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# Physical and Chemical Characteristics of Particles Emitted by a Passenger Vehicle at the Tire-Road Contact

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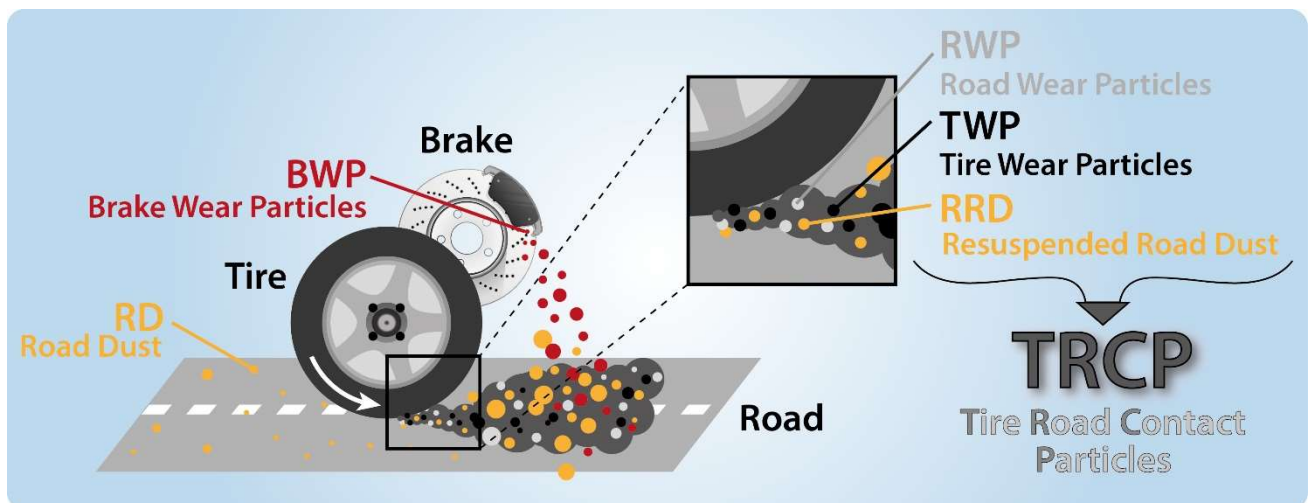
## Highlights:

- Tire Road Contact Particles (TRCP) can be classified according to their chemical composition to identify their origins
- Brake wear particles are Fe-rich particles and also contain tracers such as Ba or Mn
- Tire wear particles are carbonaceous particles containing Si, Zn, and S
- Mineral incrustation, from road wear/dust, are often embedded in the tire tread
- At the individual particle scale, TRCP are mostly contaminated by road dust

28 **Abstract:**

29 Non-exhaust emissions are now recognized as a significant source of atmospheric particulate matter  
30 and the trend towards a reduction of conventionally fueled internal combustion engine vehicles on the  
31 road is increasing their contribution to air pollution due to lower exhaust emissions. These particles  
32 include brake wear particles (BWP) and tire-road contact particles (TRCP), which are composed of  
33 tire wear particles (TWP), road wear particles (RWP) and resuspended road dust (RRD). The goal of  
34 this study has therefore been to design an original experimental approach to provide insight into the  
35 chemical composition of particles emitted at the tire-road contact, focusing on the micron ( $PM_{10-1\mu m}$ )  
36 and submicron ( $PM_{1-0.1\mu m}$ ) fractions. Through this characterization, an examination of the different  
37 TRCP generated by different materials (tire, road surface, brake system) was conducted. To achieve  
38 this, TRCP were collected at the rear of the wheel of an instrumented vehicle during road and track  
39 tests, and a SEM-EDX analysis was performed. Our experimental conditions have allowed us to  
40 demonstrate that, at the individual particle scale, TRCP are consistently associated with road dust  
41 materials and particles solely composed of tire or road materials are practically non-existent. The  
42 contribution of BWP to TRCP is marked by the emission of Fe-rich particles, including heavy metals  
43 like Ba, Mn and Cr. TWP, which result from rubber abrasion, consist of C-rich particles abundant in  
44 Si, Zn, and S. RWP, mainly composed of Al, Si, Fe, and Ca, can be either part of RRD or internally  
45 mixed with emitted TWP. The findings of this study highlight the substantial role of RRD to TRCP  
46 emissions under real driving conditions. Consequently, it underscores the importance of examining  
47 them simultaneously to achieve a more accurate estimation of on-road traffic emissions beyond the  
48 vehicle exhaust.

49  
50 **Graphical abstract:**



51

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74 **1. Introduction**

75 Contribution of atmospheric Particulate Matter (PM) to urban air pollution has been a rising  
76 concern throughout the world in recent years. Non-exhaust traffic-related sources are now  
77 acknowledged as a major contributor to PM, that may account for  $\approx 66$  wt.% of the coarse PM fraction  
78 ( $PM_{10-2.5}$ ) and  $\approx 29$  wt.% of the fine PM fraction ( $PM_{2.5-0.2}$ ), in the urban atmosphere (Matthaios et  
79 al., 2022). Both fine and coarse PM fractions coming from non-exhaust emissions include brake wear,  
80 tire and -road wear, and resuspension of road dust (Fussell et al., 2022). Many studies have focused on  
81 non-exhaust particles (NEP) and their composition (Harrison et al., 2021) and references therein. As  
82 illustrated by Figure 1, NEP include brake wear particles (BWP), a fraction of resuspended road dust  
83 (RRD) and tire-road contact particles (TRCP). TRCP include tire wear particles (TWP) and road wear  
84 particles (RWP), as well as some RRD. The latter can initially come from road use, vehicles, or other  
85 sources, as terrigenous particles (mineral dust) resuspension. TRCP emissions are likely to change as  
86 a result of many factors, mainly weather and traffic conditions, friction forces, tire types and road  
87 surface characteristics (Matthaios et al., 2022; Yan et al., 2021; Youn et al., 2021). In order to better  
88 constrain these emissions and limit their environmental and health impact, it is essential to assess the  
89 relative proportion of the different possible origins (notably TWP, RWP or RRD) in real-world  
90 conditions and better understand their physical and chemical properties, which is the aim of the present  
91 study.

