

Article

Temperature and Inflation Pressure Effects on Airborne Tire Wear Particle Measurements on a Chassis Dynamometer

Fabius Epple ^{1,*} , Nina Reijrink ², Hakan Hasan Tuncel ¹ , Sven Reiland ¹ , Miriam Chacón-Mateos ², Michael Eßl ¹, Melis Seren Celenlioglu ²  and Tjark Siefkes ¹

¹ Institute of Vehicle Concepts, German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

² Institute of Combustion Technology, German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

* Correspondence: fabius.epple@dlr.de

Abstract

Airborne tire and road wear particles (TRWP) are gaining regulatory attention, but laboratory methods for their measurement are not yet standardized. This study aimed to quantify how controllable chassis-dynamometer operating parameters affect airborne TRWP measurements and to identify the operating limits of the DLR TRWP-Measurement System. A two-level factorial design in tire inflation pressure (1.8/3.8 bar) and chamber temperature (11/35 °C) was realized in two sequential blocks at rear-wheel toe settings of 48' and 30', bracketed by reference measurements. Particle number was measured with a condensation particle counter (MCPC, 7 nm–2 µm) and an optical particle sizer (OPS, 0.3–10 µm), from which an optical mass proxy was derived. Higher chamber temperature increased the cumulative MCPC response by a factor of 3.6 (95% CI 1.8–7.2), whereas higher inflation pressure reduced the OPS number response by 18% (95% CI 12–24%); the OPS mass proxy decreased by approximately 17% with temperature. Toe settings above 48' caused progressively rising particle signals and irregular tread wear. The MCPC response under reference conditions doubled over the campaign, showing that drift monitoring and blocked, randomized run orders are prerequisites for factorial airborne TRWP testing.

Keywords: tire and road wear particles (TRWP); non-exhaust emissions; design of experiments; chassis dynamometer; method development; particle number; particulate mass; tire wear; Euro 7



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1. Introduction

Air pollution remains one of the most significant environmental and public health challenges worldwide. Although exhaust emissions from road transport have been substantially reduced through stricter emission standards, improved combustion technologies, and exhaust after-treatment systems, emissions from non-exhaust sources are becoming increasingly important [1–4]. The relative importance of non-exhaust emissions is further increased by vehicle electrification, because operational tailpipe emissions are eliminated while mechanically generated particle emissions remain. Battery electric vehicles eliminate tailpipe emissions during operation, but continue to generate particulate matter through mechanical wear processes, including tire wear, brake wear, road surface abrasion, and the resuspension of deposited road dust [3,5–7]. Consequently, non-exhaust sources are expected to account for an increasing proportion of particulate emissions from road transport as regulated tailpipe particulate matter emissions decline [3,8–11].

Among non-exhaust sources, tire and road wear particles (TRWP) have gained considerable scientific and regulatory attention. TRWP are generated through complex mechanical and thermo-mechanical interactions at the tire–road interface, including abrasion, fatigue, adhesion, and smearing. Tire-derived particles have been reported across a broad size range (from a few nanometers up to several hundred micrometers), although the source attribution and physical state of particles in the ultrafine range remain unclear and highly method-dependent [12–15]. Coarser (micrometer range) TRWP predominantly deposit near the emission source or are transported through road runoff, contributing to terrestrial and aquatic microplastic contamination. Smaller particles may remain airborne for longer periods and contribute to traffic-related particulate matter exposure, although the specific health effects attributable to airborne TRWP remain subject to ongoing investigation [2,9,12,15,16]. Freshly generated airborne TRWP may contain tire-derived polymers and fillers, mineral road material, organic additives, and trace elements, with their composition and morphology depending on tire formulation, surface properties, operating conditions, and the particle-generation mechanism. Subsequent environmental aging can further modify the particles and their associated chemical compounds [17–20].

Regulatory developments increasingly reflect the importance of non-exhaust emissions. The Euro 7 framework from the European Union introduces dedicated requirements for non-exhaust sources, with brake particle emissions addressed through PM₁₀ (particulate matter with an aerodynamic diameter less than or equal to 10 µm) limits and tire abrasion included in the regulatory framework (European Commission 2024) [11,21–23]. Current regulatory approaches to tire abrasion are based primarily on gravimetrically determined tire mass loss normalized by driving distance. Standardized test procedures have been developed and abrasion limits have now been developed for passenger car and van tires, while further implementation and activities for refinement of the framework remain ongoing [8,21,22]. However, gravimetrically determined tire mass loss does not describe the partitioning of worn material between non-airborne deposits, coarse debris and airborne particles in PM (particle mass) and PN (particle number) emissions, and this airborne fraction may differ from the total worn material in size distribution, atmospheric relevance and measurement sensitivity [9,11,15,16,24]. Reliable laboratory methods capable of quantifying airborne TRWP emissions under reproducible conditions are therefore essential for scientific research and future regulation [25–28].

TRWP measurement approaches range from material- and component-scale laboratory rigs to chassis dynamometers, controlled test-track experiments, and on-road measurements, each offering a different balance between experimental control, source attribution and real-world representativeness. On-road measurements provide real-world relevance, but are strongly affected by traffic conditions, meteorology, background aerosol concentrations, and simultaneous emissions from brakes, road wear, and resuspended dust [4,11,26]. Laboratory approaches, including tire test rigs and chassis dynamometer facilities, provide greater control over driving cycles, environmental conditions, and sampling configurations. However, unsuitable contact, loading, surfaces, third-body interactions or thermal boundary conditions may produce non-representative wear regimes despite the high degree of experimental control [27–29]. Cross-study comparability is affected at three levels: particle generation under different tire–surface and operating conditions; particle collection and transport through different sampling geometries and flow systems; and particle detection and processing using instruments with different size ranges, measurement principles, and background treatments. These differences complicate comparison of reported concentrations, particle-number responses, particle-mass estimates, and emission factors [11,28,30–32].

A further limitation is the limited use of statistically planned experimental methodologies. The interaction between operational conditions remains under-evaluated. Design of Experiments (DoE) provides a structured statistical approach for investigating several factors simultaneously, estimating interactions and comparing systematic factor effects with experimental variability, provided that randomization, replication, and experimental stability are adequately maintained [33–35]. Its application to airborne TRWP emission measurements remains limited, although such methods are essential for improving robustness and defining operational boundaries, especially because particle generation is sensitive to operating factors including tire inflation pressure, vertical and lateral loading, speed, temperature, and wheel alignment, whereas the measured response additionally depends on the particle-size range and detection principle of the selected instruments [13].

The aim of this study is to evaluate whether a factorial Design of Experiments can quantify the influence of controllable chassis-dynamometer operating parameters on airborne TRWP measurements and, at the same time, delimit the conditions under which such measurements are repeatable. Using the German Aerospace Center (DLR) TRWP-Measurement System [26,27,32] and a two-level factorial design, the influence of controllable laboratory parameters on cumulative particle number responses and an optically derived mass proxy is investigated while evaluating measurement repeatability and identifying test conditions associated with unstable or non-representative particle-generation behavior. The study therefore addresses three questions: (i) which selected laboratory factors significantly affect the particle number responses and the optically derived mass proxy; (ii) whether interactions between these factors can be resolved using factorial analysis; and (iii) whether the same experimental approach can identify conditions under which the tire–surface system no longer exhibits stable and representative wear behavior.

To answer these questions, four research tasks were defined: (T1) to identify, in a screening phase, wheel-alignment settings that cause unstable particle generation and thus define the operating window (Section 3.1); (T2) to quantify the main and interaction effects of tire inflation pressure and chamber temperature on the three responses (Sections 3.2–3.5); (T3) to separate within-point repeatability from campaign-dependent drift using repeated WLTCs and bracketing reference measurements (Section 3.6); and (T4) to derive requirements for boundary conditions and quality control in future airborne TRWP test protocols (Section 4).

2. Materials and Methods

2.1. Test Facility, Vehicle and Tire

All experiments were conducted under controlled laboratory conditions at the DLR using a chassis dynamometer facility with a climate chamber specifically configured for the investigation of airborne TRWP emissions. The four metallic-coated rollers provide a reproducible tire–surface contact, but differ from real pavement in curvature, thermal response, material composition, and third-body behavior. Consequently, the measured factor effects are interpreted as specific to the investigated tire–roller system, while the transferability of their numerical magnitude to on-road conditions is not assumed. Laboratory testing was selected to reduce variability arising from meteorology, traffic, and ambient aerosol concentrations, as well as to enable controlled variation in selected test parameters. The controlled environment enables the systematic variation in selected operating parameters while maintaining constant boundary conditions throughout the measurement campaign.

The experimental investigation was performed using the DLR TRWP-Measurement System, which has been developed to quantify airborne TRWP generated at the tire–road interface during chassis dynamometer operation [26,27]. In contrast to conventional open

(nozzle-based) sampling approaches, the DLR measurement system employs an enclosed collection concept designed to isolate the sampling volume from external influences.

In line with the DLR methodology, the collected particles are referred to as TRWP, although on the chassis dynamometer the road component is replaced by the metallic roller coating.

The main boundary conditions that were kept constant during the measurement campaign are summarized in Table 1. Experimental variables were classified into three groups: nominally fixed test-system conditions, intentionally varied DoE factors, and monitored variables. This distinction prevents intentionally varied or time-dependent quantities from being incorrectly treated as constant boundary conditions.

Table 1. Nominal fixed test-system configuration and nominally constant experimental conditions.

Category	Parameter	Condition
Test facility	Location and facility type	DLR climate-controlled chassis-dynamometer facility, Stuttgart, Germany; type MAHA AIP-ECMD 48 L/4 mot
Test facility	Dynamometer configuration	4 × 1219 mm, single driven rollers, all-wheel drive mode, simulated i3 driving resistance EPA coefficient
Vehicle	Test vehicle	BMW i3, test mass: 1353.6 kg, candidate tire (rear left) vertical load: 338.0 kg
Tire	Tire specification	225/45 R17 all-season passenger car tire
Dynamometer surface	Roller surface	Porous metallic-coated chassis-dynamometer roller
Driving procedure	Driving cycle	Worldwide harmonized Light Vehicle Test Cycle (WLTC) 3b: driven by Stähle robot driver
Driving procedure	Number of repetitions	Four consecutive WLTCs per DoE point; WLTC 1 as conditioning cycle, WLTC 2–4 as repeated measurements

2.2. Particle Generation and Sampling

The measurement system displayed in Figure 1 combines a wheel-enclosure module, a controlled extraction channel, isokinetic sampling nozzles and the time-resolved aerosol instrumentation.

The methodology follows a three-step approach comprising particle generation, particle collection and particle analysis, as illustrated in Figure 2.

In the generation step, TRWPs are produced at the tire–roller contact zone during chassis dynamometer operation. Particle generation and release are influenced by the driving cycle, tire inflation pressure, wheel alignment, chamber, and tread temperatures, vertical loading, tire condition, roller-surface properties and longitudinal slip [13,14,26]. These boundary conditions determine the mechanical interaction between the tire tread and the roller surface and therefore influence the formation of airborne particles. By conducting the experiments under controlled laboratory conditions, the generation of TRWP can be investigated with reduced interference from uncontrolled environmental effects.

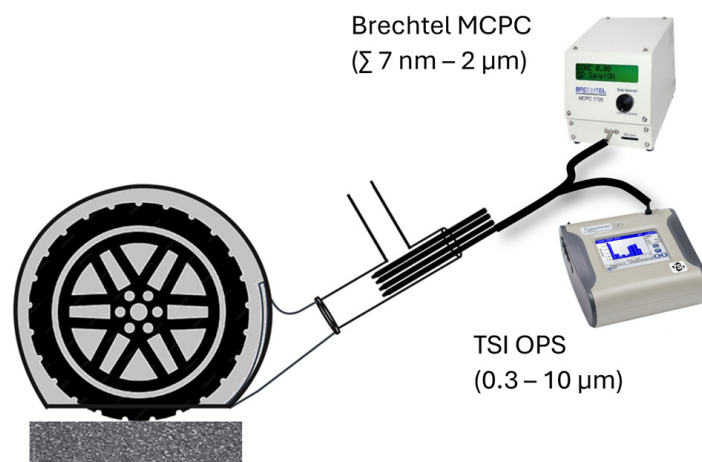


Figure 1. Schematic representation of the DLR TRWP-Measurement System encapsulating the tire and the two aerosol instruments used for this study.

