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MODEL OF TIRE WEAR IN THE URBAN CYCLE AND PHYSICAL MECHANICS OF WEAR

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Abstract

This article examines the key factors influencing tire wear in urban driving conditions, as well as the main physical and chemical mechanisms of tire and brake system wear. Tire types are taken into account. summer/winter/all-season, compound materials, tread structure, tire pressure, axle load, driving profile, road surface and ambient temperature, humidity, surface abrasiveness, braking modes, interaction of tire and braking system.

Keywords: tire wear; urban driving cycle; tire abrasion; tribological wear; thermomechanical degradation; brake wear; tire-road interaction; viscoelastic friction; particulate emissions; rubber aging.

Tire wear is considered through micromechanisms —adhesion, abrasion, fatigue, and thermal—and chemical processes (oxidation and rubber aging). The main types of wear models (empirical and semimechanistic formulas, physics-based modeling, and multiscale approaches), calibration parameters, validation methods, and sensitive analysis methods are presented. The necessary data from field and laboratory tests is described, including their format and collection frequency. Numerical methods and sources of uncertainty for modeling are discussed. The conclusion provides recommendations for further research and practical applications of the models for tire life prediction and tire-brake system optimization. Detailed comparisons of wear models, data lists, and test methods are provided in the tables.

Tire wear is determined by a complex combination of factors. Tire type, construction, and compound materials significantly affect resistance to abrasion and thermal aging. Tread structure (profile, channel depth, rubber compounds) determines grip and wear characteristics (e.g., an asymmetric tread increases local stresses). Tire pressure and axle load affect the contact area and force distribution [1]. Driving dynamics significantly influence wear: in the urban cycle, due to numerous accelerations and braking, wear can be significantly higher [2]. A high frequency of acceleration/braking leads to fatigue damage to the tread. Road surface and ambient temperature affect the condition of the rubber: at low temperatures, the rubber becomes brittle, which increases abrasive wear; at high temperatures, the wear curves shift, facilitating the development of cracks. Humidity and surface abrasiveness (gravel, sand) also increase wear. Braking modes—normal or heavy—determine the load on the brake pads and the heat flow into the wheel. Heavy braking generates significant heat, which can lead to localized tire overheating and increased wear. The interaction between the tire and the braking system is measured through the vertical load on the wheel and the force transmitted by the braking torque. The load on the brake pads and the heat generated during braking affect the temperature of the brake disc and tire, which indirectly affects tire wear.

Wear micromechanisms. Rubber tire wear involves several modes: adhesive, abrasive, and fatigue. [3] . Under very high local stresses, large fragments may break off. Adhesive wear is enhanced by strong adhesion at the atomic level: for example, rubber particles can stick to the road surface and then break off along with the transfer of material. Chemical processes make rubber harder and more brittle, reducing its wear resistance. Similar mechanisms predominate in the braking system: abrasive wear of the pads and disc, fatigue and thermal wear. In particular, research shows that during friction between the brake disc and pad, a mechanically mixed (tertiary) layer is formed, through which contact occurs [4] . Microparticles of wear are formed when this layer breaks off: in pads, these are often microparticles of the organic matrix, and in the disc, iron oxides that take root in the surface. The composition of the pad (metals, ceramics) influences the formation of primary and secondary plateaus that stabilize friction.

Approaches to modeling tire wear are divided into several categories: empirical

Validating wear models requires detailed field and laboratory measurements. The table lists key parameters, including the format and frequency of data collection:

Parameter	Measurement Format	Frequency / Methodology
Vehicle speed (v)	M/s (GNSS or inertial sensor)	Constantly (1–10 Hz) by GPS/gyroscope; telemetry recording
Accelerations (a, transverse, prod.)	*g* (accelerometer or GNSS)	Continuous (1–10 Hz); for one run, calculate σ(a) (UNR117)
Axle load	kg (weight cells or strain gauges)	Statically before testing and controlled during testing (for trucks)
Tire pressure (p)	kPa (pressure gauge, CAN bus)	Before the test; dynamic monitoring via TPMS is possible every cycle
Wheel + tire weight	g (precision scales, accuracy ±2 g)	Before and after the run; based on the results of point stops
Tread depth	mm (templates or laser sensor, accuracy ±0.1 mm)	After every 1000–5000 km of driving or before/after testing
Rubber hardness (Shore A)	% (durometer, ±5 units)	Before and after testing (may change with degradation)
Atmospheric temperature	°C (thermocouple)	Continuously (1 Hz) during the trip, or every 1–5 min
Road temperature (asphalt)	°C (IR pyrometer, thermocouple)	Periodically (every 1–5 minutes) or at key points along the route
Ambient humidity	% (hygrometer)	Continuous/intermittent (1–5 min); affects adhesion
Coating roughness	Class or Ra (profilometer)	Once before testing (describes the type of soil/asphalt)
Tire material and structure	Text characteristics	According to the manufacturer's specifications (compound, carcass, tread)
Braking modes	Number of emergency stops/intensity	In the CAN register or by GPS/accelerometer recording

Parameter	Measurement Format	Frequency / Methodology
		(braking frequency)
Brake system data	Pad load (kN), temperature(°C),wear (g)	Dynamically (force sensors, thermocouples on the disc); pad wear – check after a run

References: GPS/accelerometer dataset for motion profiling, precision scales and a depth gauge for wear assessment, temperature sensors for thermal monitoring. UN Regulation 117 requires that standard deviations in acceleration and temperature be taken into account in such tests.