92 In scientific literature, the terms “tire wear particles (TWP)” and “Tire and road wear particles  
93 (TRWP)” are often used even if what is meant is TRCP, including RRD. Therefore, difficulties arise  
94 when studying TRCP due to a lack of standardized sampling procedures and measurement techniques,  
95 which leads to non-comparable results (Mattonai et al., 2022; Piscitello et al., 2021; Zhang et al., 2023).  
96 In most previous studies, TRCP measurements and sampling have been conducted without attempting  
97 to differentiate between each source contribution (tire wear, road wear or resuspension road dust), but  
98 by considering TRCP as a complex mixture of diverse particles. Many studies have focused on TWP

99 emissions, generally using tire simulators (Cao et al., 2022), or on RWP (Baensch-Baltruschat et al.,  
100 2020; Gustafsson, 2018), while those specifically targeting TRCP emissions (including TWP, RWP  
101 and RRD) are relatively rare, due to the high contribution of RRD, which make the situation much  
102 more complex for measurement and sampling methodologies (Harrison et al., 2021). In a companion  
103 study (Beji et al., 2021) based on emission dynamics and size distribution observed during road and  
104 track measurements, tire and road wear particles were found to make up an average of 40% of the rear-  
105 of-wheel particles' (here called TRCP) direct contribution. The results depended on road surface  
106 contamination, road surface texture, driving area, and structural elements affecting road traffic. TWP  
107 were found to have varied morphologies (elongated, round, irregular, etc.) and wide-ranging elemental  
108 compositions, although they differ in physical and chemical properties from the original tire material  
109 (Wagner et al., 2018). The ultrafine fraction generated from the tire tread is generally marked by high  
110 carbonaceous content associated with silicon and sulfur (Park et al., 2018). Mineral-rich particles from  
111 TRCP, mostly in the fine fraction, are generally incrustated within rubber particles (Adachi and  
112 Tainosho, 2004; Alves et al., 2020; Rausch et al., 2022) and are mainly produced by road surface  
113 abrasion (Celo et al., 2021; Cunha-Lopes et al., 2022). The dominating mineral content of road wear  
114 particles is due to the composition of rock aggregates and other mineral fillers such as fly ash particles  
115 (Chen et al., 2022) incorporated into the asphalt mix to enable desired performance (Chousidis et al.,  
116 2016; Kim et al., 2020; Xu and Shi, 2018). All of these materials can disintegrate from the road surface  
117 and form RWP, which become part of the road dust, can be re-suspended and then included in  
118 Resuspended Road Dust (RRD), a major source of particles in TRCP. Road dusts are essentially  
119 composed of minerals, but also tire and bitumen wear particles (Gao et al., 2022; Järllskog et al., 2022).  
120 Giant road dusts generally contain a high amount of elongated particles resulting from tire abrasion,  
121 while the micrometric and submicrometric fractions contain a higher amount of angular mineral-  
122 containing particles. These mineral-containing particles potentially come from surrounded soil, but  
123 also from road traffic (brake, tire and road wear), the latter being notably characterized by the presence

124 of C, Al, Si, Ti, S, Ca, Fe and Zn (Gunawardana et al., 2012). Road dusts also contain spherical  
125 particles with smooth surfaces, which may be fly ash from asphalt (Mistry and Roy, 2016). Several  
126 studies have also identified heavy metals from previously deposited non-exhaust particles present in  
127 road dust (Candeias et al., 2020; Padoan et al., 2017). In particular, Fe exhibits the highest  
128 concentration of metals in the fine fraction, which may originate from brake wear (Yang et al., 2016;  
129 Zhang et al., 2020). BWP contribution to TRCP is limited during normal driving and acceleration  
130 conditions, but it has to be accounted during heavy braking situations (Beji et al., 2020, Mathissen et  
131 al., 2011). Once deposited on the road surface, BWP can be weathered and incorporated into the  
132 resuspended dust cloud, thus falling into the category of RRD, as previously deposited TWP and RWP.  
133 Therefore, both their chemical composition and morphology can be altered compared to freshly  
134 emitted BWP. The chemical composition of brake systems can provide valuable insight into the origin  
135 and formation processes of BWP. In most cases, the disc is made of gray cast iron. The brake pads  
136 have far more complex components, which vary considerably depending on the local market and  
137 manufacturers (Harrison et al., 2021). Fe is ubiquitous in both TWP and RWP and therefore cannot be  
138 considered exclusive of BWP emissions. However, some associated chemical elements are considered  
139 to be common tracers of brake wear, including Cu and Ba (Fussell et al., 2022; Harrison et al., 2021;  
140 Charron et al., 2019; Sanders et al., 2003).

