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Title

Vehicle non-exhaust emissions – Revealing the pathways from source to environmental exposure

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Abstract

Brakes, tyres and road deposits have become important contributors to the overall particle emissions of vehicles globally, with constituents in these wear particles considered to be harmful to human health (PM_{10} and $PM_{2.5}$). Previous research has documented mass/size distributions, physical and chemical characteristics, emission factors and long-term implications and environmental occurrences. The complex path these pollutants take from their origins to the environment, however, is not fully understood. This is partly owing to the breadth of spatio-temporal scales involved in the advection-diffusion processes (nanometers to meters, microseconds to minutes). These short timescale particle transport mechanisms impact human exposure, such as pedestrians and cyclists, and initiate the long-term interaction of these pollutants with other environmental compartments. Here, we present an analysis for urban driving conditions to highlight the opportunities to reveal these complex pathways and formulate opinions that aim to stimulate future enquiry. We describe important vehicular areas and exposure scenarios where efforts should focus. Future interdisciplinary research into these particle transport mechanisms must be prioritised as it can provide the foundation for developing urgently needed pollution control strategies, transport infrastructure layouts and transport policies that mitigate, or possibly eliminate pollution exposure risks.

Keywords: Non-exhaust; Brake wear; Tyre wear; Emission exposure; Vehicle emissions.

1. Introduction

Road transport emissions are regularly categorized into two subgroups: exhaust and non-exhaust. Non-exhaust emission sources are unregulated and typically consist of brake, tyre and road dust [1, 2]. Advances in the abatement of regulated exhaust emissions have led to these sources quickly becoming a leading contributor to particulate concentrations. Tunnel measurements in the UK and China indicate non-exhaust emissions contribute 50-75% of PM_{10} and 15-40% of $PM_{2.5}$, respectively [1, 3] These fine and ultrafine particles have physicochemical properties that have been shown to adversely affect human health from medical disorders to increased mortality [4, 5]. The outlook for non-exhaust emissions in the UK, without any abatement, is predicted to be 94% of total PM_{10} emissions and 90% of $PM_{2.5}$ by 2030 [6]. This highlights both the importance and timeliness for developing technological solutions and environmental policies to address what is a global challenge.

In order to improve our understanding of how non-exhaust emission sources pose human health risks, and develop mitigation strategies, there are two main scientific issues to consider. The first issue that has received most attention consists of measuring the physical characteristics [7, 8], chemical composition [9], emission factors [3] and overall contribution of non-exhaust PM to transport emissions [1]. The second issue is interdependent, involving the relationship between the pollution source (brakes, tyres and road), vehicle kinematics and dynamics, and the vehicle aerodynamics. Collectively, these areas influence the spatio-temporal emission distributions in the surrounding environment through variations in driving conditions [2, 10] and particle transport mechanisms from source to the environment. The latter is the focus of this short commentary as it has received much less attention in the literature.

Our analysis aims to illustrate the significant role that aerodynamics can play in defining the trajectory, composition and fate of micron and sub-micron particles to the environment. Key vehicular areas are outlined which require urgent attention to quantify their contribution to the mass transport behaviour of non-exhaust pollutants. Furthermore, the multi-scale and multi-phase numerical techniques discussed are useful tools to model transport of particle matter down to an individual particle level. This provides information that is seldom practical to obtain with experiments in real-world testing conditions and can distinguish and track particles from simultaneous sources (e.g. brakes, tyres and road) often difficult to decouple in practice [7]. This is followed by a brief discussion on the opportunity for this research direction to guide mitigation technology and support the development of evidence-based transport policy to ensure human exposure to vehicle emissions is minimised.

2. Analysis

Research on vehicle aerodynamics has been predominantly concerned with quantifying vehicle drag, and cooling performances [11]. Drag produces a force that resists vehicle motion and is therefore directly connected to fuel consumption. This relationship, combined with tighter governmental regulations on fuel consumption and efficiency, has led the automotive industry to focus on developing aerodynamic characteristics for a singular purpose – drag reduction. Wheels and tyres contribute approximately 25% of the overall aerodynamic drag, produced directly by exposure to the outside air flow and indirectly by the tyre wake interacting with the external body [12, 13]. Notably, these locations generate complex unsteady flow separation, are in direct contact with the road, and are where brake and tyre emissions originate. This suggests that vehicle air flows have a non-trivial role in dispersing particles from vehicle sources (brake, tyre) and re-dispersing residual particles from the road surface. Indeed, previous research has shown that 50-70% of brake wear debris become airborne, with the remainder depositing on vehicle and road surfaces [7]. Investigating this dispersion process is central to studies on human exposure in urban environments. For example, a recent investigation on indoor PM concentrations confirmed that road proximity is a reasonable exposure metric often used in epidemiological studies [14].

