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THEORETICAL FOUNDATIONS OF TIRE AND BRAKE WEAR PARTICLE FORMATION DURING URBAN BUS OPERATION

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Urban bus fleets emit substantial non-exhaust particulate matter (PM), driven by heavy axle loads and intensive braking cycles. This review synthesizes the mechanistic understanding of particle formation from tires and brakes under urban bus duty cycles, including core generation mechanisms, particle characteristics, and key emission factors. We discuss tire wear processes (abrasion, stick–slip, tread evaporation) and brake wear processes (frictional heating, tribochemistry), highlighting how high load and low-speed bus operation affects these. Measured emissions for heavy vehicles are summarized. Implications for particle fate, health impacts, and mitigation are addressed.

Urban buses are an important non-exhaust particle source because their duty cycle combines high axle loads, repeated acceleration and deceleration, frequent curb approaches, and sustained stop–go operation. In current evidence syntheses, non-exhaust emissions are now a dominant share of traffic PM in many cities, and their importance is rising as exhaust PM declines; official and academic reviews from the Organisation for Economic Co-operation and Development[1], the European Environment Agency[2], the World Health Organization[3], and the United States Environmental Protection Agency[4] all point in the same direction. For buses, brake wear is usually the more measurable airborne source in urban service, while tire wear often dominates total mass shed from the vehicle–road system but with a much smaller directly airborne PM fraction. The literature is much richer for light-duty vehicles than for buses, so several “bus” values reported below are either heavy-duty classifications or explicitly marked as inferred rather than directly measured.

The theoretical picture is now reasonably mature. Tire wear particles form through coupled adhesion, hysteresis, abrasive micro-cutting, thermomechanical fatigue, and crack growth in the viscoelastic tread block under multiscale pavement roughness. Brake wear particles form through rough-contact loading at pad–disc interfaces, development and destruction of primary and secondary plateaus in the friction layer, third-body flow, flash heating, oxidation, and volatilization–condensation processes that generate ultrafine modes. In both systems, mechanical and thermal mechanisms act together rather than separately. This is especially true for urban buses, where low-speed high-torque launches, cornering at stops, heavy axle loads, and repeated braking pulses produce strong local contact stresses and temperatures [10].

The most defensible urban-bus brake emission ranges in the current literature are: PM10 of about 5–45 mg/km per brake from heavy-duty dynamometer testing that included two passenger buses, and particle number of about 4.1×10^7 to 1.7×10^9 particles/km per brake from on-board measurements of a heavy-duty school bus on real-world stop–go routes. At the fleet/composition level, urban heavy-duty vehicle brake PM10 in a street canyon has been estimated at 81 ± 39 mg/km per vehicle. For tires, direct bus-specific airborne PM and PN measurements remain scarce. Total tire wear factors used for buses/heavy vehicles span roughly 192 mg/vkm in older inventory practice, about 415 mg/vkm in a recent bus-average inventory study, and 823–1235 mg/vkm for “heavy vehicles” in a recent atmospheric modeling study. Only a small fraction of total tire wear becomes airborne PM10, so direct conversion from total wear to airborne PM must be treated as uncertain.

The measurement problem is still a major research bottleneck. Brake particle methods are more advanced because enclosure-based dynamometer systems, gravimetric PM procedures, real-time PN sizing, and elemental analyses are already being standardized for regulation. Tire wear measurements are less mature because one must distinguish pure tire particles, tire-and-road wear particles, resuspended road dust, and condensed organic material, often in a highly contaminated background. Standardization has improved through recent work of the International Organization for Standardization[8] and SAE International[9], and through the brake-emission framework adopted under the United Nations Economic Commission for Europe[10], but bus-specific field validation remains limited [8].

