Non-Exhaust Emissions from Road Transport

Non-exhaust emissions (e.g., brake, tyre and road surface wear) remain largely unregulated in the UK. This briefing note considers what we do and don't know about non-exhaust emissions, why they are important, how they may respond to future changes, and how we can reduce their impacts.

Overview

- Vehicle exhaust emissions have decreased significantly in recent years, due to stringent regulation and policy.
- Non-exhaust emissions are now considered a more prominent source of particulate matter, due to tyre, brake and road wear.
- Electric vehicles will continue to produce non-exhaust emissions.
- There is a need for regulatory action to address this source that is contributing to poor air quality and health burdens.

Background

Particulate matter (PM) is recognised as a leading risk factor for premature death worldwide.[1] Exposure to PM has been linked to a range of detrimental health outcomes, including well established links with heart and lung diseases, lung cancer, and all-cause mortality.[2] There is also a growing body of evidence which suggests adverse effects on cognitive performance[3], mental health[4] and the onset of neurodegenerative diseases.[5] It is now believed that there is no safe level for ambient PM with harmful health outcomes occurring at very low exposure levels[6], supporting the need for continued air quality improvements. Transport remains a prominent source of PM worldwide[7,8], including the UK where it is estimated to contribute 13% of annual fine PM ($PM_{2.5}$) emissions.[9] Transport is also the single largest source of greenhouse gases in the UK,[9] a major producer of other air pollutants including nitrogen oxides (NO_x) from fuel combustion,[9] and a source of other health stressors such as traffic noise, road fatalities and injuries.

Primary exhaust emissions from road transport are an important source of air pollution, especially in urban environments.[10] Due to stringent regulation and technological innovation, these emissions have drastically reduced over the last 20 years,[11] and ambient concentrations of exhaust pollutants have generally decreased.[12] However, on-road transportation is also a source of non-exhaust emissions, through processes such as brake, tyre and road wear, and dust resuspension.[13,14] Whilst exhaust emissions of $PM_{2.5}$ have reduced substantially, non-exhaust emissions have continually increased and are estimated to represent over 60% of $PM_{2.5}$ (by mass) from road vehicles.[15] Rail transport (including trams and rapid transit systems) also produces non-exhaust emissions through rail-wheel-brake interfaces, and overhead line contact.[16,17]Clean air policy has almost exclusively focussed on the reduction of exhaust emissions.[18] Conversely, non-exhaust emissions have gone largely unregulated and remain a growing environmental and health policy challenge.[19,20]

Current contribution of non-exhaust emissions

According to the latest data from the UK National Atmospheric Emissions Inventory (NAEI) non-exhaust emissions are now estimated to exceed exhaust emissions of both $PM_{2.5}$ and PM_{10} by some margin.[21] By 2030 non-exhaust emissions are currently projected to be responsible for 90% of all road transport $PM_{2.5}$ emissions, and 10% of the UK's total $PM_{2.5}$ emissions.[15] This trend is similarly observed across many European countries, with non-exhaust emissions now beginning to form the dominant share of transport emissions.[22] Future projections of non-exhaust emissions are largely based on predictions for traffic growth and changes in vehicle fleet composition (e.g., uptake of electric vehicles). However, there are major uncertainties surrounding these projections, with the effects of changing vehicle design and people's travel behaviours remaining largely unknown. It is also yet to be determined what effect the future penetration of alternative vehicle technologies will have on non-exhaust emissions.[23]

'Zero-emission' technologies

As outlined in the 2019 Clean Air and 2021 Net Zero strategies, alternative fuel technologies (e.g. electric and hydrogen) will play a pivotal role in decarbonising transport and improving national air quality.[24,25] Misleadingly, however, these alternatives are often referred to as "zero-emission" and consequently seen as a cure-all for transport's air quality impacts. The term zero-emission however only refers to the primary exhaust emissions, and does not account for the non-exhaust emissions that will continue to be produced. It also does not consider the known detrimental environmental impacts associated with the whole vehicle/fuel life-cycle, such as emissions from electricity generation,[26] or the hazardous by-products created through battery production[27] and disposal.[28]