141 The aim of this study has therefore been to determine the probable origin of TRCP (i.e. brake  
142 wear, tire wear, road wear and/or road dust resuspension) based on their size range and chemical  
143 composition. Considering their significant impact on human health, we have focused more particularly  
144 on micrometric and submicrometric particles. To do this, we investigated the chemical composition of  
145 source materials (tire, road surface and brake pads) and the physical/chemical components of TRCP  
146 emissions collected in real-world using an instrumented vehicle. Individual particle analysis using  
147 automated scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy

148 (EDX) has been used to analyze the particles collected during on-road and on-test track experiments.  
149 This paper evaluates the significance of the road dust as a contributor of TRCP emissions.

150

## 151 **2. Materials and Methods**

152 Test-track and on-road measurement campaigns have been described in detail elsewhere (Beji  
153 et al., 2021). In summary, on-board measurements were carried out in two different environments: a  
154 2.3 km test track with a maximum speed of 140 km/h (semi-controlled environment) and on the road  
155 (real-driving conditions). The travelled route was a 25-km long loop in the Nantes metropolitan area  
156 (northwestern France), passing through different environments (rural, urban and motorways) and  
157 covering several road types (country roads, ring roads, city streets, etc.), with the aim of providing  
158 variable RRD, both in quantity and type. On-board measurements were conducted on the test track and  
159 on the road under the same weather conditions (wind speed below 7 m.s<sup>-1</sup>, no rain in seven days before  
160 the experiments, temperature ranges from 20 °C to 25 °C, and humidity ranges from 50% to 80%).  
161 The road surface of the test track was a semi-coarse asphalt concrete with medium macrotexture and  
162 microtexture levels. The constituent rocks, originally from local quarries, were composed  
163 predominantly of quartz and feldspars, containing the same elements as granite (O, Si, Al, Na, K and  
164 to a lesser degree Fe, Ca and Mg), but in slightly different proportions. As the test track was subject to  
165 limited traffic and was regularly cleaned of ambient dust deposition and particle emissions from  
166 previous tests, road dust contamination level was expected to be higher on the Nantes metropolitan  
167 area roads. This strategy aimed to analyze various components contributing to TRCP by examining  
168 source materials (tire, pavement, brake system, etc.).

169 The experiments were performed with a fully-equipped vehicle (Renault Clio 3, one of the most  
170 common models sold in France), fitted with commercial summer tires (Michelin<sup>TM</sup> Energy Saver,  
171 185/60 R 15 88H) and semi-metallic brake pads (TRW 8200). A trailer containing the scientific



172 instrumentation was hitched to the car (Figure 2). The same vehicle was used for all measurements,  
173 and tests were conducted by the same driver and co-driver to preserve the same driving behavior  
174 throughout the experiments. The tests provided insight into several dynamics parameters (driving  
175 speed variations, fuel consumption, brake pressure, etc.) and particle size distributions (aerodynamic  
176 diameters ranging between 7 nm and 10  $\mu\text{m}$ ) in real-time. More details about the devices used and  
177 particles sizing results are reported in Beji et al. (2021). Although variable over time, the proportion  
178 of particles from the atmospheric background (measured when the vehicle is stationary) was relatively  
179 low, reaching a maximum of 5% and 28 % for on-road and test track experiments, respectively (Beji  
180 et al. 2021). The amount of resuspended road dust was lower on the cleaned test track, resulting in this  
181 relatively greater contribution of the atmospheric background. At the end of the experiments, brake  
182 pads and tires were dismantled in order to study them by microscopy. The used surfaces of the brake  
183 pad and of the tire tread zone were thus observed and compared with unused surfaces obtained by  
184 fracture. For that, a piece on the surface of the pad is broken off and a piece of the surface of the tire  
185 previously soaked in liquid nitrogen is torn off.

186 A three-stages cascade impactor (air flow: 28  $\text{L}\cdot\text{min}^{-1}$ ) with nominal cut-off diameters (i.e.  
187 aerodynamic diameter at 50% of collection efficiency) of 10, 1.0 and 0.1  $\mu\text{m}$  was used for particle  
188 sampling. Particles were collected on nickel Transmission Electron Microscopy (TEM) grids, attached  
189 to polycarbonate membranes. The air inlets for particle collections were placed at the rear of the front  
190 tire (driver side) and in the backspace of the wheel near the braking system (Figure 2). The inlet of  
191 tire-road contact particles sampling probe was set 15 cm behind the tire and 7 cm above the ground,  
192 the best position to sample TRCP from both tire-road wear and the resuspension of road dust induced  
193 by vehicle turbulence. Moreover, the instrument's calculated aspiration efficiencies ( $\eta$ ) approached  
194 100% for particles smaller than 10  $\mu\text{m}$ , irrespective of the vehicle speed (Beji et al., 2021). Potential  
195 contamination by fresh brake wear particles emissions was also assessed by simultaneously sampling  
196 at the rear and in the backspace of the instrumented wheel (i.e. 15 cm below and 12 cm downstream

197 of the braking system). As a result, it became feasible to examine the chemical composition of brake  
198 wear particle emissions and distinguish them among TRCP emissions. For super-coarse particles  
199 (diameter larger than 10  $\mu\text{m}$ ), passive sampling on carbon adhesive attached at the end of the air inlet  
200 was used (Figure 2).