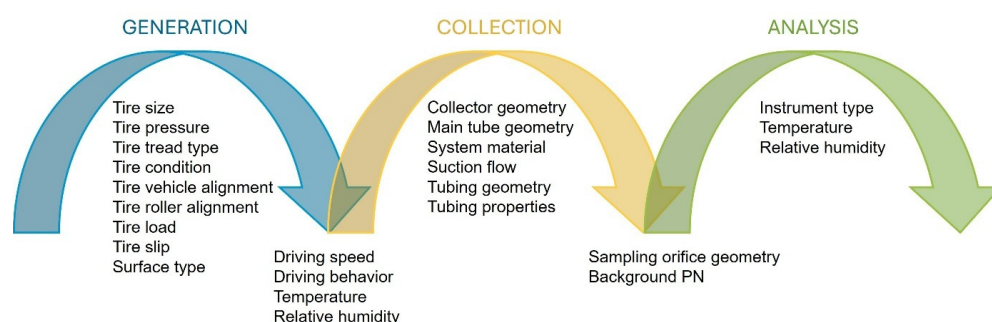


Figure 2. Three-step methodological framework for airborne TRWP measurements, consisting of particle generation, particle collection and particle analysis. Part of the DLR TRWP measurement methodology. Adapted from [26].

In the collection step, particles generated within the tire–roller contact zone are captured by an enclosed sampling system (also called a housing system) positioned around the test wheel and integrated into the wheel assembly. The enclosure reduces uncontrolled dilution with chamber air and provides a more defined extraction pathway. At the same time, it modifies the local wheel airflow and therefore forms an integral part of the collection efficiency and particle-transport characteristics of the system. The generated aerosol is continuously transported through dedicated conductive sampling lines towards the aerosol instrumentation. The extraction volume flow was 170 m³/h and identical for all test points. The aerosol instruments were placed inside the climate chamber, and their exhaust flows were routed outside the chamber. Particular attention was paid to maintaining stable sampling conditions in order to minimize particle losses caused by gravitational settling, inertial deposition, diffusional deposition or electrostatic effects during aerosol transport [32]. The enclosed sampling concept therefore supports repeatable airborne particle measurements and enables systematic investigations of experimentally controlled influencing parameters [26].

2.3. Laboratory Analysis Methods

In the analysis step, the transported aerosol is characterized using complementary particle measurement instruments. The MCPC (Mixing Condensation Particle Counter, Model 1720, Brechtel [36], Hayward, CA, USA) measured the total number concentration of particles above its nominal lower detection diameter of 7 nm (upper limit of 2 μm) without providing size-resolved information. Its measurement principle is based on enlarging small aerosol particles by condensation with n-butanol vapor so that they can be optically

counted [36]. The condensation-growth principle provides high counting sensitivity for small particles. However, the measured particle number concentration (PNC) must remain within the instrument's specified coincidence and saturation limits ($1 \times 10^5 \text{ \#/cm}^3$). In this study, size-resolved optical particle number concentrations were measured using an Optical Particle Sizer (OPS, Model 3330, TSI [37], Shoreview, MN, USA), which classifies particles into 16 optical-equivalent diameter channels over the nominal range of 0.3–10 μm . From the OPS size distribution, an optically derived mass proxy was calculated by converting the measured particle number concentration in each size channel into an equivalent particle volume, assuming spherical particles and a unit density of $1 \text{ g \#/cm}^3$. The contributions of all channels up to the selected size limit were then summed. For $m_{\text{OPS},2.5}$, the OPS channel spanning 2.156–2.685 μm was included. The resulting quantity is a size-weighted optical mass proxy and should not be interpreted as a measurement of $\text{PM}_{2.5}$ or PM_{10} . The OPS uses optical-equivalent rather than aerodynamic particle diameter, a sharp size cut instead of the conventional 50% aerodynamic cut-off, and an assumed density that is lower than the effective density typically reported for TRWP. In addition, particle sizing may be affected by optical properties, and coarse-particle transport losses were not corrected. The OPS mass proxy was therefore used only for relative comparisons between test conditions.

OPS diameters represent optical-equivalent diameters based on light-scattering measurements and the instrument calibration; differences in particle refractive index and morphology may therefore influence the reported size distribution [16]. Thus, the MCPC provides high sensitivity for particle number, whereas the OPS enables size-resolved characterization and the calculation of a size-weighted mass proxy within the optically detectable size range.

The combination of MCPC and OPS allows the airborne TRWP response to be evaluated with three complementary response variables, which are defined in Section 2.5: the cumulative MCPC number concentration, the cumulative OPS number concentration and the cumulative OPS mass proxy. This multi-instrument approach is important because changes in operating parameters may affect not only the number of particles but also their size distribution. The properties regarding design, isokinetic sampling and background influence are described in Celenlioglu et al. [32].

In addition to the online MCPC and OPS measurements, selected test conditions were sampled using an Electrical Low-Pressure Impactor (ELPI+, Dekati, Kangasala, Finland) to collect size-fractionated particles for complementary microscopic analysis. For the temperature comparison presented in Section 3.3, particles collected on ELPI stage 9, with a nominal aerodynamic cut-off diameter (D_{50}) of approximately 604 nm, were examined by scanning electron microscopy (SEM, Ultra Plus, Zeiss, Oberkochen, Germany). Comparable substrate areas were evaluated using consistent imaging conditions. Both substrates were sampled for approximately 160 min under identical flow conditions, and only one substrate per condition was analyzed. The SEM analysis was used as qualitative supporting evidence of differences in particle loading; no systematic particle counting or gravimetric quantification was performed.

2.4. Experimental Design and Test Sequence

A statistically planned Design of Experiments was employed to investigate the influence of experimentally controllable operating parameters on airborne TRWP emissions under laboratory conditions. The selected methodology enables the simultaneous evaluation of several influencing parameters while also identifying potential interaction effects between factors. This increases the information obtained from a limited number of experiments and provides improvement for a statistically robust basis for identifying the dominant sources of experimental variability [34,35]. The design and the test sequence

were defined in five steps: selection of factors, selection of factor levels, screening of the operating window, definition of the factorial run sequence, and definition of the measurement procedure at each test point.

Step 1—Selection of factors: The experimental design focused on parameters that can be adjusted during chassis-dynamometer testing and that may affect either the tire–surface generation process, the release and transport of airborne particles, or the resulting instrument-level response. Because the experiment does not independently separate these stages, the estimated factor effects are interpreted as effects on the complete generation-collection-measurement chain. Factor selection was decided by preliminary DLR investigations, technical adjustability within the test facility, and published evidence on parameters affecting tire wear and tire–road particle generation. The ETRTO (European Tyre and Rim Technical Organisation) vehicle-abrasion validation study [21] was used as contextual evidence for the sensitivity of gravimetric tire-wear testing to operational and boundary conditions, rather than as a direct basis for predicting airborne particle responses. However, the present DoE was not intended to reproduce a general tire wear index ranking or to solely investigate the parameters with the strongest expected influence on total tire wear (Table 2). Instead, the focus was on laboratory boundary conditions that can be adjusted reproducibly within the DLR TRWP-Measurement Methodology and that may affect airborne particle generation, measurement stability, and repeatability.

Table 2. Maximum impact numbers for selected factors affecting tire abrasion rate, adapted from the vehicle abrasion validation study by Oelze and Biesse [21].

Factor	Maximum Impact Number
Driving style	6.0
Road curviness and topography	4.0
Road surface	3.0
Vehicle	2.0
Tire design	2.0
Temperature	1.7
Wet/dry condition	1.3

Three controllable parameters were selected as DoE factors: tire inflation pressure, chamber temperature, and wheel alignment which are listed in Table 3. Tire inflation pressure was included because it affects the tire–surface contact patch, contact pressure distribution, and tread deformation [38]. Climate-chamber temperature was selected because it affects tire warm-up and rubber viscoelastic behavior and may also influence particle formation, volatility and transport within the measurement environment [13,38]. Wheel alignment was included because it directly affects slip conditions at the tire–surface contact and may therefore influence particle generation as well as the operational limits of the measurement configuration [11,38]. Wheel alignment was originally planned as a third factor but was finally treated as a blocking variable (Step 4). The tire specification, roller surface, nominal vehicle loading, and prescribed driving cycle which are listed in Table 3 were held nominally fixed across the investigated DoE points to reduce additional sources of variability. Tire condition, thermal history and accumulated test distance were monitored because these quantities evolved during the campaign.

Step 2—Selection of factor levels. Each factor was investigated at two levels (Table 3).

The selected factor levels were defined based on the adjustable operating range of the test facility, the technical limits of the measurement system and the need to remain within a range where stable tire operation and repeatable particle generation could be expected. Based on the proven reference test settings, the values of the factors (high and low) were chosen as a symmetrical increase and decrease from the reference. The low-level

temperature of 11 °C (12 K below reference temperature) was selected as representative of cold weather conditions in northern Europe, while the high-level temperature of 35 °C (12 K above reference temperature) was chosen to represent hot weather conditions in southern Europe. Standard reference tire pressure at 2.8 bar was increased and decreased symmetrically by 1 bar to 1.8 bar and 3.8 bar. Tire inflation pressure was varied around the reference condition to obtain a sufficiently pronounced change in tire deformation and contact-patch conditions while remaining within the pressure limits applicable to the tested tire. Previous experimental work on tire–road particulate emissions has demonstrated measurable effects using pressure variations from 2.0 to 3.2 bar around a 2.6 bar reference condition [13]. The selected pressures were additionally constrained by the tire manufacturer’s specified inflation limits and the applied wheel load. The toe settings were based on the screening phase (Step 3), which showed how the toe angle can influence tire abrasion under chassis dyno conditions. Due to the mounting of the vehicle on the chassis dyno in a fixed position, toe angles cannot be compensated by vehicle chassis orientation. Therefore, the angle effect is increased on the chassis dyno compared to on a road. The control arm of the i3 model test vehicle allows continuous adjustment of the toe angle by means of an eccentric bolt. The investigated toe levels were selected to provide a sufficiently large and reproducibly adjustable difference for detecting a potential effect, while avoiding excessively severe lateral slip conditions that could induce abnormal abrasion or a transition to a non-representative wear regime.

Table 3. Factors of the two-level factorial design, blocking variable and reference condition.

DoE Factor	Symbol	Low Level	High Level	Reference Setting	Implementation Note
Tire inflation pressure	p	1.8 bar	3.8 bar	2.8 bar	Nominal pressure was adjusted before testing. Digital manometer type CPG1500, 0–6 bar, ± 5 mbar
Climate-chamber temperature	T_{ch}	11 °C	35 °C	23 °C	The chamber set point was used as the experimental factor; ± 1 °C deviation allowed
Rear-wheel toe-adjustment position	A	30'	48'	30'	Eccentric adjustment bolt for toe angle (toe-in) was manipulated within 0° and 45° angle; this resulted in the positive toe angle values given on the left. Toe was run in two blocks and is not estimated as a factor (Step 4); the reference setting equals the low level

Step 3—Screening of the operating window. Before the factorial phase, toe settings between the reference setting and values above 48' were tested. A setting was classified as outside the operating window if the MCPC response increased progressively from cycle to cycle instead of approaching a plateau, if the coefficient of variation (CV) of WLTC 2–4 exceeded 40%, or if irregular tread wear was visible. Toe settings above 48' failed these criteria (Section 3.1), and 48' was therefore used as the upper toe setting. The screening data were used only to define the operating window and are not part of the factorial analysis.

