

## EARPA Position Paper

### Non-Exhaust Particle Emissions – Gaps and Research Needs

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#### About EARPA

Founded in 2002, EARPA is the association of automotive R&D organizations. It brings together the most prominent independent R&D providers in the automotive sector throughout Europe. At present its membership numbers 60, ranging from large and small commercial organizations to national institutes and universities.

#### Background

**Non-Exhaust Emissions (NEE)** have emerged as a dominant source of vehicular Particulate Matter (PM) pollution over the past decade, with research demonstrating that they can represent over 90% of road transport  $PM_{10}$  and 80% of road transport  $PM_{2.5}$ , as exhaust controls have proven effective<sup>1</sup>. The technological transition toward vehicle electrification presents a complex emissions trade-off rather than a simple solution to this matter as their typically 21% higher weight<sup>2,3</sup> leads to an approximate increase in tire wear  $PM_{10}$  of 7-9.8% and in brake wear  $PM_{10}$  of 11.5-17.1% (urban to motorway)<sup>2</sup>.

Euro 7 will introduce the first worldwide brake emission limits, establishing  $PM_{10}$  thresholds of 3 mg/km for Battery Electric Vehicles (BEV) from M1/N1 categories (excluding  $N_1$ , Class III), effective from 2026-2027. For Heavy-Duty Vehicles (HDV) (M2, M3, N2, N3), brake emission limits are not yet defined but are scheduled for implementation from 2030 onwards. Tire abrasion limits are established with phased implementation: C1 tires from July 2028, C2 tires from April 2030, and C3 tires from April 2032<sup>4</sup>. In addition, since there is no standardized procedure for measuring airborne emissions from tires yet, PM emission factors of tire and road wear particles are not yet in the scope of European regulations.

#### Solutions on the horizon: Evidence-based pathways to NEE reduction

In this context, a variety of **vehicle- and infrastructure-level solutions have been proposed**. At vehicle level, technologies currently under testing include **regenerative braking systems, low-wear tire and brake designs, and wear-collection methods** such as electrostatic filters or suction systems.

- Results from laboratory experiments and vehicle tests confirms that vehicles equipped with regenerative braking systems, such as BEVs, can reduce Brake Wear Particle (BWP) emissions by approximately 55-89% for  $PM_{10}$ , 38-83% for  $PM_{2.5}$ , and 67-91% for total particle number, compared with internal combustion engine vehicles that are based on full-friction braking systems<sup>5</sup>.
- Low-wear brake designs offer significant reductions: advanced brake materials such as tungsten carbide-coated discs achieve 78.9% reduction in  $PM_{10}$  and 71.4% reduction in  $PM_{2.5}$ , while carbon-ceramic discs demonstrate 81%  $PM_{10}$  reduction compared to conventional grey cast iron discs<sup>3,6</sup>.
- Some studies predicted that placing capture tunnels on both the front and rear wheels could capture around 50–60% of the total Tire Wear Particle (TWP) volume<sup>7</sup>. Additionally, another study showed that the efficiency of TWP capture increases with vehicle speed, resulting in approximately 17% to 42% reductions in TWP concentration depending on speed<sup>8</sup>.
- Additionally, one of the most effective measures to reduce tire and road wear emissions **is improving driving practices**. Recent studies demonstrate that conservative driving patterns can reduce brake wear emissions by 42-53% for  $PM_{10}$  and  $PM_{2.5}$ <sup>9</sup> while telematics systems that encourage smooth driving achieve approximately 10% reduction in brake wear<sup>1</sup>.

**On the infrastructure side, improvements to road quality**, e.g. modifying surface texture or changing pavement composition to reduce erosion, are being explored. For example, rubber-modified asphalt, incorporating ground

tire rubber into polymer binders, demonstrates 50% reduction in tire and road wear particle generation compared to concrete surfaces<sup>10</sup>.

While these technologies have demonstrated significant effectiveness under controlled conditions, their widespread deployment requires coordinated research to validate long-term performance across varied environmental conditions and to establish robust economic and operational frameworks. This position paper identifies critical knowledge gaps that need to be considered and provides evidence-based recommendations for research priorities to address the NEE challenge.