Physical testing is one approach. Mobile emission laboratories are capable of measuring particle size and concentration in transient driving cycles [15]. Recent measurement systems for on-road testing have also incorporated sophisticated sampling systems to characterise non-exhaust particle emissions [16]. Laboratory testing in controlled environments can assess the impact of important operating variables on emissions including brake temperature [17]. Although these advancements reveal novel insights on particle formation and emission factors under variable driving conditions, on-road systems are inherently invasive and laboratory measurements provide less realistic conditions to examine the source-environment interface. Additionally, these state-of-art particle sampling methods acquire scalar quantities (e.g. size and concentration) and are unable to reveal the history of the complex interaction between the emission source, vehicle and environment. Uncovering these pollutant pathways is challenging, with advection-diffusion particle transport processes occurring over multiple length- and time-scales (nanometers to meters and microseconds to minutes – Figure 1).

Advanced multi-scale and multi-phase computational fluid dynamics techniques for modelling particle-laden flows can provide deep insights to address this challenge. It can also support hypotheses derived from experimental observations of environmental pollution. These techniques are beginning to gain traction outside of scientific research due to computing advances. However, the primary use of these specialised simulation tools for the automotive industry is to study surface contamination as it affects water management and vehicle aesthetics [18]. We believe that there is an opportunity for the research community to use these techniques for interdisciplinary investigations that reveal the complex pathways of non-exhaust emission sources to the environment and reduce human exposure. To demonstrate this, an example of a simplified vehicle model of a small-sized car is considered in Figure 1. Using coupled Euler-Lagrangian simulations, we recorded the paths taken by individual brake wear particles during a short braking event at a vehicle speed of 30 mph and deceleration of 3 m/s^2, similar to urban driving conditions. Unsteady flow fields were determined by obtaining numerical solutions of the Reynolds-averaged Navier-Stokes equations and a realizable $k-\varepsilon$ approach for turbulence modelling. The motion of brake wear particles was solved using a point-particle method based on the Maxey-Riley equation and particle emission from each brake pad was based on emission rate data for urban driving [19, 20]. Four different phases of wheel rotation, separated by 30 millisecond time intervals, show microscale particles being ejected from source to environment after braking. Their motion and selectivity is highly sensitive to aerodynamic effects, including brake disc ventilation, underbody, road surface and wheel/tyre interactions with the environment. Larger diameter particles ($d_p > 10\mu m$) first emerge from wheel openings while the expulsion of the smaller airborne particles ($d_p \sim 1\mu m$) is slightly delayed in the hub region. These size-selective particle clouds are also ejected into the environment with potentially harmful trajectories for human exposure.

An example of different exposure scenarios in urban environments is shown in Figure 2. These include vehicle-person and vehicle-vehicle, or vehicle-passenger interactions that are not well understood at present. Although it is not included in this graphic, enhanced pollution exposure can also extend to indoor spaces in buildings that are located ~100 m from roads [14]. In order to quantify their significance and implications on human health, a greater understanding of particle transport processes from non-exhaust sources is required. The key vehicular areas likely to have a dominant effect on these processes, and which require investigation, are also highlighted. Future investigations should also include specific details in areas such as tyre patterns, tyre loading and contact surfaces, wheel design and brake assembly. In addition to their significance on wear particle emission rates [10, 17], these areas can also affect the flow behaviour and aerodynamics of the vehicle [21]. The present analysis suggests these will also influence the particle transport routes to the environment.

By revealing these particle transport processes, together with quantifying their environmental impact, there is a follow-on opportunity to mitigate the associated health and environmental risks through both technology and policy-based solutions. Understanding the pathway of airborne particle matter at the vehicle-environment interface can provide rich information for developing particle capture and flow control technologies for vehicles. These would complement existing research on reducing particle formation mechanisms at source [22]. Similarly, the design of transport infrastructure, temporary layouts, pedestrian routes and cycle lanes in urban areas would also benefit. Ideally, to ensure solutions are globally accessible, research efforts should account for vehicle differences (e.g. make/model independent), retrofit considerations for older vehicles, and affordability. Finally, determining the non-exhaust emission pathways from source to environmental exposure can make these pollutants ‘visible’ to non-specialist audiences, producing highly visual scientific evidence to shift perceptions, raise awareness, and influence decision makers involved in transport and environmental policies.