Step 4—Factorial run sequence. Wheel alignment was originally planned as a third factor of a 2^3 design. Because each toe change requires mechanical adjustment of the eccentric bolt and re-measurement of the alignment, the toe could not be randomized and was run in blocks. The factorial phase was therefore conducted as a 2^2 -design in inflation pressure and chamber temperature, realized in two sequential blocks: block 1 at toe 48' (DoE 6, 8, 7, 9) and block 2 at toe 30' (DoE 2, 4, 3, 5). Within each block, the chamber temperature was alternated between consecutive points, whereas the inflation pressure was changed only once. Reference measurements at 2.8 bar, 23 °C and at toe 30' were performed at the start (DoE 1) and at the end (DoE 10) of the campaign to monitor drift. Since the toe is confounded with campaign time, it is treated as a blocking variable, and no toe effect is estimated. The run sequence and the accumulated WLTC distance are given in Table 4.

Table 4. Test sequence of the factorial phase: 2^2 designs of inflation pressure and chamber temperature, realized in two sequential toe blocks and bracketed by reference measurements.

Run Order	DoE	Block (Toe/Wheel Alignment in Minutes)	Tire Pressure (bar)	Chamber Temperature (°C)	Accumulated WLTC Distance at Start (km)
1	DoE 1	Reference (30')	2.8	23	0
2	DoE 6	1 (48')	1.8	11	93
3	DoE 8	1 (48')	1.8	35	186
4	DoE 7	1 (48')	3.8	11	279
5	DoE 9	1 (48')	3.8	35	372
6	DoE 2	2 (30')	1.8	11	465
7	DoE 4	2 (30')	1.8	35	558
8	DoE 3	2 (30')	3.8	11	651
9	DoE 5	2 (30')	3.8	35	745
10	DoE 10	Reference (30')	2.8	23	838

Step 5—Measurement procedure. The experimental framework was based on the DLR TRWP measurement described in the SAE Technical Paper [26]. In the present study, the DLR TRWP measurement methodology [26] framework was extended by integrating a statistically planned Design of Experiments to evaluate the influence of controllable operating parameters on airborne TRWP emissions.

The factorial dataset was obtained in the second phase. Before each run, the relevant operating parameters were adjusted according to the run sequence in Table 4, while all remaining boundary conditions defined during the vehicle setup and measurement setup phases were kept constant. Each DoE point consisted of four consecutive WLTCs driven with only short breaks for reconditioning the temperature. Background measurements were performed prior to each measurement sequence to ensure stable measurement conditions and response correction of particle concentration. After completion of the measurements, the recorded data were processed according to the post-processing phase of the DLR TRWP methodology and subsequently used for the DoE-based statistical evaluation. WLTC 1 served as a conditioning cycle to establish a repeatable thermal state of the tire; WLTC 2–4 are repeated measurements within the same DoE point and not independent replicates (Section 2.6).

2.5. Data Processing, Response Definition and Data-Quality Criteria

The processing workflow comprised synchronization of the individual measurement signals, correction of background particle concentrations for MCPC, summation of the concentrations over the cycle, and calculation of the OPS mass proxy (Section 2.3).

To ensure consistency throughout the evaluation, identical processing steps were applied to all experiments performed during both phases. Background concentrations were determined before each measurement sequence and subsequently subtracted from the recorded MCPC particle concentrations. For each WLTC, the response is the cumulative concentration Φ , i.e., the sum of the background-corrected concentrations recorded at 1 Hz over the evaluation interval of 1800 s; therefore, it has the unit of a concentration ($\#/cm^3$ for particle number and $\mu g/m^3$ for the OPS mass proxy) and is numerically equal to 1800 times the cycle-averaged concentration. The cumulative concentration Φ is a measurement response and not an emitted quantity; an emitted particle number would additionally require the extraction volume flow, the sampling interval, any dilution and the size-dependent collection and transport efficiency. Since the extraction flow, the sampling rate and the sampling configuration were identical for all DoE points, these quantities are constant, and ratios between DoE points are identical to ratios of the cycle-averaged concentrations. Cumulative concentration is therefore used only for the relative comparison of test conditions, and no emission factors are derived. The three response variables are the cumulative MCPC number concentration (MCPC-PN), the cumulative OPS number concentration (OPS-PN) and the cumulative OPS mass proxy ($m_{OPS,2.5}$, $m_{OPS,10}$). The OPS mass proxy (Section 2.3) was summed in the same way. Representative processing outputs are shown in Sections 3.2 and 3.3. For each DoE point, the responses of WLTC 2–4 were averaged before the statistical analysis (Section 2.6).

The following predefined criteria were applied; they relate to instrument validity and test conditions rather than to the magnitude of the response: (i) MCPC and OPS concentrations below the instrument limits of $1 \times 10^5 \#/cm^3$ and $3000 \#/cm^3$, respectively, without instrument error flags; (ii) chamber temperature within $\pm 1^\circ C$ of the set point and inflation pressure adjusted to the nominal value before each DoE point; (iii) stable tread-temperature development over WLTC 2–4. WLTC 1 was excluded by design as a conditioning cycle. Apart from this conditioning cycle, no WLTC of the factorial phase was excluded. The screening-phase measurements were used only to define the operating window (Section 2.4, Step 3).

2.6. Statistical Analysis

The experimental unit was the DoE point, defined as one uninterrupted sequence of four WLTCs at a fixed combination of inflation pressure, chamber temperature, and toe setting. WLTCs 2–4 were treated as repeated measurements within the same DoE point and were averaged before the statistical analysis.

For each response, the natural logarithm of the DoE-point mean was analyzed using a model that included the overall response level, the experimental block, inflation pressure, chamber temperature, the pressure–temperature interaction, and the remaining unexplained variation. Pressure and temperature were coded as low (−1) and high (+1) levels. The block term represents the two sequential toe settings (48' first and 30' second). Each pressure–temperature combination was tested once in each block. Therefore, the residual error represents the variation between the two realizations of the pressure–temperature treatments that is not explained by the overall block effect. This provides three residual degrees of freedom. A logarithmic scale was used because the variability within a DoE point increased approximately in proportion to the mean response. Factor effects are therefore reported as ratios between the responses at the high and low factor levels, together with

95% confidence intervals and exact p -values. The estimated effects are also presented as Pareto charts, including the critical effect corresponding to $\alpha = 0.05$.

Because the experimental design was balanced, analyzing the averaged DoE-point values is equivalent, for testing the factor effects, to a nested analysis in which WLTCs 2–4 are treated as subsamples within each DoE point.

For MCPC-PN, an additional sensitivity analysis was performed to evaluate the possible influence of campaign drift. Each DoE-point mean was divided by the drift factor $2^{(\text{distance}/\text{distance_ref})}$ where distance is the accumulated WLTC driving distance from the start of DoE 1 to the start of the respective DoE point, and distance_ref = 838 km is the distance between the start of DoE 1 and the start of DoE 10. This represents a log-linear increase from a drift factor of 1 at the beginning of the campaign to a factor of 2 at the start of DoE 10, corresponding to the approximately two-fold change observed between the reference measurements (Section 3.6).

The OPS mass proxy was available only for the toe-30' block. Since this provides only one realization of each pressure–temperature combination, no independent error term was available and the corresponding effects are therefore reported descriptively (Section 3.4). Effects were considered statistically significant at $\alpha = 0.05$. All calculations were performed in Python 3.12 using the statsmodels package.

3. Results

The results are presented following the research tasks. Section 3.1 describes the screening phase that defined the operating window (T1). Section 3.2 shows the driving-cycle-resolved particle response. Sections 3.3–3.5 quantify the effects of chamber temperature and inflation pressure on the cumulative MCPC number concentration (MCPC-PN), the cumulative OPS number concentration (OPS-PN) and the cumulative OPS mass proxy (T2). Section 3.6 evaluates within-point repeatability and campaign drift (T3).

3.1. Operating Window: Wheel-Alignment Screening (T1)

The experimental program comprised two sequential phases with distinct methodological roles as explained in Section 2.4 (step 3). During the first phase, pronounced deviations from repeatable particle response behavior were observed at toe settings above 48'. These deviations were characterized by unusual high particle number concentrations and visible changes in the tire tread surface, indicating non-representative wear conditions as shown in Figure 3. The corresponding measurements were therefore not included in the statistical evaluation, but were used to identify unsuitable operating conditions and refine the experimental boundary limits. The dataset used for the statistical evaluation was obtained during the second phase, following refinement of the experimental operating range in the first phase.

3.2. Driving-Cycle-Resolved Particle Response

Time-resolved particle number concentrations measured by the MCPC exhibited characteristic variations throughout the WLTC driving cycle. Independent of the investigated operating conditions, PNC closely followed the characteristics of the driving cycle, as shown in Figure 4. Elevated concentrations were primarily observed during phases of high acceleration, high deceleration, and higher vehicle speeds (Figure 4 between 1550 and 1650 s), whereas the PNC returned towards the baseline during non-generating phases such as vehicle standstill (Figure 4 between 1000 and 1050 s). The temporal evolution of the PNC signal demonstrates that the response is not constant over the cycle but is concentrated in specific driving phases, particularly during dynamic sections of the WLTC. The two conditions shown differ in inflation pressure, chamber temperature and toe block;

their magnitudes are therefore not compared here, and factor effects are evaluated in Sections 3.3–3.5.

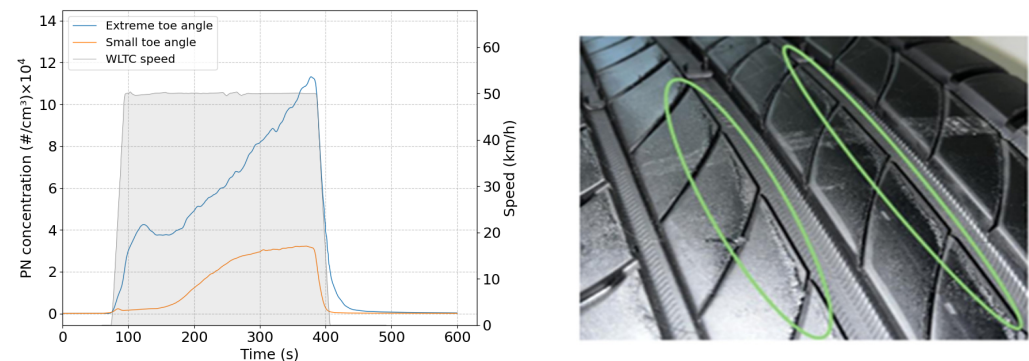


Figure 3. (Left) Example of unusually high MCPC particle number concentration observed during the boundary-condition screening phase. At the smaller toe setting, the PNC approached a plateau, whereas at a toe setting above 48' it continued to increase, reaching up to five times the baseline level and indicating unstable wear behavior. (Right) Visible tread-surface changes observed under unsuitable wheel alignment conditions.

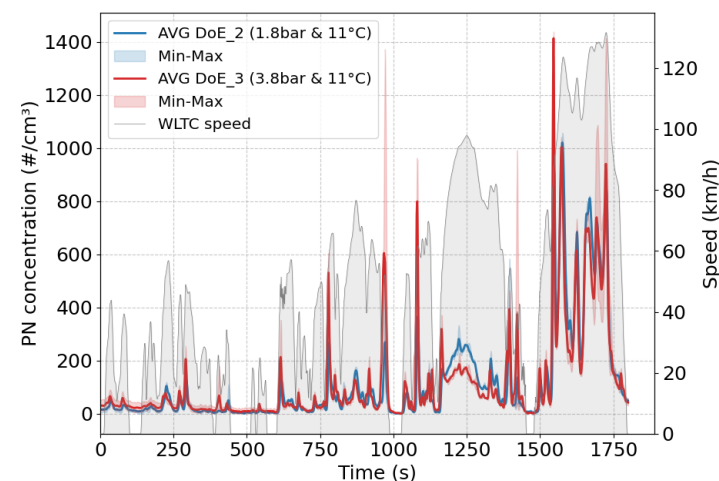


Figure 4. Time-resolved MCPC PNC profiles over the WLTC driving cycle for repeated measurements under selected DoE conditions (DoE 5 and DoE 6). DoE 5, 3.8 bar, 35 °C, toe 30'; DoE 6, 1.8 bar, 11 °C, toe 48'. The gray curve indicates the WLTC speed profile.