For mitigation, the best-supported near-term measures for urban buses are:

This article addresses the theoretical foundations of the formation of tire wear particles (TWP) and brake wear particles (BWP) during the operation of urban buses. “Urban buses” is used here in a functional sense: vehicles operating in dense, stop–go service with frequent braking events, repeated curb approaches, and high passenger-load variability. Where the underlying source explicitly refers to school buses, passenger buses, or generic heavy-duty vehicles rather than transit buses, that is stated. Because the bus-specific literature is incomplete, the review uses a hierarchy of evidence: direct bus measurements first, then heavy-duty vehicle evidence, then mechanistic and regulatory literature from light-duty systems where the underlying tribology is transferable.

The current mechanistic consensus is that tire wear is governed by a coupled contact problem involving viscoelastic rubber, multiscale road roughness, adhesion, hysteresis, frictional heating, and fatigue damage. Recent modeling work emphasizes that tread properties are not constant: they change with excitation frequency and material temperature, so the abradability of the rubber depends on the local dynamic state of the tread block rather than simply on distance traveled. In practical terms, urban-bus operation amplifies these effects because high normal loads and repeated transient maneuvers push the contact patch away from quasi-steady rolling and toward mixed rolling–sliding regimes [14].

Mechanically, five sub-mechanisms are most important. Mechanical abrasion occurs when asperities on the pavement plough or cut into the tread, generating chips and microfragments. Viscoelastic deformation causes internal hysteretic losses as rubber deforms around roughness peaks; that dissipated energy elevates local temperature and promotes crack initiation. Thermal effects include flash temperatures at microscopic contacts that soften the polymer matrix, alter filler-matrix bonding, and in severe cases promote volatilization and nucleation of ultrafine particles. Road-tire interactions determine whether particle formation is dominated by micro-cutting, fatigue, or mixed tire–road agglomeration, with roughness spectrum and skid texture being decisive. Material composition determines crack growth resistance, surface smearing tendency, and the distribution of additives such as Zn- and S-containing vulcanization products, carbon black, and silica [10].

A useful theoretical approximation is to treat local tire-wear generation as a function of contact pressure, slip velocity, viscoelastic loss modulus, and temperature:

$$\dot{m}_t \propto \int_A k_t\,(T,\omega,\text{compound},\text{road})\,p(x,y)\,v_{\text{slip}}(x,y)\,dA$$

where k_t is not a constant “wear coefficient” in the classical metallic sense, but an effective state-dependent abrasion parameter. Recent tire models therefore move beyond a purely

Archard-type description and make k_t depend on frequency-dependent viscoelasticity and thermodynamic state [14].

The viscoelastic part can be expressed through energy loss density W_d, often approximated in harmonic form as $W_d \sim \pi E'' \varepsilon_0^2$, where E'' is the loss modulus. This is important because hysteretic energy dissipation both drives rolling resistance and contributes to wear-promoting heat generation. Higher roughness, higher frequency excitation, and compounds with larger loss modulus in the relevant frequency–temperature window generally increase dissipation and therefore wear risk [14].

For buses, tire wear should be expected to rise with axle load, repeated curb turning, lateral scrub in depots and terminals, aggressive acceleration from stops, low inflation pressure, poor alignment, and road surfaces with strong macrotexture. The recent inventory and modeling literature is explicit that heavy-vehicle factors are still uncertain and under-measured. One 2024 assessment concluded that a major future priority is establishing reliable heavy-duty emission factors and understanding how climate, surface properties, and fleet characteristics modify them [8].

Brake wear arises in a tribological “third-body” system rather than from simple two-body rubbing. Under load, hard constituents in the pad form primary plateaus that carry a significant fraction of the contact load. Detached wear debris from both pad and disc then compacts against those load-bearing sites to form secondary plateaus; these structures stabilize friction temporarily, but they are continuously created and destroyed. Their breakup releases debris ranging from coarse plate-like fragments to fine and ultrafine particles. This plateau-based picture remains the most widely accepted mesoscopic explanation of brake wear.

