will explore how the composition of TRAP will change in the future, as society transitions toward environmental and net zero targets and explore what steps can be taken at an individual and regulatory level to reduce TRAP exposures with the aim of protecting public health.

4 Summary and conclusions

Key perspectives

We spend around 6% of our time commuting but this can account for around 30% of our exposure to some air pollutants[(1)].

Recommended health and legal limits for air pollution set a maximum permitted exposure to single pollutants such as nitrogen dioxide or $PM_{2.5}$ particles. However, travelling along a busy road does not expose you to just one pollutant at a time. In reality, we are exposed to a complex mixture of air pollutants that come from the exhausts of vehicles, as well as tiny particles from the wear of tyres, brakes and road surfaces. Collectively this is termed traffic-related air pollution (TRAP).

People are exposed to TRAP at several points throughout the day, whenever near or travelling along roadways. How and for how long we travel are the key determinants of our exposures, as well as our potential contribution to creating these pollutants. Car users are subject to the highest rates of in-vehicle air pollution, with up to 70% higher exposure levels than cyclists to certain pollutants, whereas walking is cited as the mode of transport with the least exposure to $PM_{2.5}$(2). Being a passenger or driver in a car or van can expose you to more air pollution than any other way of traveling by road, but this is highly dependent on in vehicle filtration systems and the air tightness of the cabin(3-5). Cars and vans are also amongst the most polluting modes of personal transport(6).

Both cyclists and bus users are generally exposed to lower levels of pollutants than car passengers and drivers, but when comparing cyclists and bus users *to each other*, their exposure levels vary markedly by pollutant(2). The paucity of peer-reviewed studies on recent in-bus exposure makes the true risk of exposure for this transport mode difficult to ascertain. Further to this, exposure levels depend on the surrounding traffic, the ventilation system in the vehicle and its air tightness, and the way that it is powered. Importantly, when considering passive (car, bus) vs. active (walking, cycling) travel modes, it must be noted that the health benefits of physical exercise associated with walking and, especially, cycling often appear to outweigh the negative impacts of TRAP exposure(7, 8).

In the short-term, TRAP exposure is associated with negative health effects on the respiratory, cardiovascular and the nervous systems. These are associated with exacerbation of symptoms in individuals with pre-existing disease, resulting in increased use of medications, GP consultations, hospital attendance and, ultimately, higher mortality levels across the population. Links have also been made between TRAP exposure and immediate physiological responses such as changes in lung function, altered heart rhythms, and inflammation, which can persist for a number of days after exposure(9).

Long-term exposure to TRAP has been associated with adverse health from pre-birth through to old age. This includes adverse birth outcomes (low birth weights, smaller babies and increased risk of preterm births), respiratory issues (including asthma, increased risk of lower respiratory infections, and chronic obstructive pulmonary disease), cardiovascular disease (ischaemic heart disease, stroke events and diabetes), as well as increased cancer risk, all contributing to the overall mortality burden(10, 11).

Our roadways are also workplaces for professional drivers and those that operate and repair our roads. For some time, the impacts of high exposures to TRAP and, especially, diesel exhaust have been considered in worker health, safety and wellbeing. Recent research in London demonstrated that professional drivers, across a range of sectors experience an average exposure to exhaust emissions one third greater than the average concentration measured alongside the busy Marylebone Road(3).

Ultimately, walking or cycling can reduce the air pollution that we breathe, as can travelling by bus, in comparison to travel by car. There are substantial opportunities to make low pollution walking and cycling routes more accessible to all commuters. Research in London showed that children breathed 33% lower concentrations of traffic pollution when walking along back roads compared with busy main roads(12). Wider studies found that pedestrians were exposed to 1.5 to 7 times more pollution on high-traffic routes when compared to low-traffic ones(1).

Beyond reducing traffic congestion and air pollution, active travel comes with a plethora of physical and mental health benefits. Many of these can apply to public transport journeys too. The value of these should not be ignored when considering traffic policy and the future configuration of our towns and cities.

Initiatives such as low emission and clean air zones, have been shown to reduce air pollution alongside roads. This will reduce exposure for those living, working and in education nearby, but the benefits spread further. Drivers, vehicle passengers and others that use the road network will also experience reduced air pollution exposure.

It is important to recognise that vehicles without combustion engines still produce particle pollution at the point of use. This comes from the wear of brakes, tyres and roads, collectively known as non-exhaust emissions. Less is known about the toxicity of particles from these sources and their associated health risks, but their early mitigation would likely help reduce future issues to our health and environment.

Policy implications

Studies in Germany and Japan indicate that low emission and clean air zones, such as London's ultra-low emission zone (ULEZ), can reduce the pollution exposure for those that live, work or go to school near major roads, as well as reduce exposure whilst travelling, which can provide an array of health benefits[(13)].

Walking and cycling can also provide health benefits. These can be further increased by good quality infrastructure to separate pedestrians and cyclists from traffic. Investment in cycle lanes and walking routes is one way to achieve this. Traffic-free cycle lanes can have air pollution concentrations that are between a quarter to a half less than those experienced while cycling in traffic[(14-16)]. Exposure can also be reduced by adopting low-pollution routes, walking through parks or quiet back roads. This could be achieved by good signposting and infrastructure for low-pollution walking routes, especially to schools, as well as school-streets to reduce traffic pollution exposure for our children.