201 Individual particle analyses were performed by automated Scanning Electron Microscopy with  
202 Energy-Dispersive X-ray spectrometry acquisition (SEM-EDX). The assumption is that super-coarse  
203 particles with highly agglomerated shapes come from various sources, so about a hundred particles  
204 have been analyzed manually to gain further insight into the chemical composition and texture of the  
205 different agglomerate fragments. This type of analysis is useful but time-consuming, so not suitable  
206 for studying a large volume of particles. For micron- and submicron-sized particles (with diameter <  
207 10  $\mu\text{m}$ ), automated analysis detected several hundred particles per impactation stage. The SEM-EDX  
208 used is a JEOL 7100F FEG-SEM, equipped with a transmitted electron detector and three ultrathin-  
209 window (30  $\text{mm}^2$ ) energy-dispersive X-ray detectors (Bruker XFlash 6/30). Spectral acquisitions were  
210 performed at 15 kV, 300 pA for 20 s. The EDX spectrometers were calibrated before analyses using  
211 the Cu  $K\alpha$ -line at 8041 eV. The elemental concentrations were calculated using the PhiRoZ  
212 quantification procedure from Esprit Software (Bruker Nano, Germany). Particles smaller than 100  
213 nm were not considered because they do not produce a sufficient X-ray signal to obtain a reliable EDX  
214 spectrum. There are various ways of processing data from individual particle analysis, ranging from  
215 manual particle classification to elaborate classifications using machine learning (Rausch et al., 2022).  
216 In our case, the resulting large databases (elemental compositions in weighted %, and particle size)  
217 were statistically analyzed by means of Hierarchical Ascending Classification (HCA), using the  
218 FactoMineR<sup>®</sup> software, clustering particles with similar elemental compositions, so probably from the  
219 same source. The particles are then sorted by sample and each cluster of a sample is assigned to a  
220 particle family among seven families (Table 1, from A to G) based on its mean elemental composition.  
221 If several clusters of a same sample were assigned to the same family (due, for example, to a variable

222 proportion of an element of no interest such as Na), these clusters were grouped together to form a  
223 single cluster. Finally, the sum of the spectra was calculated for each cluster of a sample to improve  
224 the signal to noise ratio and deduce an accurate average elemental composition of particles classified  
225 in this cluster.

### 226 **3. Results and Discussion**

#### 227 ***3.1. Source materials***

228 Tire and tire wear particles (TWP): In our study, a summer silica-based tire was used. These tires have  
229 asymmetrical structures with three straight grooves that run around the center of the rubber tread. The  
230 chemical mapping of the unused tread zone, which has never been in contact with the road, is mainly  
231 composed of Si, C and O with, to a lesser extent, S and Zn, in accordance with literature data  
232 (Supporting Information, Figure S1A). The high Si content of the tire tread is due to the use of  
233 amorphous silica in filler materials with black carbon, to enhance the mechanical and dynamic  
234 properties of rubber (Rattanasom et al., 2007). In contrast, the chemical mapping of a tread zone after  
235 used (subsequent to contact with the road surface) has a heterogeneous chemical composition with a  
236 larger number of detected elements (C, O, Si, Al, S, Na, Mg, K, Ca, Fe, Zn, Ti) (Supporting  
237 Information, Figure S1B). With the exception of Fe and Ti, all of these mineral components were  
238 previously reported by Kovoichich et al. (2021) using SEM-EDX mapping of super-coarse particles  
239 coming from three used tread surfaces. Mineral incrustations were also observed at the tire tread  
240 surface (Figure S1B). These may come from road wear or resuspended mineral dust. When a tire comes  
241 into contact with the road, some road dust is collected onto the tire surface before being stripped off  
242 and carried away by air flow. Furthermore, a portion of the particles may undergo crushing between  
243 the road and the tire tread surface, leading to potential alterations in the physical and chemical  
244 properties of emitted particles. These changes may differentiate them from road dust that has only  
245 recently settled on the tread surface and become part of the TRCP fraction.

246 Mineral incrustations found on asphalt pavement can exhibit varying contents of Al, Si, Fe, K,  
247 Ca and Mn, which can be attributed to the use of steel slag, limestone and manganese dioxide as fillers  
248 to improve mechanical performances of asphalt, facilitating self-healing capabilities (Deng et al., 2022;  
249 Wei et al., 2021). In addition to particles coming from mineral incrustations of road surface, the tire  
250 tread surface may generate both coarse elongated particles (micrometer-scale) and irregular  
251 submicrometer TWP, with a more or less rounded shape (Kim and Lee, 2018). While the large  
252 elongated particles are formed mechanically by shear and friction forces in the slip between tire and  
253 the road, the fine TWP can be emitted by volatilization processes due to frictional heat under severe  
254 conditions (Baensch-Baltruschat et al., 2020; Park et al., 2017). For Sommer et al. (2018), “pure”  
255 super-coarse TWP exist only in very low quantities in the environment and TWP are quickly mixed  
256 with RWP and BWP in high traffic roads (Eisentraut et al., 2018). The resulting mixture contains heavy  
257 metals such as Zn, Fe, Ba, Cu and Sb, in addition to Si and Ca coming from RWP. Al is ubiquitous: It  
258 is present in clayey background dust, asphalt pavement, as well as in rubber additives and brake  
259 abrasion particles (Sommer et al., 2018). In summary, the interaction of the tire tread with the road  
260 could generates various TWP through mechanical and also thermal mechanisms. These particles can  
261 originate from the degradation of the tire materials, but also from road dust previously stuck on the  
262 surface of the tread. However, frictional interaction can change both the chemical properties and the  
263 morphologies of TWP compared to the original tread materials and the deposited road dust.