Following background correction, cumulative particle number concentrations were calculated by summing the corrected time-resolved concentration profiles over the complete driving cycle. Figure 5 shows an example of corrected MCPC-PN concentration profiles after application of the background correction procedure.

The transformation from time-resolved PN concentration to cumulative PN concentration reduces the visibility of short-duration peaks while retaining their contribution to the cumulative cycle response, thereby allowing the comparison of the overall response between repeated measurements and experimental conditions. The cumulative curves show that the largest contribution to MCPC-PN occurred during the later dynamic section of the WLTC, where the concentration profiles exhibited their strongest transient peaks. The final cumulative value at the end of the driving cycle was used as the particle number response variable for the subsequent DoE-based statistical evaluation.

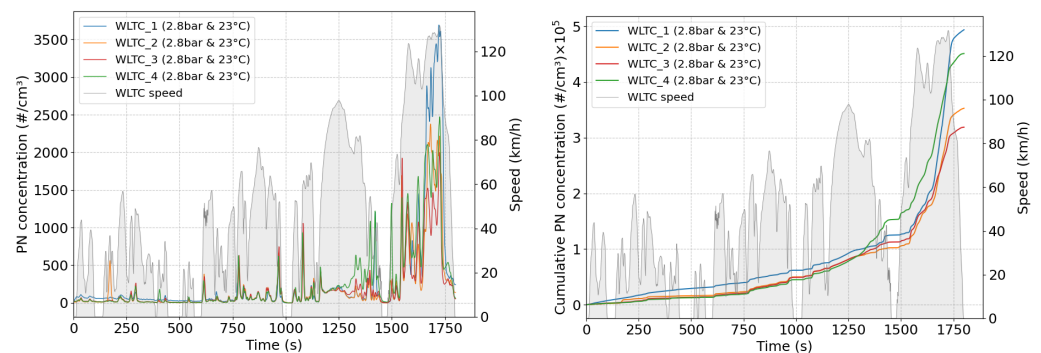


Figure 5. Transformation of time-resolved MCPC-PN concentration profiles into cumulative particle number response variables. **(Left)** panel shows the transient PN concentration profiles together with the WLTC speed profile; **(right)** panel shows the corresponding cumulative PN concentration curves used for statistical evaluation.

3.3. Effects of Chamber Temperature and Inflation Pressure on Particle Number (T2)

Representative cumulative PN responses measured by the MCPC and OPS are shown in Figures 6 and 8 for DoE points 2 to 5. These conditions allow the effects of tire inflation pressure and chamber temperature to be compared at the same rear-wheel toe setting of 30°. The corresponding points of the toe-48° block (DoE 6–9) showed the same qualitative behavior; both blocks enter the statistical evaluation in Section 3.5.

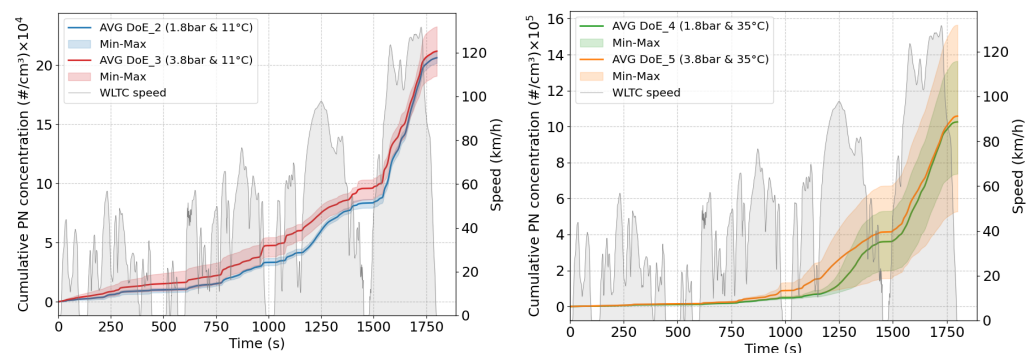


Figure 6. Representative cumulative MCPC PN profiles for selected DoE conditions **(left)**. DoE2 blue, DoE3 red, MCPC, **(right)** DoE4 green, DoE5 orange. The curves are shown together with the WLTC speed profile and illustrate the influence of the investigated operating parameters on the cumulative MCPC-PN response over the driving cycle.

In the MCPC measurements (Figure 6), the responses at 11 °C remained comparatively close across repeated measurements, with a separation between the 1.8 and 3.8 bar conditions. At 35 °C, substantially steeper increases and higher final response values were observed, particularly during the later dynamic sections of the WLTC. These observations indicate a pronounced temperature-related change in the response, accompanied by reduced repeatability at higher chamber temperatures. A consistent pressure-related ordering was not visible in the measurements. At 11 °C, the 3.8 bar condition tended to show slightly higher MCPC-PN than the 1.8 bar condition, whereas at 35 °C (Figure 6 right) the variability increased markedly, showing no clear separation between the two pressure levels.

SEM images (Figure 7) of ELPI stage 9 provided complementary qualitative evidence for the temperature-related difference observed in MCPC-PN. The substrate collected at 35 °C showed visibly greater particle coverage than that collected at 11 °C under identical sampling conditions. As only one substrate per condition was analyzed and no particle counting was performed, the comparison is qualitative only.

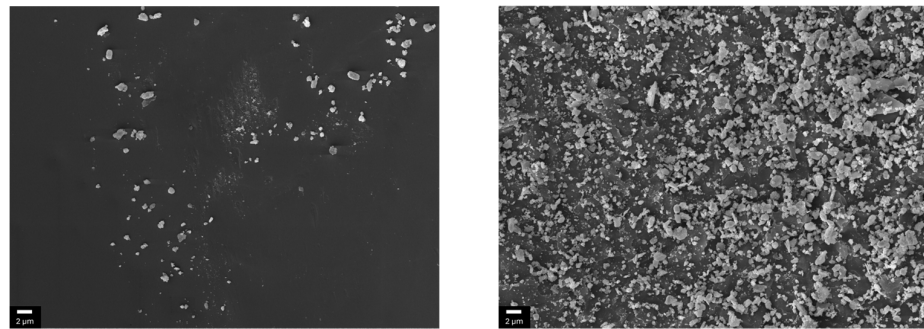


Figure 7. SEM analysis of collected particles by ELPI Stage 9 (nominal aerodynamic $D_{50} \approx 0.60 \mu\text{m}$); (left) DoE 2 11 °C, (right) DoE 4 35 °C. Magnification 2000 $\times$; identical sampling duration.

In the OPS measurements (Figure 8), the influence of tire inflation pressure was more visible. At high-level and low-level chamber temperatures, the 1.8 bar condition generally produced higher OPS-PN responses than the corresponding 3.8 bar condition. The separation was consistent at 35 °C, where the lower-pressure curves remained generally above the higher-pressure curves over the later part of the WLTC. In contrast to the MCPC results, changing the chamber temperature did not produce a consistent systematic shift in the OPS-PN response. At a given pressure level, the cumulative curves at 11 and 35 °C showed overlapping ranges, indicating that the temperature-related change was less clearly distinguishable from experimental variability in the OPS measurement range.

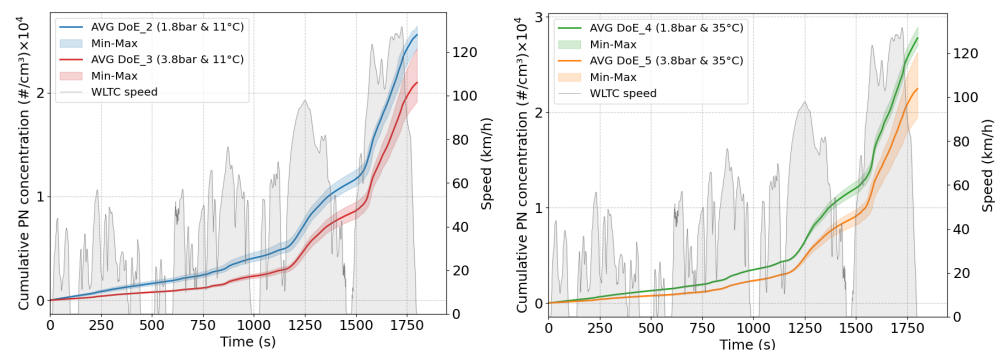


Figure 8. Representative cumulative OPS particle number concentration profiles for selected DoE conditions shown together with the WLTC speed profile. (left) OPS cumulative PN for DoE2 (blue) and DoE3 (red); (right) OPS cumulative PN for DoE4 (green) and DoE5 (orange).

Changes in pressure result in more pronounced differences in the measured particle concentrations, indicating a possible effect on the particle formation mechanisms of coarse particles. The pressure-related response is therefore more readily distinguishable from measurement variability than the temperature-related response. Nevertheless, the statistical analysis is required to confirm the significance and magnitude of these effects.

Overall, the visual comparison shows that the investigated operating parameters were reflected differently in the two particle number instruments. Chamber temperature was associated with a pronounced increase in the MCPC response and its variability, whereas tire inflation pressure was more clearly reflected in the OPS response. The magnitude and statistical significance of these effects are evaluated quantitatively in Section 3.5.

3.4. Effects on the OPS-Derived Mass Proxy (T_2)

Representative cumulative OPS mass proxies $m_{\text{OPS},10}$ and $m_{\text{OPS},2.5}$ for DoE2–DoE5 are shown in Figure 9. All four conditions were evaluated at the same rear-wheel toe setting of 30', allowing the effects of chamber temperature and tire inflation pressure to be compared directly. WLTC 1 is shown for completeness but is not used in the statistical analysis.

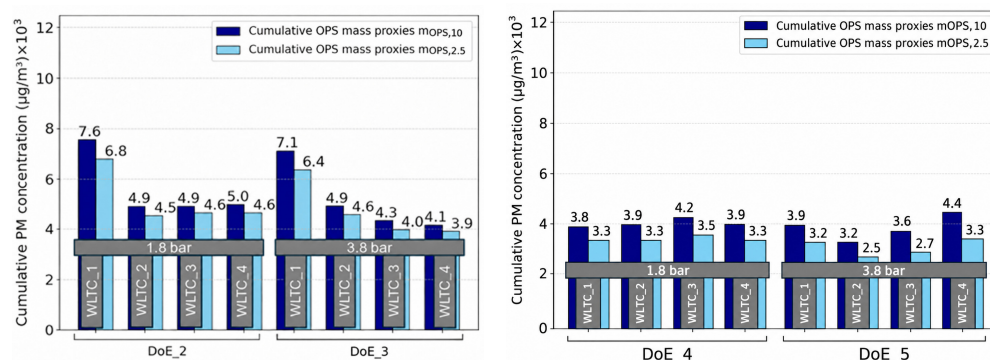


Figure 9. Representative cumulative OPS mass proxies $m_{OPS,10}$ and $m_{OPS,2,5}$ for DoE2 and DoE3 at 11 °C (left) and DoE4 and DoE5 at 35 °C (right). Grouped bars illustrate the influence of tire inflation pressure and DoE conditions on the mass proxy.