### Critical knowledge gaps

- **Health impact of NEE:** Nanoparticles (<100nm) represent a significant health threat from NEE<sup>11</sup>. These particles can cross biological barriers, causing oxidative stress and inflammation in the lungs, and in the cardiovascular and nervous systems<sup>11</sup>. However, current mass-based regulations (PM<sub>2.5</sub>, PM<sub>10</sub>) do not adequately consider the health impacts of nanoparticles<sup>12</sup>. Additionally, it has been proven that brake emissions can generate secondary PM, for which environmental and health impacts are undetermined<sup>13</sup>.
- **Environmental effects of non-airborne emissions:** Particles from vehicle brake systems and tires are dispersed throughout the environment, presenting significant risks to both ecological systems and human health. While approximately 40-45% of BWPs become airborne as PM<sub>10</sub> or finer particles during braking events, the remainder deposits on surrounding surfaces<sup>1</sup>. Tire wear pollution presents an even greater environmental challenge, as only 2-5% of the material becomes airborne, while the vast majority (95-98%) deposit on roads and roadsides<sup>1</sup>. These toxic particles can reach and contaminate aquatic systems and soil. Despite representing a significant source of vehicular pollution, this brake and tire wear contamination receives no regulatory coverage, leaving fundamental blind spots in environmental protection and mitigation measures<sup>1</sup>.
- **NEE composition and source allocation:** Significant gaps exist regarding the exact chemical components and the relative contributions of NEE sources. BWPs contain metal compounds and thermally generated volatile products formed between 160°C and 300°C, depending on the brake materials<sup>12</sup>. Tires comprise rubber polymers, additives, and transformation products, and can also evaporate volatile components when temperatures exceed 180°C<sup>14</sup>. In addition, limited understanding exists regarding weathering effects on NEE when exposed to environmental conditions and atmospheric aging processes through interaction with sunlight and oxidants<sup>1,13,15</sup>.
- **Volatile NEE Components:** Recent studies demonstrate that both brakes and tires emit volatile materials that can condense and form nanoparticle modes<sup>15</sup>. These particles may be present in the largest numbers below 10nm but are also present above 10nm<sup>16,17</sup>. The volatility of these particles from tires may be similar to that of lower volatility components in gasoline fuel. These volatile particles are currently unregulated in tailpipe emissions<sup>15</sup>. Although their specific health effects are largely unknown, their contribution is at least considered when studying the overall toxicity of engine exhaust<sup>18</sup>. Conversely, volatile particle emissions from brakes and tires are not currently planned for regulation, and health studies on these specifically are lacking<sup>18</sup>. The chemistry of solid particles emitted from braking events will be different between brake and tire sources, and so will the chemistry of volatile materials and volatile particle emissions, as they are being produced by various processes: thermal evaporation, chemical reactions, and even, specifically for brake pads, localized combustion<sup>15</sup>.
- **HDV NEE:** HDVs can generate 8 to 11 times higher emissions in tire wear than Light Duty Vehicles (LDV)<sup>19</sup> and on-road measured brake wear of up to  $1.17 \times 10^{10}$  #/km/brake<sup>20</sup>, due to their significantly greater mass and braking requirements<sup>1</sup>. Regardless of this, HDVs lack standardized testing methodologies, forcing reliance on outdated data or inappropriate extrapolations from LDVs studies<sup>1</sup>.

### Methodological constraints to overcome

- **Laboratory testing limitations:** Current laboratory component testing fails to represent real driving conditions, as traditional laboratory methods can only assess emissions from isolated components, such as brakes or tires, individually misrepresenting or overlooking critical whole-vehicle phenomena<sup>21</sup>. Emission

factor variability across studies confirms the fundamental difficulty of reproducing realistic conditions and highlights the absence of robust measurement and reference standards for measurements<sup>14</sup>. For instance, temperature effects are not incorporated into testing protocols despite tire abrasion rate (mg/km) increasing per degree Celsius above 20°C with one study suggesting  $\sim 2.7\%/^{\circ}\text{C}^1$  and brake nanoparticle formation starting between 160°C and 300°C depending on brake materials and becoming significant when the temperature reaches 400-500°C<sup>12</sup>. Chassis dyno laboratory testing can represent real driving conditions but there is the need to reach standardized methods<sup>20,22</sup>.

- **Real-world characterization challenges:** There is substantial difficulty in obtaining undisturbed TWP samples in real-world conditions due to contamination from various sources like road wear and resuspended road dust. This creates a fundamental challenge in accurately characterizing tire wear particles in real driving conditions<sup>14</sup>.

### Research priorities and way forward

These unresolved scientific gaps and methodological limitations must be addressed through coordinated research programs to develop effective mitigation strategies and evidence-based regulatory standards that are grounded in realistic emission profiles and impact considerations.