264 Brake system and brake wear particles (BWP): The brake system used in our on-board measurements  
265 was a semi-metallic brake lining with a cast iron disc. Elemental maps of an unused surface of the  
266 brake pad have underlined the heterogeneous elemental distribution at the micrometric scale  
267 (Supporting Information, Figure S2). Some areas have Fe-rich components, while others are mainly  
268 composed of carbonaceous materials or mixed carbonaceous/metal agglomerates (containing notably  
269 C, O, Al, Si, S, Fe and Mg). This heterogenous elemental distribution within the pad will generate,  
270 upon thermal process and/or mechanical degradation, various chemical compositions of BWP.

271 Moreover, during braking, friction materials from this pad and the disc act as contributor and  
272 nucleation sites for the formation of the third body inside the friction layer (Kukutschová et al., 2009).  
273 This third body is a complex and discontinuous layer of very fine wear particles that are pressed and  
274 sintered together. It has its own chemistry and microstructure which differ from the microstructure and  
275 chemistry of the phases present in the original bulk materials. Its formation and disruption greatly  
276 influence particle emission dynamics since it accounts for a large proportion of the released wear  
277 particles (Gomes Nogueira et al., 2020). Thus, the characteristics of emitted particles (size, shape,  
278 chemistry) are highly variable according to the friction material composition itself, and BWP generated  
279 from the third body may have a different composition than those of the discs and pads.

280 Particle sampling near the brake system during the on-board experiment on the test track (Figure 2)  
281 allowed us to characterize the instrumented car BWP and thereby evaluate their contribution to the  
282 composition of TRCP. Even if the sampling was performed continuously during the trip (during  
283 braking and non-braking), the position of the air inlet allowed us to collect chiefly BWP (Beji et al.,  
284 2021). Collected BWP have various morphological properties and sizes (Supporting information,  
285 Figure S3): spherical, irregular and agglomerated particles. Micron-sized BWP were often  
286 agglomerated in shape, whereas submicron-sized BWP tended to be spherical or irregular.

287 The same air inlet implementation (backspace of the wheel) was used during real driving (i.e., “on  
288 road”) experiments to determine the chemical makeup of BWP. Based on their elemental composition  
289 (except C and O, which may come from the collection substrate), particles collected near the braking  
290 system during the on-road experiment were statistically classified by the HCA technique into different  
291 clusters (Figure 3), according to their size (micron [1-10 $\mu$ m] and submicron [0.1-1 $\mu$ m] fractions). The  
292 sum of the relative contribution (RC) of two first clusters (#1 and #2) represent around 90% of analyzed  
293 particles for the two fractions. For these clusters (except R-BWP-S2), 32 to 61wt.% of analyzed  
294 particles are Fe-rich (Fig.3). With the exception of Cu, the consistent presence of Ba, Cr, Mn, Ti and  
295 Zn strongly suggests that these particles are directly emitted from brake pads and/or discs. Therefore,

296 they can be regarded as freshly emitted BWP (Fussell et al., 2022; Harrison et al., 2021). Occasionally,  
297 Na, Cl and N were detected ( $\leq 10$  wt.%). Because the last road salting in the area took place three weeks  
298 earlier, we hypothesize that these components probably come from road salt previously deposited as a  
299 de-icing agent, even if light rainfall subsequent to the salting (4.4 mm/day on average and never more  
300 than 18.7 mm/day) did occur. Despite the position of the air inlet as close as possible to the braking  
301 system (Fig. 2), the collection of RRD cannot be excluded. Indeed, the collection of particles was  
302 maintained throughout the on-road experiment and particles were inevitably collected in the absence  
303 of braking. Nevertheless, the monitoring of particle concentrations at the sampling point indicated that  
304 the relative proportion of these particles (probably RRD) was low when they were integrated over the  
305 entire duration of the on-road experiment. In fact, it is worth noting that the ubiquitous elements in  
306 road dust (Al, Si, Ca and S) were mainly (but not only) detected in minority clusters (M3, M4, and M5  
307 for the 1-10 $\mu$ m fraction and S3 and S4 for the 0.1-1 $\mu$ m fraction).

308 To sum up, the particles collected near the brake system during on-road experiments consist of both  
309 freshly emitted BWP generated during friction processes and some RRD containing elements like Na,  
310 N or Cl. Apart from C and O, Fe is the primary element identified in BWP during both test track and  
311 on-road experiments, often found in internally mixed particles with minor elements such as Mn, Ba,  
312 Cr, Ti and Zn. While Fe is widespread in all wear particles (TWP, RWP and BWP), the recurrent  
313 presence of Mn and Ba in the main groups of particles analyzed make them valuable as specific tracers  
314 of BWP emissions.

315

### 316 ***3.2. Source and characterization of Tire Road Contact Particles (TRCP)***

317 Super-coarse TRCP: Super-coarse particles are defined in this study as particles with a diameter  $> 10$   
318  $\mu$ m. Figure 4 shows representative pictures of super-coarse TRCP collected at the *rear of the wheel*  
319 during the test-track experiment (Fig.2). They often have an elongated or irregular shape and are