There also appear to be air pollution benefits from bus travel. These could be further extended by steps to reduce pollution inside buses, at bus stops and at transport interchanges. Recent upgrades to London's fleet, which is now 100% zero- or low-emission (at the tailpipe) and mostly comprising modern vehicles will have led to substantial TRAP reductions in and around London's buses.

Active travel, such as walking and cycling has many other benefits including limiting emissions that contribute to climate change, reducing urban noise, and directly combatting the burden of diseases and illnesses associated with physical inactivity that impacts life-quality and adds to our health and social-care costs. A review of studies on health and public transport found consistent positive associations with public transport use and lower body mass index[(17)].

Many people are exposed to road air pollution from road transport during their work. This includes professional drivers and people that work on our road network. There may be opportunities to improve worker-health by incorporating outdoor air pollution exposure evaluations into workplace health and safety and risk-assessments. This will require better use of information on outdoor air pollution levels by employers, guidance from organisations including the Health and Safety Executive as well as evidence-based strategies to limit exposures.

Reducing air pollution exposures will require multiple integrated solutions, including adoption of lower emission vehicles, improved vehicle design, shifts toward more sustainable transport modes, such as cycling and walking, and promotion of multiple occupancy travel models. These multiple occupancy modes range from increased car sharing to comprehensive bus provision to providing alternatives to private car use. Low emission and clean air zones, such as the ULEZ, are a way to support and accelerate many of these changes, but there is a need to emphasize the benefit these policies deliver to all road users.

Air pollution from traffic exhausts has decreased over the last few years. This is especially the case for nitrogen dioxide in central and inner London since the upgrading of fleets began ahead of the ULEZ, as nitrogen oxides (NO_x) emissions went down 18% between 2016-2019 in Greater London[(18)], and an estimated 23% reduction in NO_x emissions across London since implementation of the ULEZ in 2019[(19)]. In the longer-term we can expect large reductions in tailpipe air pollutants as the sale of new fossil-fuel engines are banned from new cars and vans from 2030[(20)]. However, exhaust standards and low emission zone (LEZ) schemes, including the ULEZ, will remain important until we have mass-market solutions for heavy-freight distribution.

The air pollution hotspots of the future may not be in the same places they are today. Reduction in exhaust emissions will mean that the particles from road, tyre and brake wear will become proportionality more important. This will shift the worst air pollution areas to places with high-volumes of faster-flowing heavier vehicles, including London's trunk road network. Regenerative braking systems on electric vehicles will help to reduce these emissions, as will emerging technologies to reduce tyre-wear emissions. Slower and more regulated traffic flows, along with lighter vehicles and a lessening of journey demand through improved distribution and urban design as well as shifts to active travel and public transport will all contribute to lower exposures to TRAP.

5 What is traffic-related air pollution (TRAP) and why is it important?

Mixtures and the growing evidence of harm

Air pollution limits define the worst pollutant concentrations permitted in outdoor air throughout the UK. These regulate individual pollutants, but because we breathe multiple pollutants simultaneously, often from the same source, it can be difficult to disentangle their separate effects on our health. This is particularly true for air pollution from traffic.

Around thirty years ago researchers began reporting health effects from exposure to the cocktail of pollutants that come from traffic [(21)](these are explored in more detail throughout the *Exposure and health* section). Many studies have found adverse health effects in people living close to roads, especially in children with asthma. These impacts were found to be related both to road proximity and the intensity of traffic. In this view of the problem, measurements of single pollutants are often used to provide information on exposure to the whole mixture rather than providing information that single pollutants are harmful, for example, measurements of the gas NO_2 or black carbon are often employed as proxies for TRAP[(11)].

Air pollution from traffic disperses and is diluted with increasing distance away from roads. The area affected by an individual road varies by pollutant, the amount of traffic and by wind conditions but may extend up to 500 m[22].

An early example of studies in this field include research on over 120,000 residents of Netherlands from 1987 to 1996[21]. This study found that greater traffic pollution exposure was associated with the worst survival rates over the ten-year study period. This effect was most pronounced in the poorest people.

In 2010, the US Health Effects Institute reviewed the emerging evidence on TRAP[10]. Based on evidence up to 2008, they concluded that exposure to traffic pollution caused worsening of asthma and found evidence that suggested that TRAP exposure was also linked to the onset of childhood asthma, other adverse respiratory symptoms, impaired lung function, illness and death from heart disease, as well as total early deaths. The UK Committee of the Medical Effects of Air Pollution (COMEAP) in 2010 also stated that TRAP likely impacts the onset of asthma symptoms in individuals who lived near busy roads, especially roads with high numbers of diesel vehicles[23].

In 2013, the World Health Organization looked at both epidemiological and toxicological studies addressing TRAP[22]. They concluded that air pollution from traffic was harming our health and that this was attributed to both vehicles exhaust emissions and particles produced from the non-exhaust sources.

In their most recent assessment in 2022, the US Health Effects Institute concluded, with high or moderate-to-high confidence, that there was an association between long-term exposure to TRAP and the adverse health outcomes including all-cause, circulatory, ischemic heart disease and lung cancer mortality, asthma onset in children and adults, and acute lower respiratory infections in children[11].

What is TRAP made of?

The composition of TRAP varies from place to place and has also changed over time as vehicle types and exhaust clean-up technologies have evolved. The main components of this mixture are described in Table 1.

Table 1. Main components of traffic-related air pollution (TRAP).