As shown in Figure 9 and Table 5, the mean OPS mass proxy response was consistently higher at 11 °C than at 35 °C. At 1.8 bar, increasing the chamber temperature from 11 to 35 °C reduced the $m_{OPS,10}$ from approximately 4.93 to 4.00 [$\times 10^3 \mu\text{g}/\text{m}^3$] and the $m_{OPS,2,5}$ from approximately 4.57 to 3.37 [$\times 10^3 \mu\text{g}/\text{m}^3$]. A similar temperature-related decrease was observed at 3.8 bar. Tire inflation pressure produced a smaller but directionally consistent change: at both temperature levels, the 3.8 bar condition generally showed lower mass-proxy values than the corresponding 1.8 bar condition. Thus, within the investigated parameter range, increasing both chamber temperature and tire inflation pressure tended to reduce the mass proxy.

Table 5. Mean, coefficient of variation (CV) and ratio $m_{OPS,2,5}/m_{OPS,10}$ of the cumulative OPS mass proxy (WLTC 2–4; means in $10^3 \mu\text{g}/\text{m}^3$; toe 30').

DoE	Condition	Mean $m_{OPS,10}$	CV $m_{OPS,10}$	Mean $m_{OPS,2,5}$	CV $m_{OPS,2,5}$	$m_{OPS,2,5}/m_{OPS,10}$
DoE2	11 °C, 1.8 bar	4.93	~1.2%	4.57	~1.3%	0.926
DoE3	11 °C, 3.8 bar	4.43	~9.4%	4.17	~9.1%	0.940
DoE4	35 °C, 1.8 bar	4.00	~4.3%	3.37	~3.4%	0.842
DoE5	35 °C, 3.8 bar	3.73	~16.4%	2.83	~14.7%	0.759

The repeated WLTC measurements additionally revealed differences in within-condition variability. As seen in Figure 9, at 11 °C, the first WLTC showed substantially higher mass responses than the subsequent repetitions for both pressure conditions, whereas WLTC2–WLTC4 were considerably more stable, particularly for DoE2. Within-point CVs were lower at 11 °C and 1.8 bar than at 35 °C and 3.8 bar (Table 5); with three cycles per point, these differences are indicative only.

Comparison of $m_{OPS,2,5}$ with $m_{OPS,10}$ provides additional information on the mass distribution within the OPS measurement range. Increasing chamber temperature clearly reduced the $m_{OPS,2,5}/m_{OPS,10}$ ratio in both pressure conditions. At 1.8 bar, the ratio decreased from 0.93 to 0.84, while at 3.8 bar it decreased from 0.94 to 0.76. In contrast, the effect of tire inflation pressure was small at 11 °C but became more pronounced at 35 °C. Thus, although the total OPS-derived mass was lower at the elevated temperature, the relative contribution of the 2.5–10 μm size range increased. The results therefore do not support a simple interpretation that lower temperature merely produced a coarser particle population.

The mass response should consequently be interpreted together with the corresponding OPS-PN results as in Section 3.3. Tire inflation pressure showed a consistent direction

in both metrics, with the lower-pressure condition generally producing higher OPS-PN and mass-proxy responses potentially due to a larger contact patch, more mechanical friction and therefore more coarse particles. In contrast, chamber temperature produced only a weak separation in OPS-PN while producing a pronounced decrease in OPS-derived mass. This divergence suggests a temperature-related modification of the size-weighted aerosol response rather than a change in particle number alone. Confirmation of a particle-size shift, however, requires evaluation of the size-resolved OPS distributions rather than the mass proxy alone.

3.5. Factorial Effect Estimates (T2)

Table 6 summarizes the effect estimates of the block model (Section 2.6) for MCPC-PN and OPS-PN, and Figures 10 and 11 show the corresponding Pareto charts. Both toe blocks enter the analysis; the error term has three degrees of freedom.

Table 6. Effects of inflation pressure (p), chamber temperature (T_{ch}) and their interaction on the cumulative MCPC-PN and OPS-PN (block model on log-transformed DoE-point means; ratio = response at the high level divided by the response at the low level; F with 1 and 3 degrees of freedom; drift-normalized analysis for MCPC-PN, see Section 2.6).

Response	Term	Ratio	95% CI	F	p	p (Drift-Normalized)
MCPC-PN	p	1.08	0.54–2.17	0.12	0.747	0.749
MCPC-PN	T_{ch}	3.59	1.79–7.20	34.0	0.010	0.012
MCPC-PN	$p \cdot T_{ch}$	1.20	0.60–2.41	0.70	0.464	0.464
OPS-PN	p	0.82	0.76–0.88	78.4	0.003	–
OPS-PN	T_{ch}	1.12	1.04–1.20	24.3	0.016	–
OPS-PN	$p \cdot T_{ch}$	0.98	0.91–1.05	0.93	0.407	–

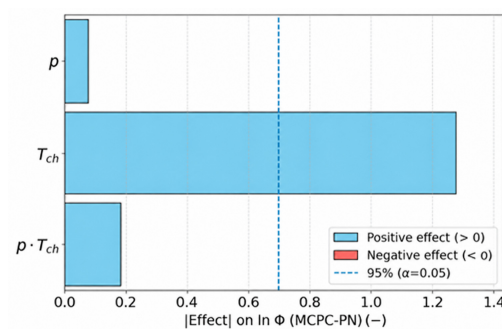


Figure 10. Pareto diagram of the effects on cumulative MCPC-PN. The bars show effects of tire inflation pressure (p), chamber temperature (T_{ch}), and their interaction. The dashed line indicates the critical value for $\alpha = 0.05$ (t-distribution, three degrees of freedom).

For MCPC-PN (Figure 10), chamber temperature exhibited by far the largest effect (ratio 3.6, 95% CI 1.8–7.2, $p = 0.010$) and was the only significant term. After normalization for campaign drift, the temperature effect remained significant (ratio 3.3, 95% CI 1.7–6.7, $p = 0.012$). The effect was positive, indicating that increasing chamber temperature increased the MCPC-PN response. Tire inflation pressure and the temperature–pressure interaction were not significant ($p = 0.75$ and $p = 0.46$).

For cumulative OPS-PN (Figure 11), a different pattern was observed. Here, tire inflation pressure showed the largest effect and was significant (ratio 0.82, 95% CI 0.76–0.88, $p = 0.003$), with a negative sign indicating that increasing tire inflation pressure reduced the OPS-PN. Chamber temperature showed a smaller positive effect (ratio 1.12,

95% CI 1.04–1.20, $p = 0.016$), which was also significant but small compared with the pressure effect. The interaction term was not significant ($p = 0.41$).

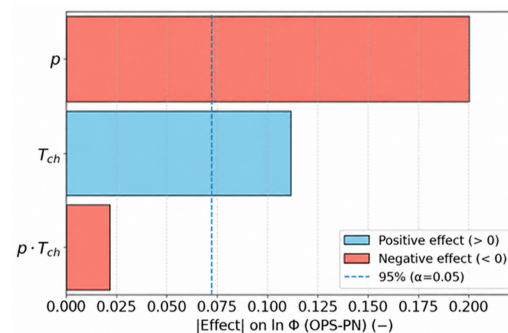


Figure 11. Pareto diagrams of the effects on cumulative OPS-PN. The bars show positive and negative effects of tire inflation pressure (p), chamber temperature (T_{ch}), and their interaction ($p \cdot T_{ch}$). The dashed line indicates the critical value for $\alpha = 0.05$.

The OPS mass proxy was evaluated for the toe-30' block only (Table 5). With a single realization of each condition, no error term is available for this response, and its effects are therefore reported descriptively. Averaged over both pressure levels, increasing the chamber temperature from 11 to 35 °C reduced $m_{OPS,10}$ by approximately 17% and $m_{OPS,2.5}$ by approximately 29%. Increasing the inflation pressure from 1.8 to 3.8 bar reduced $m_{OPS,10}$ by approximately 8% and $m_{OPS,2.5}$ by approximately 12%, in the same direction as the significant pressure effect on OPS-PN.

Overall, the statistical evaluation demonstrates that the experimentally varied parameters did not affect all particle metrics in the same way. Chamber temperature was the dominant factor for MCPC-PN and the OPS mass proxy, but with opposite directions for these two response variables, whereas inflation pressure was the dominant factor for OPS-PN. The factorial design therefore enabled both the dominant influencing parameters and the metric-dependent direction of their effects to be identified under controlled laboratory conditions.

Because the error term has three degrees of freedom, only large effects can be detected: at 80% power, the minimum detectable ratio is approximately 2.5 for MCPC-PN and 1.10 for OPS-PN. Non-significant terms, including all interactions, therefore do not demonstrate the absence of an effect.

The pressure–temperature interaction ($p \cdot T_{ch}$ in Figures 10 and 11 and Table 7) was not significant for MCPC-PN or OPS-PN.

Table 7. DoE-point means of the cumulative MCPC-PN and OPS-PN responses (mean of WLTC 2–4) used in the factorial analysis, in chronological order.

DoE	Block (toe)	Tire Pressure (bar)	Chamber Temperature (°C)	MCPC-PN ($10^5 \text{ \#}/\text{cm}^3$)	OPS-PN ($10^3 \text{ \#}/\text{cm}^3$)	Run Order
DoE 6	1 (48')	1.8	11	2.48	26.0	2
DoE 8	1 (48')	1.8	35	4.44	31.3	3
DoE 7	1 (48')	3.8	11	1.95	22.2	4
DoE 9	1 (48')	3.8	35	7.25	24.8	5
DoE 2	2 (30')	1.8	11	2.06	25.6	6
DoE 4	2 (30')	1.8	35	10.26	27.8	7
DoE 3	2 (30')	3.8	11	2.12	21.0	8
DoE 5	2 (30')	3.8	35	10.58	22.5	9

The interaction contribution remained small for all evaluated response variables, whereas the relative importance of the main effects differed substantially between MCPC-PN, OPS-PN, and OPS mass proxy. Within the investigated factor ranges, the statistically detectable response differences were therefore governed primarily by the main effects rather than by temperature–pressure interactions, within the resolution limits stated above.

3.6. Repeatability and Campaign Drift (T3)

This section evaluates how the investigated operating conditions influenced the repeatability of the DLR TRWP-Measurement System. Within-point repeatability was assessed from WLTC 2–4 of each DoE point using the final cumulative MCPC-PN and OPS-PN responses. The DoE-point means used in the factorial analysis are listed in Table 7, while Figures 12 and 13 show the corresponding distributions over the chronological measurement campaign. The toe-48' block (DoE 6–9) was measured before the toe-30' block (DoE 2–5).

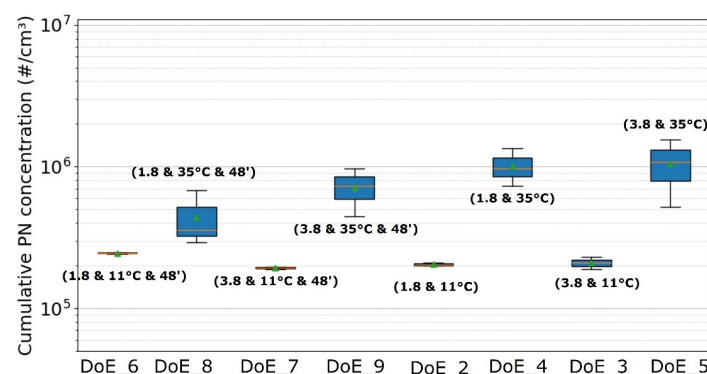


Figure 12. MCPC-PN repeatability evaluation based on box plots of cumulative particle number concentration during the optimized measurement campaign.