320 composed of various elements such as: C, O, Si, Al, S, Fe, Ca, Na, K, Mg, Mn, and Cr. The particle  
321 presented in Figure 4(a) is mineral-rich, having an irregularly shape with a rough surface, probably  
322 coming from road abrasion. Figure 4(b) shows particles with an elongated shape, typical of TWP  
323 (Gunawardana et al., 2012; Kovoichich et al., 2021; Park et al., 2018; Sommer et al., 2018). Figures  
324 4(c) and (d) are carbon-rich particles, with an irregular shape and containing mainly Ca, Si and S,  
325 which suggests that they are probably from tire tread abrasion: Black carbon, silica and chalk are used  
326 as reinforcing fillers in tire materials, while S is a vulcanization agent (Kovoichich et al., 2021). Figure  
327 4(d) shows Si- and Ca-rich particles, which strongly suggest that they likely originate from the filler  
328 mixture of the tire tread or from road abrasion. In contrast, the image in 4(e) shows a carbonaceous  
329 particle without mineral elements, which means that it is likely TWP coming from the rubber part of  
330 the tread. The “E” area of Fig.4(e) has a flaked shape at high magnification, likely coming from the  
331 tire rubber peeling (Camatini et al., 2001). Another common type of super-coarse TRCP involves the  
332 presence of agglomerated particles, which are likely from diverse sources (Figure 4-f, “F” areas  
333 images). These agglomerates are made of incrustations of mineral particles (F1) into a rubber fragment  
334 (F2). We assume that the flaked-shape surface of rubber particles offers a large contact zone, which  
335 promotes the inclusion of RWP into the rubber fraction of TWP (Knight et al., 2020; Kreider et al.,  
336 2010). Sommer et al. (2018) also observed the presence of agglomerated TWP and RWP in  
337 atmospheric super-coarse particles collected near highways.

338 According to their morphology and elemental composition, super-coarse TRCP exhibit distinct  
339 origins and can be classified into three categories. RWP, which exhibit a high-mineral content  
340 (typically including Al, Si, Fe and Ca) and an irregular shape, characteristic of road abrasion. Carbon-  
341 and metal-rich TWP that come from the wear of the tire rubber, including the filler mixture of the tire  
342 tread. This second category features an elongated shape that is more or less irregular and presents a  
343 rough surface. Lastly, agglomerated particles, which presumably consist of mineral incrustations  
344 embedded in tire rubber, i.e., an external mixture of TWP and RWP or RRD. These super-coarse

345 particles mainly reflect the mechanical abrasion of tire tread and/or road surface, as well as the  
346 subsequent agglomeration processes. Although they can be resuspended by the passage of vehicles,  
347 they probably do not have a significant impact on air quality considering their rapid sedimentation,  
348 due to their size. Nevertheless, after undergoing sedimentation and possible fragmentation, these  
349 super-coarse TRCP could serve as persistent sources of particulate pollutants and may release  
350 leachable metallic/organic compounds to roadside soils or to aquatic environments.

351 Micron and submicron TRCP in real-driving conditions: The micron and submicron fractions of the  
352 collected TRCP were of significant interest due to their presence in the respirable size range and direct  
353 link to a number of human diseases (Halle et al., 2020; Kreider et al., 2020). Figure 5 shows the HCA  
354 clusters for TRCP sampled during the on-road measurements according to their size fraction and  
355 chemical composition. The likely origin of these particles was determined by comparing their  
356 composition with that of the source materials, enabling the classification of each cluster into one of  
357 the seven families of particles (from A to G, Table 1). Particles from clusters R-TRCP-M3 and R-  
358 TRCP-S2 (Fig.5) are clearly identified as BWP (Family A, Table1), with their high iron content (30-  
359 40 wt% normalized without C and O). The detection of minor elements such as Cu, Zn, Ba, Mn, and  
360 Cr, which are considered tracers of brake emissions as observed in BWP (Figure 3), is also salient in  
361 the submicron fraction. Moreover, they have no internal mixture with road salt (Na, and N or Cl) so  
362 they can be considered as freshly emitted BWP, in contrast to particles from Family B containing road  
363 salt. In fact, with the exception of particles from Family A, all TRCP contain road salts (i.e., Na and  
364 Cl or N) and are shown to be contaminated with RRD. If the relative abundance of the main tracers of  
365 RRD (Na and Cl) differs from one cluster to another (0.1 to 10 wt.% - Fig.5), particles contaminated  
366 with RRD count for 79% of TRCP in the micron fraction and 88% in the submicron fraction. During  
367 icy periods, the salt spread on the road consists of sodium chloride (NaCl), which is prone to  
368 undergoing compositional changes over time due to the influence of anthropogenic gaseous species,  
369 such as sea salt particles during their aging process (Adachi and Buseck, 2015). In anthropogenic



370 environment, the aged salt particles often undergo internal mixing with sulfate and nitrate (Hara et al.,  
371 2005), frequently resulting in significant chloride depletion (Laskin et al., 2012). The presence of NO<sub>x</sub>  
372 in urban environments is undeniable, leading to the partial conversion of NaCl into NaNO<sub>3</sub>, which  
373 explains the frequent presence of nitrogen associated with sodium in RRD. However, this does not  
374 provide any information about their emission process. These particles could be road dust that has been  
375 resuspended due to turbulences caused by vehicle movement, or they may originate from road dust  
376 previously incrustated in the tire surface, subsequently crushed, and ejected during the tire-road contact.  
377 This assumption is based on the presence of major elements characteristic of TWP (as C, Si, Al, Fe, S,  
378 and Zn) in four out of the nine Families (Table 1, Families C, D, E and F), combined with RRD in all  
379 cases. Finally, road wear particles (RWP) composed of Ca-Fe-rich particles, along with Si, Al, S, Mg,  
380 P, and K to a lesser extent, may also be contaminated by road salt (family G in our classification –  
381 Table 1).