The following test methods are recommended for comprehensive verification of wear patterns:

- **Laboratory tire testing:** Rotating drum test rigs simulate wear under constant sliding. Examples include **vertical or horizontal drums** with ISO 4258/R117 load ratings. The INDWEAR machine can simultaneously test up to six tires on a drum. **Multimodal rigs** (elastic disc + radial/axial loads) are also used to simulate shear angles and radial forces (e.g., STRADA66-T, CFT). These tests measure tread mass/depth loss after a specified number of revolutions or distance traveled. The rigs are equipped with infrared tread temperature and pressure sensors to monitor thermal conditions.
- **Laboratory brake testing: Pin-on-disc** testing (a fixed pad slides on a rotating disc) allows for monitoring load and sliding speed. It is used both for new materials and to study the influence of pad composition. These tests examine the structure of the friction layer, pad and disc wear, and dust generation. Dynamic tests on a brake dynamometer (torque + temperature) simulate real-world cyclic braking to measure thermal wear.
- **Climate and chemical testing:** a rubber aging chamber (controlling humidity , O2 , UV, and ozone) studies chemical aging and oxidative wear (thermal-oxidative aging on tire life). These tests determine how compound materials degrade under heat.
- **Field road tests:** the key is long-term testing on a track or real route. According to UNR117, the cycle includes a mileage **of 8,000 km (±10%)** with tire wear measurements. It is recommended to use separate urban (UDDS/NYCC), suburban, and high-speed roads to account for different profiles. Instrumented driving with speed, acceleration, and temperature sensors ensures the collection of profile data. Tire weight and tread depth are measured before and after the test. Particular attention is paid to the repeatability of tests with control tires and the synchronization of braking loads.
- **Monitoring on real vehicles:** using telemetry from commercial vehicles or taxis (CAN bus data on speeds, braking, pressure, and temperatures) to collect wear statistics. This data is processed in ML models and serves as a complement to laboratory validation.

The table shows approximate methods for these tests:

Test type	Methodology and equipment
Laboratory stand "drum" (tires) *[20]*	Rotary drum (vertical/horizontal) with a preset slip coefficient and controlled load (ISO 4258/R117). Weight loss and tread depth are recorded. Tread heating is monitored by an IR sensor.
Multimodal stand (tires) *[21]*	Simulation of road conditions: vertical load + lateral shear force (longitudinal/angular slip angle). Loads and developed forces are measured. Used to study track formation and wear under combined loading.
Pin-on-disc (brakes)	Laboratory apparatus: a flat brake pad is pressed against a rotating cast iron disc. The load and sliding speed are set. The coefficient of friction,

Test type	Methodology and equipment
	pad and disc mass loss, and wear composition (microparticles) are measured. This apparatus allows for studying the effects of material composition and temperature.
Brake dynamometer (brakes)	A brake tester with an electrohydraulic drive. The brake pad load and braking mode (intermittent/emergency) are set. Heat generation, wear (pad thickness after a run), and efficiency are measured.
Climate chamber (chemistry)	UV/O2/ozone/humidity chambers. Compound samples are subjected to accelerated aging. Changes in hardness, microstructure, and chemical composition are measured. The resulting brittleness and reduction in mechanical properties are analyzed.
Field rubber track (real route)	Track and road testing according to UNR117 (a cycle of approximately 8,000 km with partial repeatability). Tire weight and tread measurements are taken every 1,000–2,000 km. Identical reference tires are used. Speed profile, acceleration, road temperature, and tire temperature are recorded.
Real-time monitoring	Installing sensors on operational vehicles: tire pressure, brake and tire temperature, GPS/accelerometer. The data is sent to a center for wear analysis (using machine learning models).

Numerical methods are used to calculate the wear model: **finite element modeling** (FEM) for localized contact and heat transfer analysis, **discrete element modeling** (DEM) for studying the interaction of individual rubber fragments and abrasive particles, and statistical methods of contact mechanics (Persson theory) for modeling microcontact statistics. Material heterogeneity and pavement roughness are often taken into account in the calculations. The main sources of uncertainty are the variation in compound properties (viscoelasticity, hardness) and road parameters (roughness, moisture content). Errors can arise in assessing local pressure and slip fields (measured by indirect methods), as well as due to the stochastic nature of the compound composition. Sensitivity analysis is performed by varying key parameters (pressure, temperature, friction coefficient) and studying the impact on the wear prediction.

To improve wear patterns, it is recommended:

- **Integrate multiphysics effects:** include the interrelationship between thermal, mechanical, and chemical processes (for example, modeling the thermal-oxidative degradation of a compound under load). This will allow for the aging of rubber at high temperatures and loads.
- **In-depth materials analysis:** study the wear of tires made with various compounds (fillers, modifiers) and develop databases of their properties. Comparisons of summer and winter tires, as well as assessments of the impact of wear on traction and energy efficiency, are a priority.
- **Multiscale modeling:** develop a link between microprocesses (contact with asphalt, breakdown of molecular bonds) and the macrodynamics of tire wear. This will require expanding existing theories of Persson/Zhivanov to include binder and filler effects.
- **Instrumental testing:** Expand field testing to include a variety of road conditions (asphalt, concrete, gravel) and extreme conditions (emergency braking, icy road) to reflect real-world urban driving cycles.
- **Practical applications:** develop predictive maintenance systems – integrated tire pressure/wear sensors, telemetry data analysis for remaining tire life forecasts. Optimize compound-tread combinations to reduce wear emissions and extend service life.

The tire wear model can be used in engineering practice to **predict tire life** and **optimize tire-braking systems** . It can be used to evaluate the effectiveness of new tire compound mixtures and designs, establish brake operating modes that minimize wear, and implement real-time tire condition monitoring systems. Future research should combine experimentation and modeling to create reliable wear prediction tools for urban driving conditions.

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