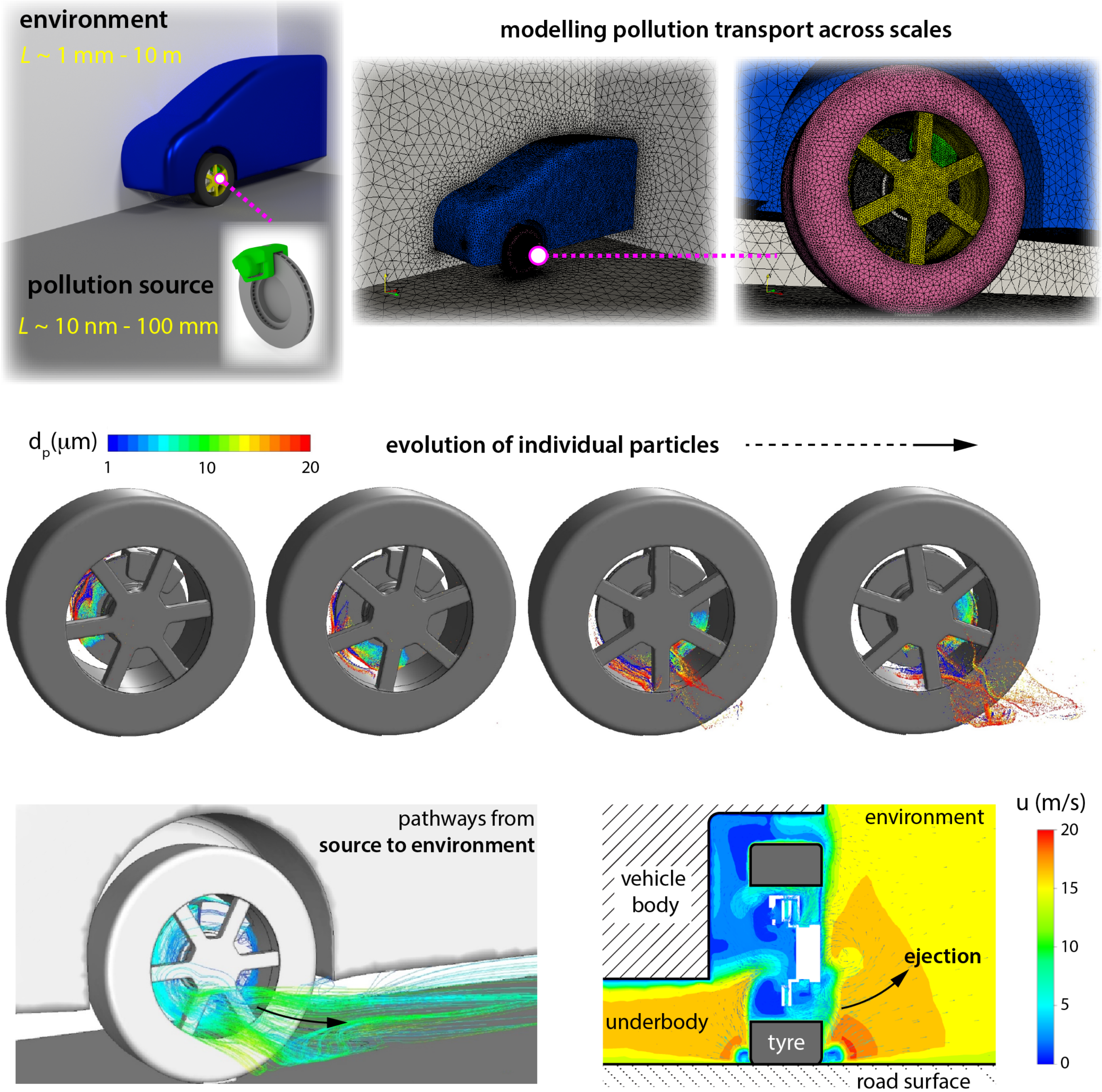

Figure 1: Brake wear particles are ejected during a braking event and follow a path from source to environment that is governed by aerodynamic interactions between the vehicle, road, wheel and brake assembly.