There is emerging evidence these alternative technologies may actually generate *more* non-exhaust emissions than conventional combustion vehicles. Electric vehicles are typically 24% heavier than their fossil-fuel counterparts, which means they have the potential to generate more PM at points of friction between brakes and wheels, and wheels and road.[29,30] Some modelling studies have consequently shown that electric vehicle uptake may not substantially improve air quality.[31,32] One of the critical factors influencing these scenarios is that of regenerative braking. Regenerative braking is a non-frictional braking system that can be used by electric vehicles to slow down and recharge their batteries. Their predicted benefits vary substantially, and many claims lack concrete data[33], but may reduce the production of brake-wear particles by 25-95%.[20] Whether electric vehicles can deliver net-reductions in non-exhaust emissions is critically dependent on the extent of regenerative braking, its real-world effectiveness[23] and the influence of any changes in driver behaviour. We need to regulate and reduce non-exhaust emissions with the same stringency that has successfully reduced exhaust emissions, including careful consideration of unintended consequences, for environment and health, of rapid fleet decarbonisation. The value of these technologies cannot be understated, and will provide immense benefit through reduced emissions of greenhouse gases and other air pollutants, reduced noise pollution, and reduced fossil-fuel consumption. They are not, however, a panacea for air quality impacts of transport. Progress towards the latest World Health Organisation's 2021 global air quality guidelines[34] will necessitate incremental air quality gains, which will require non-exhaust emissions (including those from electric vehicles) to become a part of national clean air policy.

Greater health effects of non-exhaust emissions?

PM is a complex mixture of particles with varying physical and chemical characteristics that may influence ability to induce harm.[35] There is some evidence to suggest that traffic-sourced PM may pose greater risks to human health.[36] Compared to the wealth of literature available for exhaust emissions[37], studies on the health effects of non-exhaust particles are very limited, despite becoming a significant component of urban air pollution[38], and their relative contributions to human health effects remains unclear.[39] In 2020 the Committee on the Medical Effects of Air Pollutants (COMEAP) released a statement on the evidence for health effects of exposure to non-exhaust emissions.[40] They highlighted the current data pool is small, with studies that differ largely in design and outcome, and acknowledged exposure to non-exhaust emissions likely poses some health risks however, there was a lack of sufficient evidence to quantify this risk. They recommended further health research is needed to better understand the potential risks and provide a basis for policy development.

Case study: Microplastics

Over its lifetime, a vehicle tyre loses between 10-15% of its mass through wear and tear processes[41] releasing substantial amounts of rubber particles (a form of microplastic) into the environment. Tyre wear is estimated to account for 5-10% of plastics in the ocean globally.[42] It is also recognised as a component of airborne particulate pollution[43], and may contribute 3-7% of ambient $PM_{2.5}$.[41] The inhalation of airborne microplastics may pose significant risks to human health[44], including the disruption of immune functions and development of neurodegenerative diseases[45], and a recent study, for the first time, has detected microplastics in the human bloodstream.[46] Currently, however, there is a shortage of epidemiological evidence for toxicological effects arising from human exposure.[37]

Measurement and modelling

Understanding the individual contributions and compositions of specific emission processes, including specific non-exhaust mechanisms, can help better understand individual health effects and allow for targeted interventions.[47,48] Characterising non-exhaust emissions is however extremely complex, with emissions varying between different brake, tyre and road surface materials[49], vehicle and road types[47], driving speed and behaviour[50,51] , and meteorological conditions.[52] Consequently, current estimates of UK non-exhaust emissions are highly uncertain.[15] Current emissions factors are further largely based on data from the 1990s, and have not been updated to reflect major changes in vehicle design and fleet composition.[15] Furthermore, the national emissions inventory currently does not report road dust resuspension, despite it being recognised as an important source of PM in ambient air.[53] There is a need for standardised measurement methods, for each separate non-exhaust source, with a better representation of real-world conditions and the current vehicle fleet. Emissions reporting requires greater harmonisation and consistency, and the inclusion of dust resuspension.[20] These developments could help provide the basis for future policy and regulation.