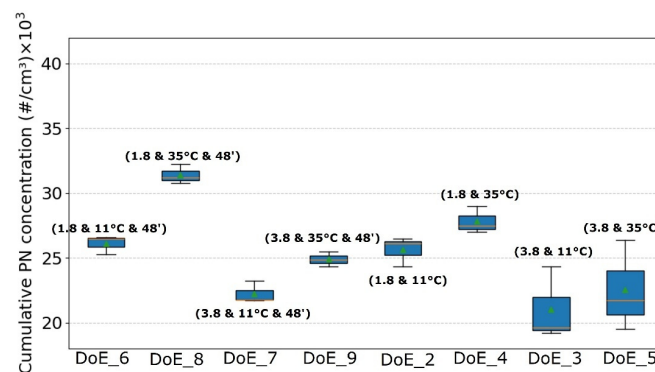


Figure 13. OPS-PN repeatability evaluation based on box plots of cumulative PN concentration during the optimized measurement campaign. The repeated measurements show sufficient stability for statistical comparison, while variability increased for selected operating conditions and later measurement points.

The MCPC results in Figure 12 demonstrate that repeatability depended strongly on the investigated operating condition. The low-temperature DoE points were characterized by comparatively tightly grouped repeated responses, with cumulative values remaining close to approximately $2 \times 10^5 \text{ \#/cm}^3$ for DoE2, DoE3, DoE6, and DoE7. In contrast, the 35 °C conditions produced both higher MCPC responses and substantially greater between-run variability. This effect was already visible in the toe-48' block (measured first), where DoE8 showed a range of $\approx 2.9\text{--}5.0 \times 10^5 \text{ \#/cm}^3$ and DoE9 $\approx 5.0\text{--}9.5 \times 10^5 \text{ \#/cm}^3$. The spread became even more pronounced for selected conditions in the subsequent toe-30' block. DoE4

was centered close to $\approx 1.0 \times 10^6 \text{ \#/cm}^3$, while DoE5 extended from a $\approx 0.5\text{--}1.4 \times 10^6 \text{ \#/cm}^3$. These observations are consistent with Section 3.5, where chamber temperature was identified as the dominant statistically significant factor for MCPC-PN and the elevated-temperature conditions were accompanied by increased between-repetition variability.

The OPS response showed a different repeatability pattern (Figure 13). Across the campaign, the cumulative OPS-PN responses remained within a substantially narrower absolute range of $20\text{--}30 \times 10^3 \text{ \#/cm}^3$. DoE2, DoE4, and the majority of the toe-48' conditions exhibited closely grouped repetitions. Larger spreads were nevertheless visible for selected points, particularly DoE3, which extended from 19×10^3 to $24 \times 10^3 \text{ \#/cm}^3$, and DoE5, which extended from 19×10^3 to $26.5 \times 10^3 \text{ \#/cm}^3$. The comparison therefore demonstrates that repeatability was response-metric dependent: the MCPC response was considerably more sensitive to conditions associated with elevated small-particle concentrations, whereas the OPS response remained comparatively less dispersed over most of the campaign. This difference is consistent with the distinct temperature and pressure sensitivities identified for MCPC-PN and OPS-PN in the statistical evaluation.

To assess longer-term evolution independently of the factorial conditions, identical reference measurements were performed before and after the campaign (DoE1 and DoE10; Figure 14) at 2.8 bar, 23 °C, and at toe 30'. The start-of-campaign reference measurements reached MCPC-PN responses of $\approx 1.6\text{--}2.2 \times 10^5 \text{ \#/cm}^3$, whereas the corresponding end-of-campaign measurements reached $\approx 3.1\text{--}4.9 \times 10^5 \text{ \#/cm}^3$ (Figure 14 right). The mean response therefore increased by approximately a factor of two with increased spread between repeated measurements, over an accumulated WLTC distance of approximately 840 km.

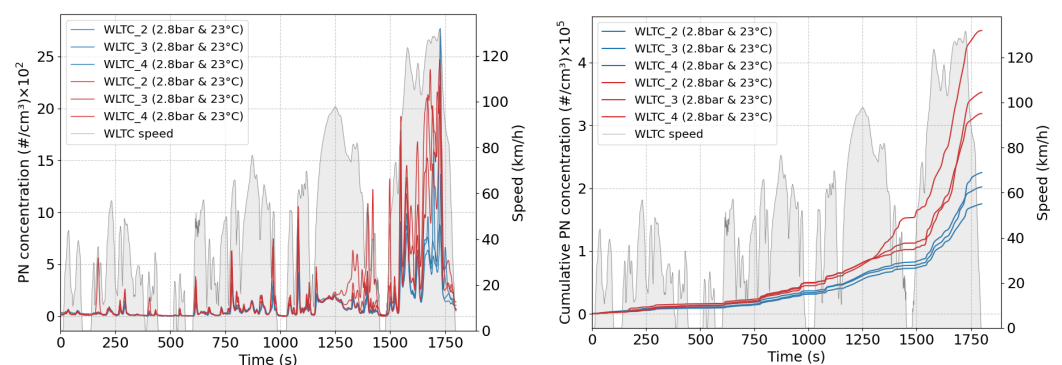


Figure 14. Reference measurements of DoE1 (blue) and DoE10 (red) MCPC, (left) PN concentration, (right) cumulative PN concentration.

This trend indicates an additional contribution from campaign-dependent processes such as accumulated tire mileage, evolution of the tread and tire-roller interface, thermal history, particle deposition or resuspension within the measurement system, or other time-dependent experimental effects. The reference measurements are therefore essential for distinguishing short-term within-point repeatability from longer-term campaign stability.

Overall, the results show that the DLR TRWP-Measurement System can provide sufficiently repeatable particle responses for statistical factor evaluation once suitable experimental boundary conditions are established, but repeatability is strongly dependent on both the operating condition and the selected particle metric.

4. Discussion

The findings demonstrate that statistically planned experimentation provides a structured framework for identifying dominant influencing factors, quantifying their relative importance, and defining operational boundaries for reliable airborne TRWP measurements.

Unlike studies primarily aimed at comparing tire types or driving conditions [13,39–41], the present work emphasizes the characterization of the measurement methodology itself. This distinction is particularly relevant because repeatable and reliable laboratory measurements constitute a prerequisite for meaningful comparison between different tire concepts and for the development of future standardized test procedures.

4.1. Interpretation of Temperature and Pressure Effects (T2)

The operating parameters chamber temperature and tire inflation pressure showed distinct effects on the measured airborne TRWP responses. Their influence differed depending on the particle metric considered, consistent with the response-specific factor effects identified in the ANOVA and Pareto analysis in Section 3.5.

As shown in Figure 10 for MCPC-PN, which measures total particle-number concentration from 7 nm to 2 μm , chamber temperature exhibited a statistically significant effect. Increasing chamber temperature led to higher MCPC-PN indicating that thermal boundary conditions strongly affected the measured small airborne particle response, although the present measurements cannot distinguish between changes in particle generation, airborne release, transport, agglomeration, condensation and volatile or semi-volatile particle formation mechanisms. This behavior is plausible from a tribological perspective, as tire rubber exhibits temperature-dependent viscoelastic properties. Higher temperatures result directly in higher tread temperature which can modify tread deformation, local frictional behavior, and wear mechanisms within the tire–roller interaction, potentially altering both particle generation and the size distribution of the released aerosol [13,14,40,41]. In contrast, tire inflation pressure showed a considerably weaker influence on the MCPC response within the investigated pressure range, suggesting that pressure-induced changes in contact mechanics had only limited impact on the ultrafine particle fraction measured by the MCPC.

In contrast, the PN measurements in the fine and coarse fraction (OPS measurements, from 0.3 to 10 μm) showed a different response pattern. While chamber temperature also influenced the OPS-PN response, tire inflation pressure became more relevant with an opposite effect compared to MCPC. Variations in tire inflation pressure alter the contact area, contact pressure distribution, and local tread deformation, which can affect the abrasion process and the resulting particle size distribution [13]. Lower tire pressure increases tire deformation and enlarges the contact patch, which can increase rolling resistance, tread block movement, and shear stresses in the tire–road contact area. Higher tire pressure reduces the contact-patch area and tire deformation, but increases the local contact pressure, particularly near the center of the tread. This can shift wear towards the center of the tire and may also change the particle size distribution of emitted tire wear particles. These mechanisms suggest that the relationship between inflation pressure and tire wear may not be linear over a broader pressure range; however, the present two-level design evaluates only the directional response between 1.8 and 3.8 bar. The stronger and statistically significant pressure response in OPS-PN, compared with the small non-significant MCPC pressure effect, indicates that the pressure-related response was more clearly expressed within the OPS optical measurement range. Differences in instrument size sensitivity and measurement principle should, however, be considered when interpreting this contrast.

Since the aerosol instruments were located inside the climate chamber, all concentrations refer to chamber conditions. Normalized to a common reference temperature, the concentrations at 35 °C would increase by approximately 8% relative to those at 11 °C (308 K/284 K). This correction would slightly enlarge the positive temperature effects

on MCPC-PN and OPS-PN and does not change any of the conclusions. Given its small magnitude, the temperature effect on OPS-PN is not interpreted mechanistically.

For the OPS mass proxy, the interpretation differs again because it is strongly weighted by particle diameter (mass $\sim$ diameter³). Even small shifts in the particle size distribution can therefore lead to pronounced changes in the calculated mass response. The Pareto charts show that the investigated operating parameters did not affect all particle metrics in the same way, but instead influenced different fractions of the airborne TRWP. In particular, increasing temperature produced a strong positive effect on MCPC-PN but a significant negative effect on the OPS mass proxy, while the OPS-PN temperature effect remained comparatively small. This divergence indicates that temperature altered the size-weighted aerosol response and the direction of any underlying particle size distribution needs to be investigated more. The OPS mass proxy showed the same negative direction, but the effect remained below the significance threshold. Thus, the pressure-related response was more clearly expressed in particle number than in the calculated mass within the OPS range.

The different behavior of MCPC-PN, OPS-PN, and OPS mass proxy also indicates that the measured aerosol should not be interpreted as a single homogeneous particle fraction. The MCPC response includes very small particles that are not captured by the OPS, while the OPS mass proxy response is dominated by larger particles within the optically detectable size range. If no thermal conditioning is applied, the measured PN should be interpreted as total particle number rather than solid particle number. In this study, preliminary measurements and separate experiments with a catalytic stripper confirmed the presence of a volatile contribution to the measured particle-number signal [15]. Such particles may originate from volatilization or degassing of tire constituents or from thermo-mechanical processes occurring at the tire-roller interface [11]. Therefore, the strong positive temperature response observed by the MCPC cannot be attributed exclusively to an increase in solid wear-particle generation. This distinction is important because volatile or semi-volatile particle formation, nucleation processes, or organic aerosol components may contribute to the small-particle signal and can partly decouple PN trends from OPS mass proxy trends.

4.2. Wheel Alignment as Operating Boundary (T1)

Wheel alignment differed fundamentally from the other investigated parameters because its influence extended beyond changes in particle emission magnitude. During the initial boundary-condition assessment, the increased toe setting was associated with strongly elevated and unstable particle responses together with visible alterations of the tire tread surface. These observations indicated that the investigated operating conditions exceeded the range in which representative airborne TRWP measurements can be obtained. Therefore, wheel alignment was used to define the operational boundary of the measurement configuration. In the factorial phase, only toe 30' and 48' were used, and the toe was treated as a blocking variable; since it is confounded with campaign time, its effect on the particle response cannot be separated from drift.

4.3. Campaign Drift, Thermal Control and Consequences for Factorial Test Design (T3)

The assessment of measurement repeatability and variability provides the basis for deriving the operational limits of the experimental methodology. Following refinement of the alignment settings, the second measurement phase provided sufficiently stable conditions for statistical evaluation, although repeatability remained dependent on the investigated operating condition. The results should therefore be interpreted primarily in a relative manner, i.e., as differences between controlled laboratory conditions within the applied DoE framework, rather than deducing absolute emission factors. This distinction is

important because the objective of the study was not to derive regulatory tire wear emission factors, but to evaluate the robustness, sensitivity, and applicable operating range of the DLR TRWP-Measurement System.