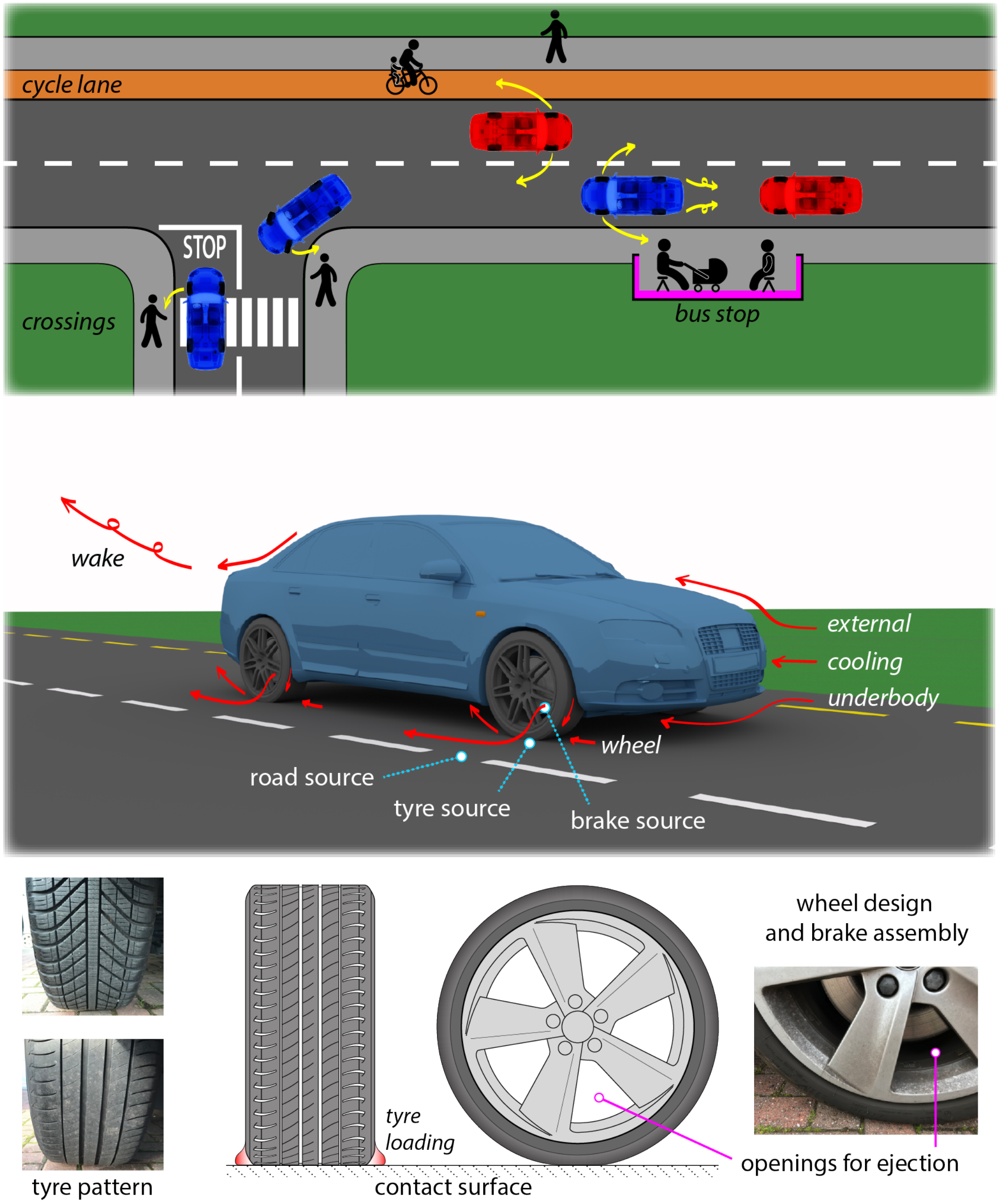

Figure 2: Exposure risk scenarios in urban environments (top) and key vehicular areas that influence pollution transport from brake, tyre and road sources to the wider environment (middle and bottom).

Conclusions

Non-exhaust emissions from vehicles are becoming an increasingly important contributor to the overall levels of particulate matter from road transport. Although research over the past decade has advanced scientific knowledge on particle formation, composition and environmental occurrences, the complex pathways these emissions take from the source to the environment is, for the most part, unresolved. These particle transport processes connect emission sources to human exposure and remain elusive due to the challenges in accurately quantifying their fate using non-invasive, real-world experiments. In this commentary, we discuss the key areas and opportunities to address this including the use of advanced multi-scale and multi-phase simulations that can uncover a detailed understanding of the initial interactions between vehicles and the environment. The routes and composition of particles released to the environment are highly sensitive to vehicle aerodynamics. It is important, therefore, that these particle transport mechanisms are studied and combined with interdisciplinary research collaborations. This way, the connection and risk of non-exhaust sources to human health and the environment can be thoroughly quantified and addressed.

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