382 In conclusion, while the chemical composition of particles greatly differs according to the size fraction,  
383 this study confirms the importance of road dust as a source of TRCP and demonstrates that in the real  
384 environment and at the scale of the individual particle, no TRCP is derived solely from tire or road  
385 source materials. Indeed, all TWP and RWP are internal mixtures with road dust and it is difficult to  
386 distinguish RRD from TWP, RWP and/or BWP because TRCP are always contaminated by road dust.  
387 Moreover, the high contribution of these agglomerated particles in the submicron fraction indicates  
388 that a significant fraction of the TRCP resulting from RRD are submicronic particles.

389 Micron and submicron TRCP emissions in the absence of road salting: An additional experiment was  
390 performed the day after the on-road measurements on a pre-cleaned test track to reduce the contribution  
391 of road dust to TRCP emissions as much as possible. The TRCP collected exhibited the same various  
392 morphologies, e.g., spherical, agglomerated or elongated (data not reported here), as particles sampled  
393 during the on-road experiment. As expected, the contribution of road salts to TRCP is significantly  
394 lower than for the on-road measurements (Figure 6). As a consequence, no contribution of road dust

395 was observed in BWP emissions (Table 1, right column, Families A and B). The contribution of  
396 clusters containing RRD from road salting to agglomerated brake-, tire- and road-wear particles fell  
397 from 87 to 60% (Family C) and from 39 to 26% (Family D), which is expected considering the low  
398 road surface dustiness of the pre-cleaned test track compared to the road. The contribution of road dust  
399 is only discernable for particles identified as TWP (Family F, Table 1) and RWP (Family G), but the  
400 related clusters proportion correspond to < 10% of analyzed particles. The only exception is the  
401 residual presence of RRD from road salting in particles likely coming from tire rubber abrasion  
402 (Family E), which represent 43% of submicron TRCP analyzed. Thus, we assume that, despite the  
403 washing of the road surface before the test-track measurements, these remaining road salts probably  
404 come from aged particles previously encrusted at the surface of the tire tread during the earlier on-road  
405 experiment and ejected during the test-track measurements carried out the next day. The absence of  
406 road salts in collected BWP confirms this hypothesis. Therefore, when measuring/quantifying TWP in  
407 real-environment, it is essential to consider the re-emission phenomenon of road dust.

408

#### 409 **4. Conclusion**

410 The aim of the present study was to develop an original experimental approach that offers insights into  
411 the chemical composition of TRCP emissions and to explore the diverse origins of TRCP, linked to  
412 the source materials (tire, road surface, brake system, etc.). Super-coarse TRCP can be classified into  
413 three categories: carbon- and metal-rich TWP, high-mineral content RWP, and agglomerated particles  
414 including RRD. The measurements in real-driving conditions have allowed us to demonstrate the  
415 significant contribution of road dust to the micron and submicron fractions of TRCP emissions (79%  
416 and 88% of particles, respectively). Moreover, on an individual particle scale, TRCP are consistently  
417 associated with road dust compounds, and it is rare to find TWP or RWP composed solely of tire or  
418 road materials, respectively. BWP contribution to TRCP is characterized by the emission of Fe-rich  
419 particles, including related heavy metals like Ba and/or Mn. In addition to rubber abrasion producing

420 C-rich particles, TWP present in TRCP are made up of an abundance of Si and Zn from the filler  
421 mixture of the tire tread, as well as S, acting as a rubber vulcanization agent. Apart from the presence  
422 of compounds from road dust, RWP are distinguished by their high-mineral content, primarily  
423 comprising Ca and Fe, along with smaller amounts of Si, Al, S, Mg, P, and K. Complementary  
424 measurements on a pre-cleaned test track have shown that road dust contamination to TRCP emission  
425 might be from aged particles incrustated at the surface of the tire and re-emitted by friction with the road  
426 surface.

427 Our study highlights the challenge of accurately characterizing TRCP emitted in a real environment,  
428 disregarding the particles previously deposited on the road surface, as their nature and quantity are  
429 independent of the characteristics of the vehicle tested. For this reason, we recommend that future  
430 studies aiming to gain a better understanding of the particles emitted at the tire-road contact should  
431 systematically characterize both the dustiness and the road surface (roughness) simultaneously. While  
432 challenging to achieve under driving conditions, the use of an on-board high-frequency image  
433 acquisition camera combined with an intelligent recognition system should make it possible to  
434 correlate TRCP emissions with the specific characteristics of the roadway (roughness and dust  
435 emission). Nevertheless, experiments on test tracks in a controlled environment seem to be essential  
436 for a more accurate assessment of wear particles from vehicles alone.

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619 **List of Table**

Family	Major elements detected in individual particles by EDX analysis	Probable origin	“On-road” (R-) clusters	“On test track” (T-) clusters
A	Fe-rich	Fresh-BWP	R-TRCP-M3 (21%) R-TRCP-S2 (12%)	T-TRCP-M3 (20%) T-TRCP-S2 (29%)
B	Fe-rich and other heavy metals (with Na, N/Cl)	BWP (and RRD from road salting)	R-TRCP-M2 (32%) R-TRCP-M5 (2%)	-
C	C-rich and Si, Al, Fe (with Na, N/Cl)	Agglomerated BWP + RWP + TWP (and RRD from road salting)	R-TRCP-S1 (80%) R-TRCP-S4 (3%) R-TRCP-M4 (4%)	T-TRCP-M2 (26%) T-TRCP-M4 (17%) T-TRCP-S3 (17%)
D	C-rich and Fe (with Na, Cl)	Agglomerated BWP + RWP + TWP (and RRD from road salting)	R-TRCP-M1 (39%)	T-TRCP-M1 (26%)
E	C-rich (with Na, Cl)	TWP (rubber tread abrasion) (and RRD from road salting)	R-TRCP-S3 (5%)	T-TRCP-S1 (43%)
F	C-rich and Si, S, Zn (with Na, Cl)	TWP (and RRD from road salting)	-	T-TRCP-M5 (9%) T-TRCP-S5 (4%)
G	Ca-Fe-rich and Al, Si, Mg, S, P, K (with Na, Cl)	RWP (and RRD from road salting)	R-TRCP-M6 (1%)	T-TRCP-M6 (3%) T-TRCP-S4 (5%)