Interventions

1. Reducing Non-exhaust emissions at source

Reducing use of road vehicles

Reducing the use of on-road transportation effectively reduce both exhaust and non-exhaust traffic emissions, and provides numerous co-benefits including climate change mitigation, reducing noise pollution and reducing road traffic related injuries.[54] Accelerating modal shift to active travel can reduce the need for on-road vehicles, and is a primary objective of the 2021 Transport Decarbonisation Plan.[55] Active transport provides further co-benefits by improving health through physical activity[56] and providing greater travel satisfaction.[57]

Additional strategies to reduce the use of polluting forms of transport include road pricing (i.e., increasing the cost per vehicle mile via tax or fuel tariffs), workplace parking levies, local congestion charging and odd-even license number plate restrictions.[58]

Driving practices

Vehicle speed and driving behaviour (e.g., sharp cornering and braking) influence non-exhaust emissions. Introducing speed limits and traffic calming measures, and promoting smooth driving styles can reduce brake usage and dust resuspension, thereby reducing emissions.[20,59] Driving behaviour may further benefit from intelligent Driver Assistance Systems that will become increasingly available in electric/autonomous vehicles.[20]

Wear-resistant materials

Choice of brake, tyre and road surface material significantly impacts non-exhaust emissions,[47] therefore regulating which materials are used may be an effective intervention. Titanium, aluminium and ceramic brake discs are promising alternatives to conventional cast iron, that are more wear-resistant and may reduce brake-wear emissions.[60] However their application is presently limited due to high material and manufacturing costs.[59] Some studies have shown adding rubber crumbs to traditional asphalt mixtures can reduce tyre wear emissions by 30-50%, whilst also reducing road wear and traffic noise.[61,62] A number of regulations affecting brake and tyre production already exist worldwide[63] and could be revised to include non-exhaust regulations.

2. Mitigation after release

Capturing/trapping emitted particles

Several innovative technological systems to collect brake and tyre wear particles at the source have been trialled, with promising results.[64,65] Their efficacy however remains debated, with further practical concerns regarding large-scale production.[59]

Road sweeping, washing, and dust suppressants

These have all been suggested as potential strategies to reduce road dust resuspension.[66] However, their effectiveness is strongly influenced by local conditions, and their outcomes vary significantly across Europe.[58] Some studies have observed notable benefits[67] however these are often short-lived, and trials have so far proven inconsistent.[15] Such measures may have particular best practice applications for locations such as construction sites.[15]

3. Reducing exposure to non-exhaust emissions

The concentrations of traffic-related pollutants, including non-exhaust, are highest at roadsides,[68] therefore all steps should be taken to maximise the distance between people and traffic to minimise their exposure and related health impacts. For instance, increasing the distance between cycle lanes and traffic can reduce cyclists' exposure,[69] and walking along a side street, as opposed to a main road can reduce exposure by up to a half.[70]

Physical barriers can also help mitigate a person's immediate exposure.[71] Vegetation barriers can reduce roadside elevations up to 50%,[72] and also provide important eco-system services (e.g., sustainable urban drainage and biodiversity).[73] This may be especially useful where large numbers of people and/or vulnerable people come into close proximity with traffic, such as around schools.[74]

Authors

This briefing note was prepared on behalf of the TRANSITION Clean Air Network by Harry Williams (University of Birmingham).

Contact

Institute of Applied Health Research
University of Birmingham
Edgbaston B15 2TT
Email: info@transition-air.org.uk

Funding

TRANSITION Clean Air Network has received funding from UK Research and Innovation under grant agreement NE/V002449/1.

Suggested citation: Williams, H., Landeg-Cox, C., Levine, J. G. and Pope, F. D. (2022). 'Non-Exhaust Emissions from Road Transport', TRANSITION Clean Air Network, Birmingham, UK. Available online:
https://doi.org/10.25500/epapers.bham.00004108

References

[1] Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R. and Feigin, V., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, *389*(10082), pp.1907-1918.