The reference response approximately doubled over approximately 840 km of WLTC driving (Section 3.6). For factorial TRWP studies, this has a direct consequence: consecutive cycles within one setup quantify short-term repeatability, but not the variability between realizations of the same condition, which in this campaign was dominated by campaign time. Using the within-point scatter as an error term would therefore overstate the precision of factor effects. Future designs should (i) randomize the run order within blocks of hard-to-change factors, (ii) interleave reference points at least once per block, so that drift can be modeled rather than interpolated, and (iii) replicate complete setups rather than cycles. The present analysis, which uses the between-block variability as an error term, shows that the principal temperature and pressure effects remain detectable under these conditions.

The outcome illustrates an important methodological aspect of laboratory TRWP investigations. Experimental boundary conditions must first provide sufficiently stable and repeatable tire–roller interactions and particle measurement responses before individual influencing parameters can be evaluated quantitatively. In this study the benefit of the present approach is that it allows the operating limits of the measurement methodology to be identified. Within this study, elevated chamber temperature was found to increase measurement variability, particularly at 35 °C, as shown in Figure 15. This indicates that future investigations should define an acceptable variability range for thermal boundary conditions and implement measures to control temperature-related effects more strictly. Such measures may include longer cooling periods between driving cycles, improved thermal conditioning of the tire, continuous monitoring of the inner tread temperature, and stricter criteria for restarting a measurement only after the tire has returned to a defined thermal state.

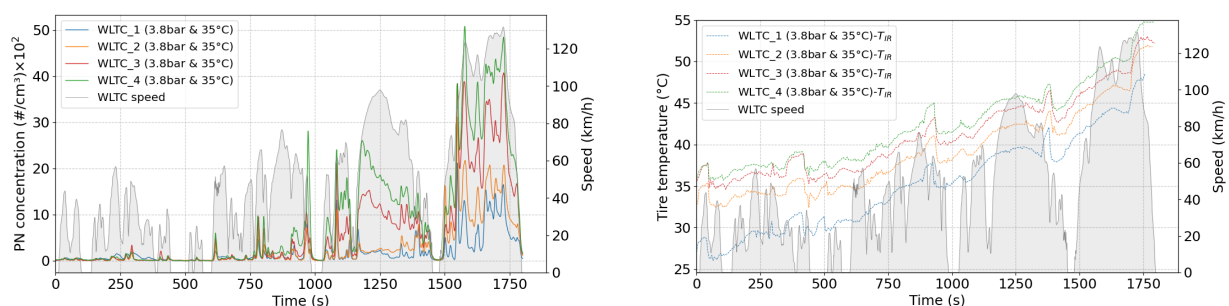


Figure 15. (Left) MCPC particle number concentration and (right) tire tread temperature profiles during a measurement point conducted at elevated chamber temperature.

Under the reference setup, as shown in Figure 13, repeated WLTCs produced closely comparable tread-temperature trajectories, with the temperature increasing from approximately 30–33 °C at cycle start to approximately 49–50 °C at the end of the WLTC. This indicates repeatability of the thermal history rather than a constant tire temperature. In the selected elevated-temperature example shown in Figure 16, greater divergence was observed between repeated tread-temperature trajectories, while the corresponding MCPC-PN signals exhibited substantially larger between-run differences. The particle response varied more strongly than the tread-temperature trajectories themselves, indicating increased sensitivity of the measurement response under this operating condition.

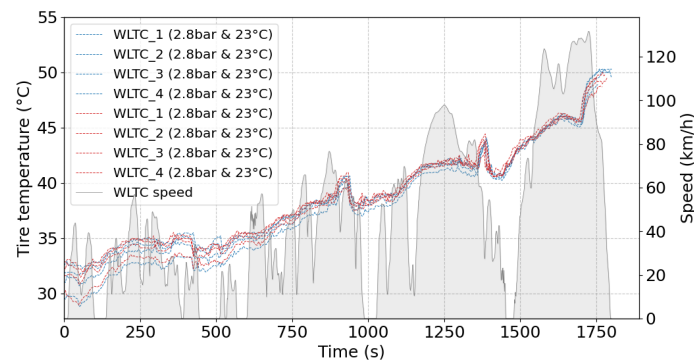


Figure 16. Tire tread temperature profiles during reference measurements under standard temperature conditions.

A second relevant boundary condition was the increasing variability observed over the course of the measurement campaign due to time effects. This suggests that the accumulated driving distance on the chassis dynamometer may progressively affect the stability of particle generation. One possible explanation is a change in the tire–road contact condition due to the gradual loss or alteration of the third-body layer between tire and drum surface. Within this campaign, variability increased from the sixth point of the run sequence onward, after approximately 470 km of accumulated WLTC driving; this coincides with the change from the toe-48' to the toe-30' block, so that accumulated distance and toe setting cannot be distinguished as causes. The approximated value observed in this campaign should therefore be treated as a campaign-specific indicator rather than as a transferable upper limit. As a methodological recommendation, an accumulated laboratory distance, connected with comparable external factors, may therefore be considered a practical upper limit before tire conditioning should be refreshed. If tire reconditioning is introduced, the procedure itself must be validated. Potential approaches may include controlled external driving or a dedicated laboratory reconditioning protocol, but their ability to restore a reproducible tread-surface state remains to be demonstrated.

Overall, these findings show that the DoE approach provides not only information on the relative influence of selected operating parameters, but also a systematic basis for defining the valid operating window of the measurement method.

4.4. Implications for Future Test Protocols (T4)

Current international efforts to regulate tire wear emissions primarily focus on abrasion mass, whereas standardized procedures for quantifying the airborne fraction remain under development. The present study demonstrates that laboratory operating parameters exert a measurable influence on airborne particle emissions and therefore require careful definition within future standardized measurement procedures.

In particular, the response-specific effects of chamber temperature, the sensitivity of the tire–roller system to wheel alignment, and the campaign-dependent evolution observed in the repeated reference measurements demonstrate that laboratory boundary conditions can materially affect the reported particle response. Consequently, future standardized airborne TRWP methodologies should specify not only the measurement instrumentation and sampling configuration but also the relevant experimental boundary conditions and quality-control procedures. Based on the present findings, these should include defined wheel-alignment conditions, tire inflation pressure, chamber temperature, thermal initialization of the tire, monitoring of tread temperature, reference measurements interleaved within the test sequence, randomized run orders within blocks of hard-to-change factors, and criteria for acceptable within-condition variability and longer-term response drift. The present study does not establish universal acceptance thresholds for

these parameters; rather, it identifies variables for which quantitative validity criteria should be developed and validated in future interlaboratory investigations.

The results also show that the definition of the reported particle metric requires harmonization. MCPC-PN, OPS-PN, and OPS mass proxy exhibited different sensitivities to the investigated parameters. Future protocols should clearly distinguish total particle number from solid particle number, define the relevant particle-size range, document any thermal conditioning or volatile-particle removal, and specify the assumptions used when optical size distributions are converted into derived mass metrics.

The integration of statistically planned experimental methodologies including the DoE systematic, reference point measurements and variability assessments into measurement protocol development may therefore contribute to improved reproducibility across laboratories and enhance comparability between independent studies. Additionally, with Euro 7 legislation and higher measurement standards for TRWP emission testing, reliable and reproducible methods, environmental and operational boundary conditions become integral parts of measurement protocols rather than secondary laboratory settings. Their systematic identification and control can improve comparability between laboratories and support the development of harmonized TRWP testing procedures.

4.5. Limitations of the Study

Several limitations should be considered when interpreting the presented findings. The experimental investigation was performed using a single tire configuration under controlled laboratory conditions. Consequently, the observed parameter effects cannot be directly generalized to different tire types, vehicle categories, dyno types, wheel loads, road/roller/pavement surfaces and measurement configurations. The investigated operating parameters represent laboratory boundary conditions rather than the full range of variables influencing tire wear under real-world driving conditions. The tire was operated against a metallic-coated chassis-dynamometer roller rather than a real pavement surface. The resulting contact mechanics, surface texture, airflow, particle resuspension, and tire-surface interaction therefore differ from on-road conditions. The results should consequently be interpreted as system-specific laboratory responses rather than direct representations of real-road TRWP emission factors.

The evaluated response variables were based on cumulative particle concentrations rather than total emitted particle number or distance-normalized emission factors. No correction for dilution, extraction flow, transport losses, or collection efficiency was applied to convert the measured concentration response into an absolute airborne emission rate. Accordingly, the present analysis is most appropriate for relative comparison between controlled experimental conditions.

The MCPC measurements represent total particle number within the instrument response range because no thermal conditioning was applied upstream of the instrument during the DoE campaign. Volatile and semi-volatile particles may therefore contribute to the measured ultrafine particle response. Separate catalytic-stripper measurements indicated a volatile contribution, but these measurements were not incorporated into the factorial dataset. The strong positive MCPC temperature effect therefore cannot be attributed exclusively to solid tire-wear particle formation.

Finally, the study was performed within a single laboratory and measurement system. It therefore evaluates repeatability but does not establish reproducibility across laboratories. Interlaboratory studies using harmonized protocols and common reference conditions are required before the methodology can be considered transferable for standardized application. In addition, the statistical analysis focused on two experimentally controllable parameters. Although this enabled efficient identification of dominant effects, additional

factors such as road surface characteristics, tire compound, vehicle load and humidity may also influence airborne TRWP emissions and should be addressed in future studies. The factorial error term has three degrees of freedom, so only large effects are detectable. Inflation pressure was changed only once per block and the run order was not randomized, so that drift may bias the within-block pressure contrast; for MCPC-PN, this was addressed by the drift-normalized analysis. The OPS mass proxy was available for one block only and could therefore be evaluated only descriptively. The toe is confounded with campaign time. Finally, the concentrations were not normalized to standard temperature and pressure conditions.

5. Conclusions

This study evaluated whether a factorial Design of Experiments can quantify the influence of controllable operating parameters on airborne TRWP measurements on a chassis dynamometer and delimit the conditions for repeatable measurements. The conclusions are given per research task.

(T1) Toe settings above 48' produced progressively increasing particle signals and irregular tread wear on the investigated tire–roller system. The factorial tests were therefore limited to toe 30' and 48', and wheel alignment must be treated as a boundary condition of the method.

(T2) Within the tested ranges, chamber temperature was the dominant factor for the MCPC number response (ratio 3.6 between 35 and 11 °C, also after correction for campaign drift), inflation pressure was the dominant factor for the OPS number response (ratio 0.82 between 3.8 and 1.8 bar), and the OPS mass proxy decreased by approximately 17% with temperature. No interaction was detected, although only large interactions could have been resolved. Because the MCPC response includes volatile particles, its temperature effect cannot be attributed to solid wear particles alone. A single particle metric is therefore not sufficient to characterize airborne TRWP.

(T3) Consecutive WLTCs within a design point are not independent replicates, and the response under reference conditions approximately doubled over the campaign. Within-point repeatability therefore overestimates the precision of factor effects; campaign drift has to be monitored and included in the statistical analysis.