### Impact assessment of NEE on health and environmental effects

- **Health-impact focused regulation standards emphasize particle toxicity, concentration, and distribution over mass analysis.** It is necessary to direct research towards metrics that may be relevant to health impacts. Currently, particle number metrics for brakes and tires only consider non-volatile particles for brakes along with mass metrics<sup>21</sup>. Still, emissions of volatile materials and particles should also be considered for study, along with their chemical composition and health effects<sup>18</sup>.
- **Comprehensive environmental fate studies for non-airborne NEE fractions and their ecosystem impacts.** Research should investigate tire and BWPs dispersion pathways through soil and water systems to understand how this wear contamination affects ecosystems, and address its potential impacts<sup>1,18</sup>.

### Improved quantification Methods

- **Real-world standardized field campaigns.** Field campaign methodologies can provide representative data essential for accurately reflecting NEE across diverse real-world operating conditions and informing regulatory decisions that address actual emission behavior<sup>23</sup>. Research is needed in parallel to develop online and offline sampling methods that can distinguish particles from different sources during roadside measurements and prevent cross-contamination<sup>14,20</sup>.
- **Whole-vehicle emission assessment methodologies.** Research should consider all relevant particle emissions metrics, control systems and interacting braking approaches; and employing simulation, real-world and laboratory testing<sup>17</sup>. Transitioning from component-level testing to whole-vehicle approaches would allow us to integrate the thermal-mechanical dynamics that influence real-world NEE emissions<sup>21</sup>.
- **Harmonized measurement protocols.** There is a need to develop standard monitoring procedures, guidelines, and recommendations across European cities and countries for NEE to address the high variability in emission factors estimated in different studies<sup>1,24</sup>, including temperature effects.
- **HDV standards.** Mitigation measures must address the absence of standardized methodologies equivalent to GTR24 for LDVs. Strategies must account for the unique characteristics of HDVs, including different weights, driving patterns, double- and single-wheel braking and components that differentiate their emission factors from LDVs<sup>1</sup>.

### NEE Reduction measures

- **Lightweight materials promotion.** The weight-induced emission factor highlights the need for NEE research focused on lightweight material innovations<sup>2</sup>. Research areas should consider low-density materials for vehicle structures to reduce overall vehicle mass without compromising safety or performance<sup>1</sup>. Developing these material solutions is essential to ensure that the transition to electric mobility achieves genuine

particulate matter emission reductions rather than merely shifting emission sources from exhaust to non-exhaust pathways<sup>1,2,12</sup>.

- **Integrated driving behavior and vehicle control strategies for NEE mitigation.** Driving behavior represents a controllable factor for reducing NEE, necessitating research into behavior modification programs, traffic management systems, and driver education initiatives that promote smoother driving patterns<sup>1</sup>. Complementing these behavioral interventions with advanced vehicle control strategies should minimize NEE through optimized powertrain control, intelligent routing algorithms, and precise torque management on individual wheels, thereby reducing abrupt braking and acceleration events<sup>12</sup>. This integrated approach necessitates multidisciplinary collaboration across urban planning and engineering fields to develop comprehensive solutions that combine human behavioral factors with technological control systems for substantial reduction in particle pollution<sup>1</sup>.
- **Climate change adaptation strategies.** To mitigate the escalating impact of climate change on NEE, mitigation measures should account for the higher abrasion rates of winter tires compared to summer tires. Additionally, regional meteorological factors should be considered in emission modeling and NEE mitigation measures<sup>14</sup>.
- **Innovative brake, tire material and design.** For brakes, research must focus on low-wear compositions to minimize particle generation and heavy metal content while preserving brake efficiency and performance under varied temperature and load conditions<sup>10</sup>. For tires, research should focus on tire compounds that improve abrasion resistance without compromising wet grip and rolling resistance<sup>10</sup>.
- **Road surface materials and maintenance.** As friction between roads and tires generates wear particles, road surface materials and road conditions are influencing factors in the generation of NEE<sup>25</sup>. Therefore, research should focus on determining and understanding optimal combinations between these elements as well as identifying materials and cost-effective maintenance interventions that will minimize abrasion and dust resuspension<sup>25</sup>.

EARPA applauds all EU-funded projects dedicated to exploring NEE; however, recent research activities have increasingly revealed significant disparities in research results, persistent knowledge gaps, and unexplored domains that require substantial and ongoing efforts to be adequately addressed. Even though the European Commission has recognized the importance of NEE by allocating funding in the Horizon Europe Work Programme 2025, future project results will not fully resolve the issue. Given the scale and complexity of the NEE challenge, sustained research investment beyond individual project cycles is essential, underscoring the need for continued dedicated attention and resources throughout the Horizon Europe 2.0 program to develop practical and effective solutions for this critical environmental and public health challenge.

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