[2] Chen, J. and Hoek, G., 2020. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. *Environment international*, *143*, p.105974.

[3] Shehab, M.A. and Pope, F.D., 2019. Effects of short term exposure to particulate matter air pollution on cognitive performance. *Scientific reports*, *9*(1), pp.1-10.

[4] Borroni, E., Pesatori, A.C., Bollati, V., Buoli, M. and Carugno, M., 2022. Air pollution exposure and depression: A comprehensive updated systematic review and meta-analysis. *Environmental Pollution*, *292*, p.118245.

[5] Shi, L., Wu, X., Yazdi, M.D., Braun, D., Awad, Y.A., Wei, Y., Liu, P., Di, Q., Wang, Y., Schwartz, J. and Dominici, F., 2020. Long-term effects of PM2· 5 on neurological disorders in the American Medicare population: a longitudinal cohort study. *The Lancet Planetary Health*, *4*(12), pp.e557-e565.

[6] Brunekreef, B., Strak, M., Chen, J., Andersen, Z.J., Atkinson, R., Bauwelinck, M., Bellander, T., Boutron-Ruault, M.C., Brandt, J., Carey, I. and Cesaroni, G., 2021. Mortality and Morbidity Effects of Long-Term Exposure to Low-Level PM2. 5, BC, NO2, and O3: An Analysis of European Cohorts in the ELAPSE Project.

[7] McDuffie, E.E., Smith, S.J., O'Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E.A., Zheng, B., Crippa, M., Brauer, M. and Martin, R.V., 2020. A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): an application of the Community Emissions Data System (CEDS). *Earth System Science Data*, *12*(4), pp.3413-3442.

[8] Harrison, R.M., Van Vu, T., Jafar, H. and Shi, Z., 2021. More mileage in reducing urban air pollution from road traffic. *Environment International*, *149*, p.106329.

[9] Department for Transport (2021) Transport and Environment Statistics: 2021 Report. Statistical Release. https://www.gov.uk/government/statistics/transport-and-environment-statistics-2021.

[10] Pant, P. and Harrison, R.M., 2013. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmospheric environment*, *77*, pp.78-97.

[11] Winkler, S.L., Anderson, J.E., Garza, L., Ruona, W.C., Vogt, R. and Wallington, T.J., 2018. Vehicle criteria pollutant (PM, NOx, CO, HCs) emissions: how low should we go?. *Npj Climate and atmospheric science*, *1*(1), pp.1-5.

[12] Air Quality Expert Group (2021) Exhaust Emissions from Road Transport. Available online at: https://uk-air.defra.gov.uk/research/aqeg/.

[13] Thorpe, A. and Harrison, R.M., 2008. Sources and properties of non-exhaust particulate matter from road traffic: a review. *Science of the total environment*, *400*(1-3), pp.270-282.

[14] Amato, F., Cassee, F.R., van der Gon, H.A.D., Gehrig, R., Gustafsson, M., Hafner, W., Harrison, R.M., Jozwicka, M., Kelly, F.J., Moreno, T. and Prevot, A.S., 2014. Urban air quality: the challenge of traffic non-exhaust emissions. *Journal of hazardous materials*, *275*, pp.31-36.

[15] Air Quality Expert Group (2019) Non-Exhaust Emissions from Road Traffic. Available online at: https://uk-air.defra.gov.uk/research/aqeg/

[16] Abbasi, S., Jansson, A., Sellgren, U. and Olofsson, U., 2013. Particle emissions from rail traffic: A literature review. *Critical reviews in environmental science and technology*, *43*(23), pp.2511-2544.

[17] Moreno, T., Martins, V., Reche, C., Minguillón, M.C., de Miguel, E. and Querol, X., 2018. Air quality in subway systems. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, (pp. 289-321).

[18] European Topic Centre on Air pollution, transport, noise and industrial pollution (2020) Transport Non-exhaust PM-emissions. European Environment Agency (EEA), Eionet Report – ETC/ATNI 2020/5.