Pollutant	Description and sources
$PM_{2.5}$ and PM_{10}	Particulate matter (PM) refers to very small airborne particles which can pass beyond our nose and throat and enter the respiratory system. $PM_{2.5}$ particles are smaller than PM_{10}.
Nitrogen oxides - NO_2 and NO_x(10)	Nitrogen oxides (NO_x) are a group of pollutant that includes nitrogen dioxide, a known toxic gas. Nitrogen dioxide (NO_2) breaches legal limits alongside many of London roads. The main source of NOx in London is road transport, as it predominately comes from combustion engines such as those used in cars, lorries, and vans. Other transport sources also contribute including the aviation, rail and shipping industries(24). Gas heating is an important contributor but close to roads diesel exhaust remains the largest source(25).
Black carbon (BC) and elemental carbon (EC)	Black carbon and elemental carbon particles form part of $PM_{2.5}$ and are commonly known as soot. They are produced during the burning of diesel, gas and coal, as well as biomass (wood). Exhaust particle filters have led to substantial reductions over the last decade, but diesel traffic remains the main source close to roads(26).
Ultra-fine particles (UFP)	UFP are very small particles. They are produced by chemical reactions including combustion and reactions between other gaseous and particle pollutants. Although within the $PM_{2.5}$ their small size means that they have little mass, despite being very numerous. Concentrations have fallen in the near road environment, but new evidence shows that the smallest particles may be evading exhaust clean up systems(27). In London, aircraft engine emissions in connection with Heathrow Airport is a substantial source of UFP that can be measured many km from the airport(28).
Tyre wear particles	Tyre wear particles enter the air as our tyres abrade on road surfaces. They often include fragments of tyre and road material in the same particle. Chemically, tyre wear includes polymers and zinc(29, 30).
Road wear particles	Road wear particles come from the wear of road surfaces, including road markings. Their chemical compositions vary according to road composition. Road wear particles may also contain bitumen(29, 30).
Brake wear particles	Brake wear particles are produced by the abrasion of brake pads and rotor surfaces in friction brakes. Their chemical composition includes barium, copper, antimony and tin(29, 30).
Carbon monoxide (CO)	Emitted from the incomplete combustion of fossil fuels. Exhaust catalysts have led to marked reductions in outdoor concentrations. Legal limits have been met in London since 2001(31).
Hydrocarbons and volatile organic compounds (VOCs)	Mainly emissions of gases and particles from unburnt fuel. Many of these have been decreased by exhaust technologies(25).

6 Exposure and health

How we travel alters both our contribution to TRAP, as well as our exposure. Evidence demonstrated that these exposures can have both immediate health implications within vulnerable populations, occurring within minutes or hours of exposure, as well as long-term adverse health effects that develop as exposure accumulates over time.

Short-term effects of TRAP exposure are associated with negative health effects on lung function, blood pressure, and the nervous system[10]. These are associated with exacerbation of symptoms, increased use of medications and ultimately, higher mortality levels across the population[10].

Long-term exposure to TRAP has been associated with adverse health effects across the life cycle, as with exposure to air pollution in general[32]. Health effects of long-term exposure to TRAP contribute toward adverse birth outcomes (low birth-weights, smaller babies and increased risk of preterm births), respiratory issues (related to asthma, respiratory infections and chronic obstructive pulmonary disease, cancer), cardiovascular outcomes (heart disease, stroke risk and diabetes), all contributing to an increased risk of poor health in old age and early death[10].

This section explores the exposure levels and health risks associated with different modes of transport, divided into two categories: motor transport (cars and buses) and active travel (cycling and walking).

1. Motor transport

Car travel and user exposure

Each year, the average individual in England takes an estimated 429 private transport trips via car or van[9]. While 68% of commuter journeys across Great Britain were made using a car or van in 2020 (an increase of 9% from 2019), due to the availability of public transport, the London average sees just 27% of residents using cars for their commute[33]. However, this still equates to an estimated 2,375,190 car users commuting on a regular basis in London, both contributing to and experiencing enhanced exposure to TRAP.

The environment an individual is exposed to during their commute can contribute up to 30% of their daily air pollutant exposure burden[1]. While in a vehicle, TRAP exposure of drivers and passengers has been found to impair lung function, demonstrating the irritant properties of these pollutants[9]. Personal monitors measuring ultra-fine particles and $PM_{2.5}$ absorbance (an indirect measure of exhaust particle emissions) found that lung function was more negatively affected in car users than cyclists[9]. Car users can be exposed to high concentrations of exhaust gases and particles, which enter their vehicle through the vents[1]. In a 2021 review comparing exposure between car users to those using active travel, 18 out of 48 studies found that car users experienced higher exposure levels to TRAP, whether or not they had their windows open or closed while driving[1]. An earlier review in 2017, cited that car commuters had higher exposure rates in 30 of 42 comparisons with active travellers' exposure rates[34].

The impact of exposure is not only an issue for those commuting to work. Varaden et al. (2021) found that children's exposure to $PM_{2.5}$ during journeys to school in London was 8% higher for children who travelled by car (7.3 μgm^{-3}), when compared with children who walked through quieter back streets (6.3 μgm^{-3})[12]. As children are some of the most vulnerable to the effects of air pollution, understanding and mitigating against these exposures should be a key priority. If car journeys are essential, measures can be taken to help reduce exposure levels to TRAP.