The contact is highly nonuniform. Surface asperities, pad composition, rotor metallurgy, and pre-existing tribolayer structure create local stress concentrations and hot spots. At lower temperatures and gentler braking, mechanical abrasion, adhesion, and fragmentation dominate. At higher temperatures, oxidative transformation of iron-rich debris, thermal degradation of organics, and volatilization of semi-volatile species become increasingly important. Recent work on new vs. used discs also shows that rough fresh rotor surfaces can increase PN by orders of magnitude, with particles below 100 nm dominating the increase. A compact physical formulation writes frictional heat generation as:

$$\dot{Q}_f = \mu\, p\, A\, v$$

and braking work over an event as:

$$W_b = \int_{t_0}^{t_1} P_b \; dt = \int_{t_0}^{t_1} T_b \; \omega \, dt$$

Recent heavy-duty on-road modeling then links emitted particle number to dissipated brake work through a simple event-scale linear model, $PN = aW_b + b$, which worked better than temperature-only formulations in field data. This is conceptually important for buses because their routes are dominated by repeated discrete braking events[27]

For cumulative wear volume, an Archard-type surrogate remains common in brake FE models:

$$V_w = K \frac{F_N s}{H}$$

or, in differential form, $dV \propto p \, v \, dt/H$. However, in practice K is strongly state-dependent because roughness evolution, tribofilm growth, and temperature alter both real contact area and material response. That is why the newest brake-emission models increasingly combine energetic descriptors, thermal submodels, and data-driven calibration[13]

Brake measurement is currently more mature than tire measurement. Off-line gravimetric filters remain foundational for PM mass, while real-time instruments such as CPC, SMPS/FMPS/EEPS, APS, OPC, ELPI+, and TEOM/QCM provide PN, transient dynamics, and partial size resolution. The recent brake-UFP review argues that mobility-based sizing and CPCs are essential for UFPs, while optical counters and mass-only methods underrepresent them. For brake chemistry and morphology, SEM/EDX, TEM, ICP-MS/OES, XRF, Raman, and thermo-gravimetric methods are common.

Tire and TRWP measurement is harder because samples must be separated from road dust and other carbonaceous material. The main standardized/standardizing methods include Py-GC/MS for ambient-air and environmental TRWP quantification, road-simulator generation methods, and framework documents for physical/chemical characterization. Recent reviews also emphasize the need for combined physical and chemical markers rather than single tracers, because tire composition varies by tire class and manufacturer.

A practical classification is into empirical, mechanistic, CFD/FE-coupled, and stochastic/data-driven models. Empirical models use route-average emission factors or weight-scaled factors such as $EF \propto m_{veh}$. The OECD synthesis cites an approximate increase in brake PM10 of 0.004 mg/km per kg of vehicle mass and tire PM10 of 0.0041 mg/km per kg, illustrating why heavy buses are intrinsically high emitters compared with passenger cars.

Mechanistic tire models combine viscoelastic constitutive response, roughness excitation, and thermal state. A general structure is:

$$\dot{m}_t = f\big(p,\, v_{\text{slip}},\, T,\, E'(\omega,T),\, E''(\omega,T),\, R_q,\, \text{compound}\big)$$

with a thermal balance such as

$$C_t \frac{dT}{dt} = \eta \dot{Q}_{\text{fric}} - hA(T - T_a)$$

where η is the fraction of frictional power entering the tread. Recent work specifically argues for updating tread properties “instant by instant” as a function of excitation frequency and temperature.

Mechanistic brake models often link event-scale heating and emissions to braking work. Steinmetz et al. modeled brake-disc temperature rise as a function of braking work, modeled cooling as a function of the integrated disc-to-air temperature difference, and modeled PM as linearly related to braking work. This is especially relevant for urban buses, whose duty cycles can be represented as sequences of short braking events separated by incomplete cooling intervals.