[19] Amato, F. ed., 2018. *Non-exhaust emissions: an urban air quality problem for public health; impact and mitigation measures*. Academic Press.

[20] OECD (2020), *Non-exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge*, OECD Publishing, Paris. Available online at: https://www.oecd.org/environment/non-exhaust-particulate-emissions-from-road-transport-4a4dc6ca-en.htm.

[21] NAEI, 2021. UK National Atmospheric Emissions Inventory. Available online at: https://naei.beis.gov.uk/.

[22] EMEP (2021) EMEP Centre on Emission Inventories and Projections. Available online at: https://www.ceip.at/webdab-emission-database/reported-emissiondata.

[23] Harrison, R.M., Allan, J., Carruthers, D., Heal, M.R., Lewis, A.C., Marner, B., Murrells, T. and Williams, A., 2021. Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review. *Atmospheric Environment*, *262*, p.118592.

[24] HM Government (2021) Net Zero Strategy: Build Back Better. Available online at: https://www.gov.uk/government/publications/net-zero-strategy.

[25] Department for Environment, Food & Rural Affairs (2019) Clean Air Strategy. Available online at: https://www.gov.uk/government/publications/clean-air-strategy-2019.

[26] Holdway, A.R., Williams, A.R., Inderwildi, O.R. and King, D.A., 2010. Indirect emissions from electric vehicles: emissions from electricity generation. *Energy & Environmental Science*, *3*(12), pp.1825-1832.

[27] Notter, D.A., Gauch, M., Widmer, R., Wager, P., Stamp, A., Zah, R. and Althaus, H.J., 2010. Contribution of Li-ion batteries to the environmental impact of electric vehicles.

[28] Mrozik, W., Rajaeifar, M.A., Heidrich, O. and Christensen, P., 2021. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy & Environmental Science*, *14*(12), pp.6099-6121.

[29] Timmers, V.R. and Achten, P.A., 2016. Non-exhaust PM emissions from electric vehicles. *Atmospheric environment*, *134*, pp.10-17.

[30] Beddows, D.C. and Harrison, R.M., 2021. PM10 and PM2. 5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. *Atmospheric Environment*, *244*, p.117886.

[31] Alam, M.S., Hyde, B., Duffy, P. and McNabola, A., 2018. Analysing the Co-Benefits of transport fleet and fuel policies in reducing PM2. 5 and CO2 emissions. *Journal of cleaner production*, *172*, pp.623-634.

[32] Soret, A., Guevara, M. and Baldasano, J.M., 2014. The potential impacts of electric vehicles on air quality in the urban areas of Barcelona and Madrid (Spain). *Atmospheric environment*, *99*, pp.51-63.

[33] Timmers, V.R. and Achten, P.A., 2018. Non-exhaust PM emissions from battery electric vehicles. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, pp.261-287.

[34] World Health Organization. (2021). WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. https://apps.who.int/iris/handle/10665/345329. License: CC BY-NC-SA 3.0 IGO

[35] Kelly, F.J. and Fussell, J.C., 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmospheric environment*, *60*, pp.504-526.

[36] Committee on the Medical Effects of Air Pollutants (2015) Statement on the evidence for differential health effects of particulate matter according to source or components. Available online at: https://www.gov.uk/government/publications/particulate-air-pollution-health-effects-of-exposure.

[37] Health Effects Institute, 2010. Traffic-Related Air Pollution: A Critical Review Of The Literature On Emissions, Exposure, And Health Effects. HEI Special Report 17. Health Effects Institute, Boston.

[38] Kelly, F.J. and Fussell, J.C., 2020. Toxicity of airborne particles—established evidence, knowledge gaps and emerging areas of importance. *Philosophical Transactions of the Royal Society A*, *378*(2183), p.20190322.

[39] Stafoggia, M. and Faustini, A., 2018. Impact on Public Health—Epidemiological Studies: A Review of Epidemiological Studies on Non-Exhaust Particles: Identification of Gaps and Future Needs. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, pp.67-88.