Ventilation settings in vehicles can reduce exposure by up to 75%[35]; recirculating air is the best way to minimise exposure to outdoor air pollutants, whereas keeping windows open can worsen air quality inside your car[36]. Further measures, like installing filters or air purification systems into the vents can be effective at removing air pollution from the cabin, however they may not make a significant decrease in exposure[3]. The Tartakovsky et al. (2013) trial found that air purifiers could remove up to 99% of fine particles from the vehicle[4]. Newer electric vehicles are now being made with high-quality filters that prevent the entry of pollutants more effectively. However, the results of these advancements are still variable, with studies finding that recirculation mode in vehicles lowered the exposure to some compounds ($PM_{2.5}$), but increased the exposure to others (such as VOCs)[5]. Ultimately, commutes via car still results in higher TRAP exposure than active travel, the risks of which are explored below.

Professional drivers and outdoor workers

Individuals working on our roads will have greater TRAP exposure compared with the wider public. This includes professional drivers as well as outdoor workers that maintain and operate the road network.

The London-based Driver Diesel Exposure Mitigation Study (DEMiSt) explored the exposure levels of different driving occupations: taxi drivers, couriers, waste removal workers, heavy freight drivers, utility services, bus drivers, and emergency services providers[3]. This study found that individuals who drove as part of their job had an average exposure that was one third greater than the average concentration alongside the busy Marylebone Road and four times greater than the average concentration in central London, as measured in North Kensington. Taxi drivers had the longest on-shift driving time (6.5 hours) as well as the highest exposure levels while driving. Conversely, heavy freight drivers who had the second longest driving shifts (6.1 hours) had the fourth highest level of exposure. This variance likely reflects periods spent travelling outside of the congested inner-city areas, compared to the exposures typically experienced by London's taxi drivers.

DEMiSt also provided insights into how air pollutants act within vehicles. Several participants experienced high exposure events while driving in congested traffic, which caused in-vehicle pollutants to spike and remain high within the vehicle cabin for up to 10-60 minutes, even after they have had travelled away from pollution hotspots. Blackwall and Rotherhithe tunnels also caused spikes in BC exposures which remained in the vehicles for up to 20 minutes. Driver exposure was significantly lower on the weekends when there was less road traffic than during the weekday. The study also showed that exposure varied due to many factors: location, time of day, day of the week, wind and vehicle speeds, window position and background air pollution during the study, few of which can be controlled or adapted by the driver.

Beyond DEMiSt, other studies have explored the health impacts of vehicle-related air pollutants. Diesel exhaust has been identified as one of the most harmful mixtures in air and is associated with increased risk of occupational lung cancer in the UK[36, 37]. Exposure to elemental carbon (EC) from diesel emissions has been associated with excess lung cancer deaths in truck workers in the USA[36, 38]. A small study of particulate matter exposure of New York taxi drivers found BC and $PM_{2.5}$ levels to be double that of background readings[39]. Studies of highway patrol officers found in-vehicle exposure to air pollutants—including $PM_{2.5}$—was associated with rapid changes in inflammation, coagulation (blood clotting) and heart-rate variability[40].

The findings from these studies are indicative of the exposure and risk that road-based professionals face. And while it can be assumed the general population is not exposed to TRAP at the levels or durations of these occupations, these studies exemplify the potential health risks TRAP pose to the wider population.

Lastly, there is a growing body of evidence regarding the health impacts of inhalable tyre, brake and road wear particles. Laboratory studies have observed DNA damage and inflammatory effects when human lung and white blood cells were exposed to tyre wear particles; higher concentrations causing cell death and increased DNA damage[41]. Inflammation has also been seen within the nose and respiratory tract after exposure to tyre and pavement particulates[41-43], although this has still only been confirmed in lab conditions. While the specific linkages between this form of air pollutants and human health requires more research[41, 44], the anticipation that these non-exhaust pollutants will become relatively more significant with time[45] means that any early actions to mitigate them would likely aid the reduction of future risks to human health. Importantly, the UK government's Committee on the Medical Effects of Air Pollutants, whilst acknowledging the health impacts associated with tailpipe emissions, has concluded that based on current evidence it is not possible to definitively state that separate components of $PM_{2.5}$ can be viewed as more or less harmful to human health, meaning that in terms of $PM_{2.5}$ mitigation, all sources of TRAP currently need to be considered when evaluating strategies to improve human health[46, 47].

Bus travel and user exposure

There are 31,000 local buses in use in England, 79% of which are still using diesel engines[48]. The London bus fleet comprises of 9,000 buses which are now 100% compliant with the ULEZ standards, meeting or exceeding the Euro VI emission standards, which reduces emissions of nitrogen oxides by up to 90%[49]. A thousand of these buses are entirely zero emission, making this the largest zero emission bus fleet in Western Europe, with the aim of the entire fleet being emission free by 2034[50]. In the meantime, the London bus fleet is completely low- or zero-emission exhausts, which comprise of electric, hydrogen, hybrid and even compliant diesel vehicles[49]. London bus use accounts for 52% of all local bus journeys made in England in 2022, whereas across the UK, a total of 69% of public transport journeys were made on local buses[33].

In London, bus use has been relatively steady, hovering at just over 2 billion bus passenger journeys per year since 2005, until the drop in use during and since the Covid-19 pandemic (2020 onwards)[51]. At the end of 2022, bus passenger journeys in London were on the rise from the previous two years, at an estimated 1.5 billion passenger journeys[51]. There is a clear peak in passenger use during commute hours (06:00-09:00 and 15:00-18:00), when traffic volumes are at their greatest, along with levels of TRAP.