(T4) Future airborne TRWP protocols should specify wheel alignment, inflation pressure, chamber temperature and the thermal initialization of the tire, and should include interleaved reference measurements, randomized run orders within blocks of hard-to-change factors, and predefined criteria for repeatability and drift. Under these conditions, factorial designs provide a transferable framework for developing harmonized laboratory procedures, including those required under Euro 7.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
CV	Coefficient of variation
DoE	Design of Experiments
DLR	German Aerospace Center
ELPI	Electrical Low-Pressure Impactor
ETRTO	European Tyre and Rim Technical Organisation
MCPC	Mixing condensation particle counter
TRWP	Tire and road wear particles
OPS	Optical particle sizer
m _{OPS,x}	OPS-derived mass proxy for optical-equivalent diameter $\leq x \mu\text{m}$
Φ	Cumulative concentration
PN	Particle number
PM	Particulate matter
PNC	Particle Number Concentrations
PM _{2.5}	Particulate matter fraction $\leq 2.5 \mu\text{m}$ aerodynamic diameter
PM ₁₀	Particulate matter fraction $\leq 10 \mu\text{m}$ aerodynamic diameter
SAE	Society of Automotive Engineers
SEM	Scanning Electron Microscopy
WLTC	Worldwide harmonized Light Vehicle Test Cycle

References

1. 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.; et al. Urban air quality: The challenge of traffic non-exhaust emissions. *J. Hazard. Mater.* **2014**, *275*, 31–36. [CrossRef] [PubMed]
2. Fussell, J.C.; Franklin, M.; Green, D.C.; Gustafsson, M.; Harrison, R.M.; Hicks, W.; Kelly, F.J.; Kishta, F.; Miller, M.R.; Mudway, I.S.; et al. A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures. *Environ. Sci. Technol.* **2022**, *56*, 6813–6835. [CrossRef] [PubMed]
3. OECD. *Non-Exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge*; OECD Publishing: Paris, France, 2020.
4. Costagliola, M.A.; Marchitto, L.; Giuzio, R.; Casadei, S.; Rossi, T.; Lixi, S.; Faedo, D. Non-Exhaust Particulate Emissions from Road Transport Vehicles. *Energies* **2024**, *17*, 4079. [CrossRef]
5. Timmers, V.R.; Achten, P.A. Non-exhaust PM emissions from electric vehicles. *Atmos. Environ.* **2016**, *134*, 10–17. Corrigendum in *Atmos. Environ.* **2016**, *147*, 492. <https://doi.org/10.1016/j.atmosenv.2016.10.047>. [CrossRef]
6. Harrison, R.M.; Allan, J.; Carruthers, D.; Heal, M.R.; Lewis, A.C.; Marner, B.; Murrells, T.; Williams, A. Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review. *Atmos. Environ.* **2021**, *262*, 118592. [CrossRef]
7. Beddows, D.C.; Harrison, R.M. PM₁₀ and PM_{2.5} emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. *Atmos. Environ.* **2021**, *244*, 117886. [CrossRef]
8. Polukarova, M.; Hjort, M.; Gustafsson, M. Comprehensive approach to national tire wear emissions: Challenges and implications. *Sci. Total Environ.* **2024**, *924*, 171391. [CrossRef] [PubMed]
9. Giechaskiel, B.; Grigoratos, T.; Dilara, P.; Franco, V. Environmental and Health Benefits of Reducing Tyre Wear Emissions in Preparation for the New Euro 7 Standard. *Sustainability* **2024**, *16*, 10919. [CrossRef]
10. EEA. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023: Update 2025, 1.A.3.b.vi–vii Road Tyre and Brake 761, 2025: Technical Guidance to Prepare National Emission Inventories. Luxembourg. Available online: <https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2023/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-vi> (accessed on 19 August 2025).
11. Schubert, L.; Ketan, E.E.; Schabauer, M.; Lex, C.; Hausberger, S. Tire Wear Particle Emissions: A Review of Measurement Approaches and Impact on Reported Results. *Aerosol Air Qual. Res.* **2026**, *26*, 65. [CrossRef]

12. Kreider, M.L.; Panko, J.M.; McAtee, B.L.; Sweet, L.I.; Finley, B.L. Physical and chemical characterization of tire-related particles: Comparison of particles generated using different methodologies. *Sci. Total Environ.* **2010**, *408*, 652–659. [CrossRef] [PubMed]
13. Schläfle, S.; Zhang, M.; Unrau, H.-J.; Gauterin, F. Influence of Vertical Load, Inflation Pressure, and Driving Speed on the Emission of Tire–Road Particulate Matter and Its Size Distribution. *Atmosphere* **2024**, *15*, 502. [CrossRef]
14. Xu, R.; Sheng, W.; Zhou, F.; Persson, B.N.J. Rubber Wear: History, Mechanisms, and Perspectives. *Tribol. Lett.* **2025**, *73*, 90. Correction in *Tribol. Lett.* **2025**, *73*, 123. <https://doi.org/10.1007/s11249-025-02057-1>. [CrossRef]
15. Haugen, M.; Bühler, P.; Schläfle, S.; O’Loughlin, D.; Saladin, S.; Giorio, C.; Boies, A. Method development and analysis of nanoparticle size fractions from tire-wear emissions. *Environ. Sci. Atmos.* **2024**, *4*, 1079–1090. [CrossRef]
16. Muresan, B.; Truong, X.; De Oliveira, T.; Lumière, L.; Cerezo, V.; Watanabe, N.; Do, M. A study of the direct emission of tire wear particles on different types of roads. *Sci. Total Environ.* **2024**, *958*, 178018. [CrossRef] [PubMed]
17. Rødland, E.S.; Gustafsson, M.; Jaramillo-Vogel, D.; Järlskog, I.; Müller, K.; Rauert, C.; Rausch, J.; Wagner, S. Analytical challenges and possibilities for the quantification of tire-road wear particles. *TrAC Trends Anal. Chem.* **2023**, *165*, 117121. [CrossRef]
18. Weyrauch, S.; Seiwert, B.; Voll, M.; Reemtsma, T. Environmental aging of tire and road wear particles and tire additives: A long-term field study. *Environ. Sci. Processes Impacts* **2025**, *27*, 3498–3505. [CrossRef] [PubMed]
19. De Oliveira, T.; Muresan, B.; Ricordel, S.; Lumière, L.; Truong, X.-T.; Poirier, L.; Gasperi, J. Realistic assessment of tire and road wear particle emissions and their influencing factors on different types of roads. *J. Hazard. Mater.* **2023**, *465*, 133301. [CrossRef] [PubMed]
20. Dall’Osto, M.; Beddows, D.C.; Gietl, J.K.; Olatunbosun, O.A.; Yang, X.; Harrison, R.M. Characteristics of tyre dust in polluted air: Studies by single particle mass spectrometry (ATOFMS). *Atmos. Environ.* **2014**, *94*, 224–230. [CrossRef]
21. Oelze, B.; Biesse, F. ETRTO Abrasion testing with vehicle method–validation results. In *15th International Munich Chassis Symposium 2024 (Proceedings)*; Pfeffer, P.E., Ed.; Springer: Berlin/Heidelberg, Germany, 2025; pp. 9–19.
22. UNECE. Update to GRPE on Submission of a New UN Regulation on Tyre Abrasion Performance of C1 Tyres. Available online: <https://wiki.unece.org/display/trans/TF+TA+session+36> (accessed on 18 September 2026).
23. UNECE. UN Adopts Global Standard to Measure and Limit Brake Particle Emissions. Available online: <https://unece.org/environment/press/un-adopts-global-standard-measure-and-limit-brake-particle-emissions> (accessed on 19 August 2026).
24. Saladin, S.; Boies, A.; Giorio, C. Airborne Tire Wear Particles: A Critical Reanalysis of the Literature Reveals Emission Factors Lower than Expected. *Environ. Sci. Technol. Lett.* **2024**, *11*, 1296–1307. [CrossRef] [PubMed]
25. Celenlioglu, M.S. Vehicles’ Non-Exhaust Emissions: Setup of Experimental Approaches for On-Road Characterization of Tire 817 Wear and Road Dust Particles. Doctoral Thesis, University of Milano, Milano, Italy, 2025.
26. Celenlioglu, M.S.; Eppele, F.; Reijrink, N.; Löber, M.; Reiland, S.; Vecchi, R.; Philipps, F. DLR Tire and Road Wear Particle Emission Testing Methodology–Collection System Influence and Repeatability Assessments. In *Proceedings of the 17th International Conference on Engines and Vehicles, Capri, Italy, 14 September 2025*; SAE Technical Paper Series; SAE International: Warrendale, PA, USA, 2025. [CrossRef]
27. Bondorf, L.; Löber, M.; Grein, T.; Köhler, L.; Eppele, F.; Schripp, T.; Aigner, M.; Philipps, F. Characterization of airborne tire particle emissions under realistic conditions on the chassis dynamometer, on the test track, and on the road. *Aerosol Sci. Technol.* **2025**, *59*, 623–634. [CrossRef]
28. Wahlström, J.; Lyu, Y.; Lundberg, J.; Pagels, J.; Hjelm, R. Advancing Tyre and Road Wear Particle Measurements: Balancing Laboratory Conditions and Real-World Relevance. *Atmosphere* **2025**, *16*, 588. [CrossRef]
29. Costagliola, M.A.; Marchitto, L.; Piras, M.; Mariani, A.; Giuzio, R. Measurements of brake and tire wear particulate emissions from light-duty vehicles under WLTC driving conditions. *Sci. Total Environ.* **2026**, *1016*, 181462. [CrossRef] [PubMed]
30. Harrison, R.M.; Alghamdi, M.A. Measurement of tyre dust particles in the atmosphere using chemical tracers. *Atmos. Environ.* **2023**, *298*, 119607. [CrossRef]
31. Zhang, Q.; Liu, J.; Wei, N.; Song, C.; Peng, J.; Wu, L.; Mao, H. Identify the contribution of vehicle non-exhaust emissions: A single particle aerosol mass spectrometer test case at typical road environment. *Front. Environ. Sci. Eng.* **2023**, *17*, 62. [CrossRef]
32. Celenlioglu, M.S.; Eppele, F.; Reijrink, N.; Chacon Mateos, M.; Reiland, S.; Vecchi, R.; Philipps, F. Advancing Standardization in Tire and Road Wear Particle (TRWP) Emissions: A Repeatability Assessment Across New and Post Break-In Tire Conditions. Available online: <https://elib.dlr.de/216752/> (accessed on 19 August 2025).
33. Box, G.E.P.; Hunter, J.S.; Hunter, W.G. *Statistics for Experimenters: Design, Innovation, and Discovery*, 2nd ed.; Wiley Series in Probability and Statistics; Wiley-Interscience: Hoboken, NJ, USA, 2005.
34. Montgomery, D.C. *Design and Analysis of Experiments*; Wiley: Hoboken, NJ, USA, 2020.
35. Siebertz, K.; van Bebber, D.; Hochkirchen, T. *Statistische Versuchsplanung*; Springer: Berlin/Heidelberg, Germany, 2026.
36. Brechtel Manufacturing Incorporated. Model 1720 Mixing Condensation Particle Counter Manual: Version 2.2. Available online: <https://www.brechtel.com/product/mixing-condensation-particle-counter-mcpc/> (accessed on 19 August 2026).
37. TSI Incorporated. Optical Particle Sizer: Model 3330. Available online: https://tsi.com/getmedia/bc700c47-1a63-40bc-999f-22d58c589200/7741848330_2024_PI_OPS-3330_US_5001323_RevH_Web.pdf?ext=.pdf (accessed on 19 August 2026).

38. Schläfle, S.; Unrau, H.-J.; Gauterin, F. Influence of Longitudinal and Lateral Forces on the Emission of Tire–Road Particulate Matter and Its Size Distribution. *Atmosphere* **2023**, *14*, 1780. [[CrossRef](#)]
39. DHesse, D.; Feißel, T.; Kunze, M.; Bachmann, E.; Bachmann, T.; Gramstat, S. Comparison of Methods for Sampling Particulate Emissions from Tires under Different Test Environments. *Atmosphere* **2022**, *13*, 1262. [[CrossRef](#)]
40. Sina, N.; Nasiri, S.; Karkhaneh, V. Effects of resistive loads and tire inflation pressure on tire power losses and CO₂ emissions in real-world conditions. *Appl. Energy* **2015**, *157*, 974–983. [[CrossRef](#)]
41. Anghelache, G.; Negrus, E.M.; Ciubotaru, O. Investigation of Shear Stresses in the Tire-Road Contact Patch. In *Proceedings of the SAE 2003 World Congress & Exhibition, Detroit, MI, USA, 3 March 2003*; SAE Technical Paper Series; SAE International: Warrendale, PA, USA, 2003. [[CrossRef](#)]

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