[40] COMEAP (2020) Statement on the evidence for health effects associated with exposure to non-exhaust particulate matter from road transport. Available online at: https://www.gov.uk/government/publications/non-exhaust-particulate-matter-from-road-transport-health-effects.

[41] Lassen, C., Hansen, S.F., Magnusson, K., Norén, F., Hartmann, N.I.B., Jensen, P.R., Nielsen, T.G. and Brinch, A., 2012. Microplastics-Occurrence, effects and sources of. Significance, 2, p.2.

[42] Kole, P.J., Löhr, A.J., Van Belleghem, F.G. and Ragas, A.M., 2017. Wear and tear of tyres: a stealthy source of microplastics in the environment. International journal of environmental research and public health, 14(10), p.1265.

[43] Panko, J.M., Hitchcock, K.M., Fuller, G.W. and Green, D., 2019. Evaluation of tire wear contribution to PM2. 5 in urban environments. Atmosphere, 10(2), p.99.

[44] Wright, S.L. and Kelly, F.J., 2017. Plastic and human health: a micro issue?. Environmental science & technology, 51(12), pp.6634-6647.

[45] Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C. and Rocha-Santos, T., 2020. Environmental exposure to microplastics: An overview on possible human health effects. Science of the total environment, 702, p.134455.

[46] Leslie, H.A., van Velzen, M.J., Brandsma, S.H., Vethaak, D., Garcia-Vallejo, J.J. and Lamoree, M.H., 2022. Discovery and quantification of plastic particle pollution in human blood. *Environment International*, p.107199.

[47] Padoan, E., Amato, F., 2018. Vehicle non-exhaust emissions: impact on air quality. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, pp. 21–65.

[48] Denier van der Gon, H.A., Gerlofs-Nijland, M.E., Gehrig, R., Gustafsson, M., Janssen, N., Harrison, R.M., Hulskotte, J., Johansson, C., Jozwicka, M., Keuken, M. and Krijgsheld, K., 2013. The policy relevance of wear emissions from road transport, now and in the future—an international workshop report and consensus statement. Journal of the Air & Waste Management Association, 63(2), pp.136-149.

[49] Piscitello, A., Bianco, C., Casasso, A. and Sethi, R., 2021. Non-exhaust traffic emissions: Sources, characterization, and mitigation measures. Science of the Total Environment, 766, p.144440.

[50] Kwak, J.H., Kim, H., Lee, J. and Lee, S., 2013. Characterization of non-exhaust coarse and fine particles from on-road driving and laboratory measurements. Science of the Total Environment, 458, pp.273-282.

[51] Beji, A., Deboudt, K., Khardi, S., Muresan, B., Flament, P., Fourmentin, M. and Lumière, L., 2020. Non-exhaust particle emissions under various driving conditions: Implications for sustainable mobility. *Transportation Research Part D: Transport and Environment*, *81*, p.102290.

[52] Amato, F., Schaap, M., van der Gon, H.A.D., Pandolfi, M., Alastuey, A., Keuken, M. and Querol, X., 2012. Effect of rain events on the mobility of road dust load in two Dutch and Spanish roads. Atmospheric Environment, 62, pp.352-358.

[53] Harrison, R.M., Jones, A.M., Gietl, J., Yin, J. and Green, D.C., 2012. Estimation of the contributions of brake dust, tire wear, and resuspension to nonexhaust traffic particles derived from atmospheric measurements. *Environmental science & technology*, *46*(12), pp.6523-6529.

[54] Xia, T., Zhang, Y., Crabb, S. and Shah, P., 2013. Cobenefits of replacing car trips with alternative transportation: a review of evidence and methodological issues. *Journal of*

environmental and public health, *2013*.

55 Department for Transport (2021) Decarbonising Transport: A Better, Greener Britain. Available online at: https://www.gov.uk/government/publications/transport-decarbonisation-plan.

56 De Nazelle, A., Nieuwenhuijsen, M.J., Antó, J.M., Brauer, M., Briggs, D., Braun-Fahrlander, C., Cavill, N., Cooper, A.R., Desqueyroux, H., Fruin, S. and Hoek, G., 2011. Improving health through policies that promote active travel: a review of evidence to support integrated health impact assessment. Environment international, 37(4), pp.766-777.