Studies exploring passenger exposure levels to TRAP on buses have produced mixed results, but generally in-bus exposure appears lower than that of in-car exposure[34]. One study in Bogota found strong relationships between vehicle emission standards and the concentrations of $PM_{2.5}$, BC and CO in vehicles with the conclusion that passenger in newer buses (Euro IV onwards) experienced less air pollution compared with people on older buses. For the vehicle mix in Bogata, where around 1/3 of the buses sampled were pre-Euro IV, an average round trip on their bus system contributed roughly 60% of $PM_{2.5}$ and 70-90% of BC out of a day's exposure. Round-trip bus users were inhaling 1.2 times the World Health Organization (WHO) guideline for $PM_{2.5}$ exposure in a 24-hour period. The study also reported $PM_{2.5}$ levels in the bus eight times higher than in background air measurements. Importantly, those people on newer buses, experienced far lower air pollution concentrations; particle pollution ($PM_{2.5}$ and BC) was around half that of people on older buses and CO was lower too.[52].

Studies have found mixed results when comparing bus exposure levels to those of car users and cyclists[1, 2]. PM_{10} and BC exposure levels were generally found to be lower in buses[1], but the same was not always true for $PM_{2.5}$. A review by de Nazelle (2017) reported that bus users were exposed on average to 50% greater $PM_{2.5}$ concentrations than pedestrians, but had similar exposure levels to cyclists, and lower exposure levels than car users[32]. However, some studies found UFP and BC concentrations to be lower in buses than for pedestrians[2]. The average ratios of exposure levels for bus users versus pedestrians were inconsistent: while bus users were exposed to less BC than pedestrians, they were exposed to greater levels of UFP and carbon monoxide, however, the differences were marginal[2]. Studies also found that fleet type played a significant role; $PM_{2.5}$, BC and UFP exposure levels were all lower in electric buses than diesel ones[2, 16].

These studies demonstrate that while the difference between TRAP exposure levels on buses and modes of active transport may be small, buses appear a better option for transport, with lower TRAP exposure levels, when active travel is not an option—contingent on the bus vehicle type and general vehicular traffic composition. With London's fleet being 100% zero- or low-emission (at the tailpipe) and mostly comprising of modern vehicles, there is reduced risk for exposure in or around buses. Additionally, if more commuters took buses instead of private cars, there is great potential to reduce vehicular traffic and the subsequent air pollution from private vehicles.

2. Active travel

Cyclists and TRAP exposure

Around 4% of commuters in England use a bicycle for their journey[33]. Commuter miles conducted via bicycle went up 46.1% the year the COVID-19 pandemic started (2020), and has dropped 28% in the subsequent two years[53]. In London in 2022, cycling levels had increased 13% since 2019, with an estimated 1.2 million cycling journeys made a day in the capital[54]. The increase in cycle use also coincided with the expansion of the London cycle network: 260 km of safe cycle routes were added by March 2021, with 1 in 5 Londoners living in close proximity to the cycle network[55]. By 2024, London's Cycleway network is projected to be more than 450 km long, with the aim for 70% of Londoners to live within 400 metres of the cycle network by 2041[56].

Cycling provides several health benefits, including improved cardiovascular and mental health[57, 58]. While cycling does not contribute to tailpipe emissions, nor carbon emissions, road cyclists are clearly still exposed to TRAP from other road users, which poses potential concerns for regular cycle commuters.

When compared with car users, cyclists are exposed to lower levels of TRAP, with average exposure levels for cyclists down 20% for $PM_{2.5}$ and 70% for BC[2]. As with studies exploring TRAP exposure on buses, exposure levels vary depending on the type of pollutant. Studies comparing cyclist exposure to in-bus exposure levels have been inconsistent[2]. However, evidence generally supports the contention that cyclists are exposed to less TRAP than car users, with active commuter exposure levels 18% lower than car drivers[16]. However, when considering exposures in cyclists it is also important to consider exposures in terms of inhaled dose. Sommar et al. (2020) found cyclists had an inhalation dose of all air pollutants which was 4.5 times that of car drivers, due to cyclists' depth of breathing and generally higher respiration rates[16]. Woodcock et al. (2013) found that the $PM_{2.5}$ inhalation dose for cyclists was 3 times higher than that of car drivers[59]. However, despite these findings, studies have consistently shown that the long-term health benefits of regular physical activity outweigh the health risks associated with increased air pollution inhalation[7, 8, 60].

There are other additional factors to consider when determining cyclists' exposure to TRAP: the proximity to traffic, the types of vehicles, weather, seasonality, topography, traffic rates and temperature, etc. Proximity to busy roads can be a large determining factor for cyclists' exposure and rates of inhaling pollutants. Traffic-free cycle lanes can have air pollution concentrations that are between a quarter to a half less than those experienced while cycling in traffic [14-16]. Evidence has shown that dedicated cycleways and segregated cycle routes can promote the uptake of cycling and maximise the benefits, while minimising air pollution exposure risks. Furthermore, reducing overall traffic and changing the composition of vehicles from diesel or gas to low- or zero-tailpipe emission vehicles can reduce cyclists' exposure and inhalation rates[16].