CFD-coupled models add aerosol transport and dilution to a wear-generation model. For example, recent urban TWP modeling in Stockholm[3] converted heavy-vehicle wear factors into atmospheric concentrations and estimated annual TWP-PM10 at roof level from about 0.2 μg/м^3 in moderate-traffic areas to about 1.2 μg/m^3 near busy highways, with 0.7–1.1 μg/m^3 in selected street canyons. Such models are useful for bus-route exposure analysis, but they still depend sensitively on emission-factor choice, deposition assumptions, and street-canyon mixing.

The timeline reflects a transition from broad source-apportionment studies toward source-specific mechanistic, toxicological, and regulatory work, with brake methods currently ahead of tire methods but both moving toward harmonization.

After emission, particle fate depends strongly on size and composition. Coarse TRWP and larger BWP deposit rapidly near the source and then enter either runoff pathways or resuspension cycles; finer and ultrafine fractions remain airborne longer, undergo aggregation, oxidation, and mixing with ambient aerosol, and can deposit deeper in the lung. Recent reviews note that BWP UFPs can also change reactivity through atmospheric aging and shifts in metal speciation, while gaseous brake emissions may produce secondary particles after photooxidation.

For TRWP in air, the Stockholm modeling study found annual average TWP-PM10 concentrations of roughly 0.2–1.2 μg/m^3, highest near busy highways and in poorly ventilated street canyons. This is not specific to buses, but it is directly relevant for bus corridors that combine heavy traffic with canyon-like urban geometry. Nearby road dust and roadside environments also show strong distance gradients for traffic-derived microplastics. The health significance follows particle size and chemistry. The EPA notes that PM10 can be inhaled into the lungs and that PM2.5 poses the greatest health risk because it penetrates more deeply and can enter the bloodstream; the WHO's 2021 guideline update reflects the strength of current evidence linking PM exposure to cardiovascular and respiratory disease. Because brake wear often emits metal-rich PM2.5 and UFPs, and tire wear adds organic-rich PM plus additive-related toxicants, both sources are relevant to urban-bus exposure.

Toxicologically, recent brake evidence is especially concerning. Salva's review summarizes oxidative stress, inflammation, mitochondrial dysfunction, and epithelial barrier effects associated with metal-rich UFPs. Parkin et al. demonstrated that copper-enriched brake-wear PM perturbs human alveolar cellular homeostasis and, in their experimental system, may do so more strongly than diesel exhaust PM. Tire-particle reviews similarly report ecotoxicological and human-health concerns, particularly due to additive leaching and interactions with co-pollutants, though mechanistic inhalation toxicology remains less mature than for brake particles.

Mitigation should be thought of at four levels. Materials: low-emission pad formulations, high-durability/low-abrasion tire compounds, low-copper or copper-free systems where performance can be maintained, and improved disc coatings or surface engineering. Vehicle system design: regenerative braking, brake-by-wire blending, thermal management, and route-control strategies that reduce harsh braking. Operations and maintenance: tire pressure, alignment, suspension condition, brake bedding and replacement strategy, wheel-end cleanliness, and driver training against aggressive start/stop behavior. Urban infrastructure and policy: roadside cleaning, runoff capture, pavement optimization, curbside management, and emission standards. The recent regulatory direction is clear: UNECE announced global brake-particle standard adoption in 2026, and Euro 7 introduces brake PM10 limits for light-duty vehicles, but tire-emission regulation is still much less mature.

The most important knowledge gaps for urban buses are straightforward. First, there are still too few direct bus measurements, especially for tire PN and size-resolved airborne PM. Second, there is no broadly accepted way to convert total tire wear into directly airborne PM for buses under real routes. Third, studies rarely measure tires and brakes simultaneously with harmonized chemistry, making source separation inconsistent. Fourth, bus-specific route and loading effects are under-characterized. Fifth, regulations remain focused on PM mass and do not yet handle the toxicologically important ultrafine-number domain well. Research should therefore prioritize instrumented bus-route campaigns, standardized wheel-end capture methods, route-aware multiphysics models, and toxicology tied to source-resolved material composition rather than bulk PM alone.

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