57 Ye, R. and Titheridge, H., 2017. Satisfaction with the commute: The role of travel mode choice, built environment and attitudes. Transportation Research Part D: Transport and Environment, 52, pp.535-547.

58 Public Health England (2019) Review of interventions to improve outdoor air quality and public health. Available online at: https://www.gov.uk/government/publications/improving-outdoor-air-quality-and-health-review-of-interventions.

59 Querol, X., Amato, F., Robusté, F., Holman, C. and Harrison, R.M., 2018. Non-technological measures on road traffic to abate urban air pollution. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, (pp. 229-260).

60 Gramstat, S., 2018. Technological Measures for Brake Wear Emission Reduction: Possible Improvement in Compositions and Technological Remediation: Cost Efficiency. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, (pp. 205-227).

61 Bressi, S., Fiorentini, N., Huang, J. and Losa, M., 2019. Crumb rubber modifier in road asphalt pavements: state of the art and statistics. *Coatings*, *9*(6), p.384.

62 Frolova, O., Salaiová, B., Olexa, T. and Mandula, J., 2016. Using crumb rubber from waste tires to reduce road traffic noise. In *MATEC Web of Conferences* (Vol. 73, p. 04022). EDP Sciences

63 Grigoratos, T., 2018. Regulation on brake/tire composition. In: Amato, F. (Ed.), Non-Exhaust Emissions. An Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Academic Press, London, (pp. 89-100).

64 Hascoet, M. and Adamczak, L., 2020. At source brake dust collection system. *Results in Engineering*, *5*, p.100083.

65 Fieldhouse, J.D. and Gelb, J., 2016. New developments of an on-vehicle brake pad waste collection system. *SAE International Journal of Passenger Cars-Mechanical Systems*, *9*(2016-01-1949).

66 Amato, F., Querol, X., Johansson, C., Nagl, C. and Alastuey, A., 2010. A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods. Science of the total environment, 408(16), pp.3070-3084.

67 Amato, F., Escrig, A., Sanfelix, V., Celades, I., Reche, C., Monfort, E. and Querol, X., 2016. Effects of water and CMA in mitigating industrial road dust resuspension. *Atmospheric environment*, *131*, pp.334-340.

68 Karner, A.A., Eisinger, D.S. and Niemeier, D.A., 2010. Near-roadway air quality: synthesizing the findings from real-world data. *Environmental science & technology*, *44*(14), pp.5334-5344.

69 MacNaughton, P., Melly, S., Vallarino, J., Adamkiewicz, G. and Spengler, J.D., 2014. Impact of bicycle route type on exposure to traffic-related air pollution. *Science of the total environment*, *490*, pp.37-43.

70 Carrington, D., 2017. Side street routes to avoid city pollution can cut exposure by half. The Guardian, 14 June. Available online at: https://www.theguardian.com/environment/2017/jun/14/side-street-routes-avoid-city-pollution-cut-exposure-by-half.

71 Gallagher, J., Baldauf, R., Fuller, C.H., Kumar, P., Gill, L.W. and McNabola, A., 2015. Passive methods for improving air quality in the built environment: A review of porous and solid barriers. *Atmospheric environment*, *120*, pp.61-70.

72 Air Quality Expert Group, 2018. Impacts of Vegetation on Urban Air Pollution. Available online at: https://uk-air.defra.gov.uk/research/aqeg/.

73 Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T.S., Hoang, U., Hama, S., Tiwari, A., Sharma, A. and Abhijith, K.V., 2019. The nexus between air pollution, green infrastructure and human health. *Environment international*, *133*, p.105181.

74 Kumar, P., Omidvarborna, H., Barwise, Y. and Tiwari, A., 2020. Mitigating Exposure to Traffic Pollution In and Around Schools: Guidance for Children, *Schools and Local Communities.* Available online at: https://www.surrey.ac.uk/global-centre-clean-air-research/publications/reports-and-technical-articles.