Pedestrian exposure to TRAP

In 2020, 10% of commuters in England walked to work, with an average commute time of 16 minutes, indicating that the popularity of walking is dependent on commute distance[33]. While the average walking commuter may be spending just 16 minutes on their commute, 32% of all transportation journeys (including walks to school, shopping, personal business and leisure) are made as pedestrians[33]. When compared with all other modes of road transport, walking was associated with the lowest exposure to $PM_{2.5}$; pedestrian exposure was 30%, 40% and 50% lower when compared to cyclists, car users and bus users, respectively[2]. In addition to lower exposure levels, walking also comes with added health benefits, which are explored further in '*The health benefits of active travel'* below.

The route taken also clearly makes a difference, though often the magnitude of the benefit is underestimated. Varaden et al. (2021) examined children's exposure to air pollution during their school commute and found that air pollution on their morning journey was on average 52% higher than exposure levels at school[12]. Beyond that, children who walked along busy main roads were exposed to 33% higher levels of air pollution than those who walked along quieter or smaller back streets. This was supported by a study by Mitsakou et al. (2021), which found that pedestrians were exposed to 1.5 to 7 times more pollution on high- versus low-traffic routes[1].

For those who work within traffic, exposure time and therefore risk levels, can be much higher. Studies on the impacts of TRAP on traffic police have showed decreased lung function related to the officer's age and years of service[61]. Traffic police were also more susceptible to upper airway respiratory symptoms including coughs, phlegm and rhinitis[61]. Further studies examining traffic police officers found evidence that vehicular pollution exposure was associated with both short- and long-term health effects, and increased morbidity and mortality overall[62]. Conversely, research has shown that those who wore protective masks had better lung function[63, 64].

With high levels of air pollution exposure essentially a component of certain occupations, it is vital to consider ways to reduce air pollution and improve the health of workers. The British Safety Council have called for air pollution exposure for outdoor workers to be recognised as an occupational exposure issue[65].

The health benefits of active travel

Active travel, both walking and cycling come with substantial health benefits from the increased daily exercise, compared with car travel.

The health of approximately 260,000 working people from across England, Scotland and Wales was tracked for an average of five years[(66)]. The 16,000 people who cycled as part of their commute were the healthiest, with lower rates of heart disease and cancer. They were also living longer compared with those who commuted in cars or used public transport. Similar health benefits were also seen in those that had mixed mode commuting, where cycling was part of their journey. The 14,000 walkers had lower heart disease than car commuters, reinforcing the benefits of any active travel.[(66)]

A study published in 2012 analysed how active travel could reduce costs to the UK's National Health Service[(7)]. Researchers assessed the changes that would occur if the average person in the UK reduced their driving distance from 14 to 10 kilometres per day, and walked or cycled this distance instead. This reduction of four kilometres per day is about a 45-minute walk or a 15-minute cycle. Considering the increased risk of accidents via road travel, this travel change was estimated to lead to savings of £17 billion for the NHS (at 2010 prices) over a twenty-year period. This would arise from reduced prevalence of type 2 diabetes, dementia, ischaemic heart disease, cerebrovascular disease and cancer, with even greater savings as the population aged, and not yet considering wider benefits to individuals' wellbeing.

Another view on the benefits from active travel arises from studies on cycle hire schemes, as demonstrated by an assessment in Barcelona where researchers compared car driving with the use of rental bikes[(8)]. Their study included a consideration of the possible disbenefits from increased pollution dose from harder breathing by the cyclists in comparison to sitting in a car, as well as the potential increased accident risk. For people who used the bikes, the health benefits from the exercise were estimated to be 77 times greater than the downsides[(8)]. Further studies, such as Woodcock et al. (2013), found that the benefits of active commuting, such as walking or cycling, outweighed the potential risk of accidents and increased inhalation dose[(59)].

A health impact assessment was carried out on London cycle scheme users between April 2011 and March 2012[(67)]. During this time, 578,607 individuals made over seven million trips and cycled for over two million hours. Only 6% of users had swapped car journeys for cycle hire. Most people took trips that would otherwise have been done by public transport, by walking or riding their own bicycles. However, the increased exercise from cycling still meant that London's cycle scheme had an overall beneficial public health impact, especially for older people, and simultaneously reduced overcrowding on public transport.

The majority of studies on the health benefits of active travel focus on walking and cycling. In 2019 a systematic review of evidence on public transport and cardiometabolic health found consistent positive associations with public transport use and lower body mass index (BMI). Most of these studies considered bus or light rail use[(17)].

Immediate health impacts from walking along roads

Whilst the greatest health impacts from air pollution comes from the long-term exposure from air pollution over many years, a small number of studies have looked at the effects that occur over shorter periods in transport micro-environments.

Two sets of experiments were undertaken in London between 2003 and 2005 and then again between 2012 and 2014. In each case volunteers were asked to undertake two walking routes: one along London's Oxford Street, for a high exposure to TRAP; and the other around the Round Pond in Hyde Park, a lower pollution route. The first experiment involved people with mild to moderate asthma and examined changes in the lung function and upper airway inflammation[68]. This study found, that compared to the walk in Hyde Park, there was an acute reduction in lung function in the asthmatics during their walk along Oxford Street that was even sustained the following day. The magnitude of this change was relatively small but was found to be associated with EC and UFP exposure and the presence of active inflammation in the upper airway[68]. The second experiment involved people over the age of 60 with pre-existing heart problems or diagnosed chronic obstructive pulmonary disease (COPD), as well as a group of healthy individuals of the same ages[69], all walking the same routes. In this study, improvements in lung function were seen in all groups during their walk in the park—demonstrating the beneficial effects of exercise—but these positive responses were absent during the exposures on Oxford Street. These results were interpreted by the authors as showing that in the vulnerable populations examined, the high TRAP environment was in part negating the positive effects of exercise.

A recent study in New York also provided evidence that very short-term exposures to air pollution can have impacts on health[70]. Researchers looked at the times of hospital admissions for heart attacks (myocardial infarctions) and found that heart attack risk was significantly increased in the six hours following a peak in outdoor nitrogen dioxide pollution.

Ultimately, increasing the distance between pedestrian routes and busy roads would be extremely beneficial to reducing the health impacts of exposure rates of pedestrians, and the same is true of cyclists and cycle pathways. Further to this, reducing vehicle traffic in general and improving vehicle standards in line with lower emission rates, would vastly benefit roadside occupations, walking commuters and the public.

7 Actions to reduce or prevent TRAP

1. Reducing exhaust emissions

Since the turn of the century there have been notable successes for some exhaust abatement technologies.

For some pollutants the addition of ever more sophisticated engine and exhaust clean-up systems have been effective. These systems include engine controls, catalysts to reduce harmful gaseous emissions and particle filters. These technological approaches have not been equally successful for all pollutants. For example, emissions of nitrogen oxides, including nitrogen dioxide from diesel engines, have been very problematic due to wide gaps between the performance of vehicles in regulated tests versus their real-world performance when on our roads. This led to substantial increases in nitrogen dioxide alongside roads, especially from vehicles sold during the first decade of this century[71]. This problem has been made worse by rise in the proportion of diesel vehicles cars and vans in our vehicle fleets, which emit much more nitrogen oxides and particle pollution than their petrol engine equivalents[25]. Although diesel vehicles may have lower carbon dioxide (CO_2) emissions at the tailpipe, wider analysis of the impacts from BC emissions, as well as the refining and production of diesel, suggest that the increased numbers of diesel cars and vans on Europe's roads did not have a beneficial effect on the climate[72].

Other interventions have included improvements to the quality of road fuel, notably the reduction in the permitted sulphur content in 2007 that led to a reduction in UFP of up to 65% alongside Marylebone Road and substantial reductions elsewhere[73].

Upgrades to local vehicle fleets can also help. During 2010 to 2016 a small number of roads in London experienced sharp drops in NO_2 concentrations, mainly due to successful targeted steps to upgrade buses[74, 75]. At the same time many roads, especially those in outer London experienced increases in the local air pollution from traffic. This led to a prediction that it would take London a further 193 years to reach the legal limits for NO_2 that were set in 1999 to be met by 2010[76]. This patchy and slow overall progress was one of the contexts for the creation of London's T-charge and then ULEZ.

Lessons can also be learned from the London-based School Streets initiative, which temporarily closed or restricted streets along school entrances during drop-off and pick-up times and reported NO_2 reductions of up to 23%, with less vehicles in the area[77]. Post-initiative surveys also found that 18% of parents and carers were generally using their vehicles less as a result of the programme[77], demonstrating how relatively small changes could lead to larger benefits through behaviour change and, ultimately, even greater emission reductions.

Beyond TRAP, road vehicles also release CO_2, the most abundant greenhouse gas. As the transport industry in the UK contributed to 27% of greenhouse gas emissions in 2019 (and 26% of emissions in 2020)[6], the majority of which came from passenger vehicles[78], reducing vehicle emissions has the added co-benefit of reducing not just TRAP but the transport sector's overall greenhouse gas emissions, which would help the UK government's commitment to reach net zero carbon emissions by 2050[79] and the London 2030 target.

2. Clean air, low and ultra-low emission zones (LEZ and ULEZ)

There is strong and accumulating evidence on the effectiveness of London's LEZ and ULEZ schemes, as well as the hundreds of similar schemes that operate in Europe. The zones can reduce TRAP and deliver health benefits, if they are sufficiently ambitious[80].

In 2008, London's first low-emission zones led to improvements in particle pollution from traffic along busy suburban roads[81]. Tightening the zone in 2012 created further improvements, compared with areas outside the capital[82], but progress became slow and patchy[76].

The ultra-low emission zone, or ULEZ, in London started in 2017 with fleet upgrades and the T Charge (a charge on older diesel and petrol cars), before expansion to a full central zone operation in 2019 and subsequent expansion to inner London in 2021. By October 2022, it had reduced nitrogen dioxide from traffic in inner London by an estimated 47%[83]. The benefit across inner London during this time frame is an estimated 21% reduction[83].

Evidence did not support the contention that air pollution deteriorated outside these zones as a result of diverting vehicles. Instead, the experience from London and cities in Germany show that policies accelerate the upgrading to cleaner vehicles in the surrounding area, spreading the benefit[82, 84]. The inner London ULEZ also accelerated air pollution improvements on the boundary roads.

To date, eight studies in Germany, Japan and the UK have investigated health improvements from low emissions zones using health survey results, GP and hospital records and death registrations[13]. Despite the differences in approach, five of the eight LEZ studies have reported reductions in heart and circulatory problems following LEZ implementation. These included fewer admissions to hospital, fewer deaths from heart attacks and strokes, and fewer people with blood pressure problems.

One of the German studies analysed hospital data from 69 cities with LEZs. It found a 2-3% reduction in heart problems and 7-12% reduction in stroke[85]. The improvements were greatest for older people and resulted in estimated health cost savings of €4.4bn (£3.8bn). Five studies, again covering zones in Germany, Japan and the UK, looked at breathing and lung problems. Two found improvements and the remainder showed no definite result; none showed a negative effect[13].

Despite these improvements, it is clear that air pollution concentrations in all parts of London remain above World Health Organization Guidelines and are still causing significant health impacts to London's population, even at relatively low ambient concentrations[86, 87].

3. Reducing non-exhaust emissions

There are no single, simple solutions to reduce non-exhaust emissions.

Cleary actions to reduce traffic would also lead to reduced TRAP but care must be taken to avoid unintended consequences from changing driver and travel behaviour.

Changing vehicles and driver behaviour

Increased vehicle weight, high speeds along with sharp acceleration, braking and cornering are all known to increase non-exhaust emissions from tyre, road and brake wear. Reducing these behaviours through driver education, feedback or by road design would decrease emissions[29].

Changes to traffic emissions during the COVID pandemic illustrates a number of these factors. During lockdown, 32% of the traffic disappeared from London's Marylebone Road. Less traffic meant less congestion, but the remaining traffic went faster. Although brake pad derived particles decreased with less stop-start conditions, the air pollution from tyres stayed the same. Faster traffic meant more tyre wear from each vehicle, but the study does provide evidence that reducing vehicle speeds in London may also reduce TRAP[88]. Lower speed limits can reduce non-exhaust emissions from tyre wear, road wear and resuspension, as drivers are less likely to accelerate or brake suddenly or severely[25].

There are other factors beyond speed limit that can impact non-exhaust emissions, including tyre material, driving style and environmental conditions such as road surface type or wetness. Regenerative braking available on many electric vehicles may also be a significant factor in reducing non-exhaust emissions.

Non-exhaust particles emissions have a strong relationship with heavy vehicles. Analysis of air pollution data from London between 2010 and 2014 showed an increase in coarse particles pollution (part of PM_{10}) which offset the decrease in tailpipe emissions. This was especially the case on roads in outer London where an increase in the number of heavy goods vehicles

(HGVs) was seen. Careful management of logistics and distribution may therefore also play a role in managing non-exhaust particles.

Poorly inflated tyres and misaligned wheels will also add to non-exhaust emissions, especially from tyre wear. As part of Innovate UK's projects within the Clean Air Programme, an automated sensor was developed to continuously check wheel alignment on heavy goods vehicles and buses, providing instant driver feedback and enabling rapid rectification[89]. More research in this area can help direct both urban planning initiatives and car manufacturers to help collectively minimise non-exhaust emissions.

Avoiding exposure

The benefits of reducing vehicular emissions can be further supported by the separation of vehicular traffic from walking and cycling routes which would clearly lead to reduced TRAP exposure for non-divers. Similar conclusions were found from research on clean air walking routes[90]. These field experiments tested alternative routes between points in Central London. Smaller, quieter back streets had between 30-60% lower BC concentrations, and therefore less exhaust exposure compared with routes that followed main roads. The field experiments focused on popular commuter and leisure journeys, such as Embankment Station to Covent Garden (47% reduction in BC along back streets) and Euston Station to King's Cross (a 51% reduction via back streets).

Knowing which roads are the most polluted is not easy. There are substantial opportunities to incorporate low pollution walking and cycling routes (such as the CityAir app) into mobile phone mapping applications that many people use for daily travel. Infrastructure development to make walking routes more accessible, as well as raising public awareness through educational and marketing campaigns could be key to implementing societal behaviour change of this scale.

8 Looking to the future

Transport de-carbonisation and increased active travel look set to make substantial changes to the composition of TRAP, but air pollution from exhaust and non-exhaust sources will remain for many years to come.

The UK's ban on the sale of new diesel and petrol engine cars and vans is planned for 2030, with the exception of hybrid-vehicle sales which will be allowed to continue to 2035. After this new cars and vans will have to be "zero emission at the tail-pipe"[20]. By 2030 transport emissions of nitrogen oxides in London are predicted to have fallen by 78% compared with 2019. $PM_{2.5}$ emissions from transport are expected to fall by around 33% over the same period[86].

There is considerable uncertainty about future emissions of non-tailpipe TRAP[29]. This is mainly due to the unquantified impact of increased vehicle weight of battery electric vehicles, their high torque, and a projected increase in vehicle mileage due to lower running costs. This will be balanced, to some degree, by less emissions from regenerative braking on electric vehicles compared with the friction brakes on today's cars and vans. This difference may reduce brake wear emissions by around 60-90%. The balance between the increases and reductions will vary through a journey. It is likely that electric vehicles would have greater emissions on fast open roads where little braking takes place. This is may lead to a shift in the location of roads with greater TRAP concentrations, from busy congested city streets to faster dual carriageways and trunk roads in London[30].

Many of the studies that have measured air pollution concentrations and exposure while travelling have taken place in traffic and air pollution environments that are far different to those that we will have in the future[30]. There is an urgent need for ongoing studies to track the changes to our TRAP exposure—especially from non-exhaust sources—and the associated health implications as we progressively decarbonise our transport systems and adapt our cities for more active travel.

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