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*Table 1 : Overview of the different TRCP families and their probable origins. The assignment of particles from the micron (TRCP-M) and the submicron (TRCP-S) fractions collected during “on-road” (R-) and on “test track” (T-) experiments is reported in the two last columns respectively, with their relative contribution (%) in parentheses.*

624 **Figure Captions**

625

626 **Figure 1:** Schematic view of Non-Exhaust Particles (NEP) emissions.

627 **Figure 2:** Illustrations (upper and lower panels) and schematic view (middle panel) of the  
628 instrumental set-up implemented to monitor particulate emissions from the tire-road interface. The  
629 orientation and velocity of streamlines were calculated at stabilized driving speeds using  
630 Computational Fluid Dynamics (CFD) modeling with the Ansys Fluent application. The red coloring  
631 represents the highest velocities. (*Reprinted from Beji et al., 2021 – Courtesy of Elsevier©*).  
632 The black adhesive disk used for passive sampling of super-coarse particles is visible at the end of  
633 the air inlet.

634 **Figure 3:** Chemical composition (in wt. %) of BWP (total analyzed particles =768), collected on-road  
635 (R), for the micron (1-10  $\mu\text{m}$ ) and submicron (0.1-1  $\mu\text{m}$ ) size fractions. Numbering system used is as  
636 follows: the clusters numbered # are named “R-BWP-M#” and “R-BWP-S#” for the micron (M) and  
637 submicron (S) fractions, respectively. The relative contribution (RC) of each cluster is indicated below  
638 the cluster name.

639 **Figure 4:** SEM pictures of super-coarse TRCP sampled during the test-track experiments with  
640 different origins: a) road wear, b) and c) tire wear, d) filler mixture of tire tread, e) tire rubber, f)  
641 agglomeration of particles from both tire and road wear.

642 **Figure 5:** Chemical composition (in wt. %) of TRCP (total analyzed particles =925) collected on-  
643 road (R) for the micron (1-10  $\mu\text{m}$ ) and submicron (0.1-1  $\mu\text{m}$ ) size fractions. The clusters numbered #  
644 are named “R-TRCP-M#” and “R-TRCP-S#” for the micron (M) and submicron (S) fractions,  
645 respectively. The relative contribution (RC) of each cluster is indicated below the cluster name.

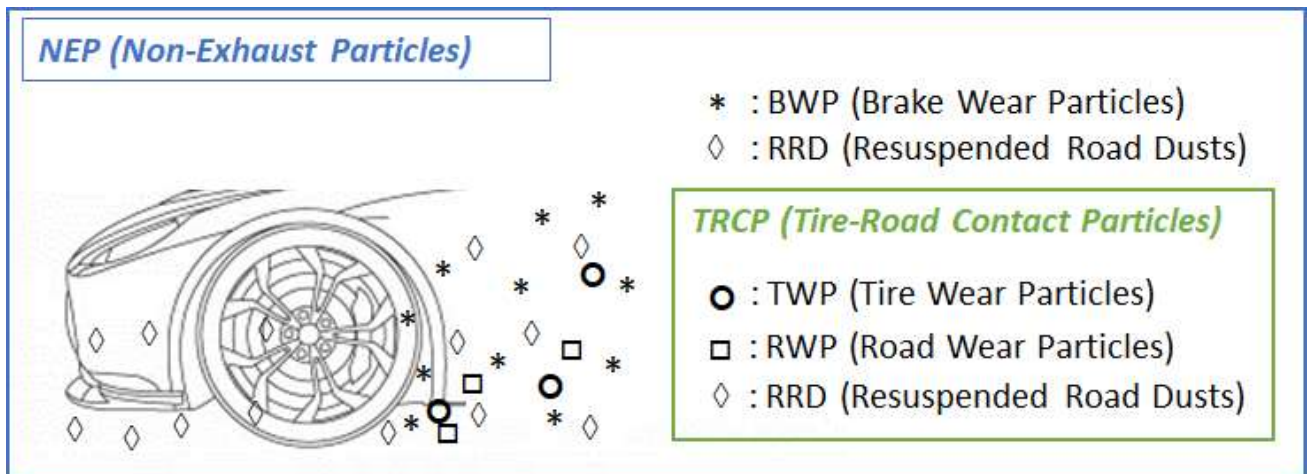
646 **Figure 6:** Chemical composition (in wt. %) of TRCP (total analyzed particles=617) collected on the  
647 cleaned test track (T) for the micron (1-10  $\mu\text{m}$ ) and submicron (0.1-1  $\mu\text{m}$ ) size fractions. The clusters

648 numbered # are named T-TRCP-M# and T-TRCP-S# for the micron (M) and submicron (S)  
649 fractions, respectively. The relative contribution (RC) of each cluster is indicated below the cluster.

650

651 **Figure 1**

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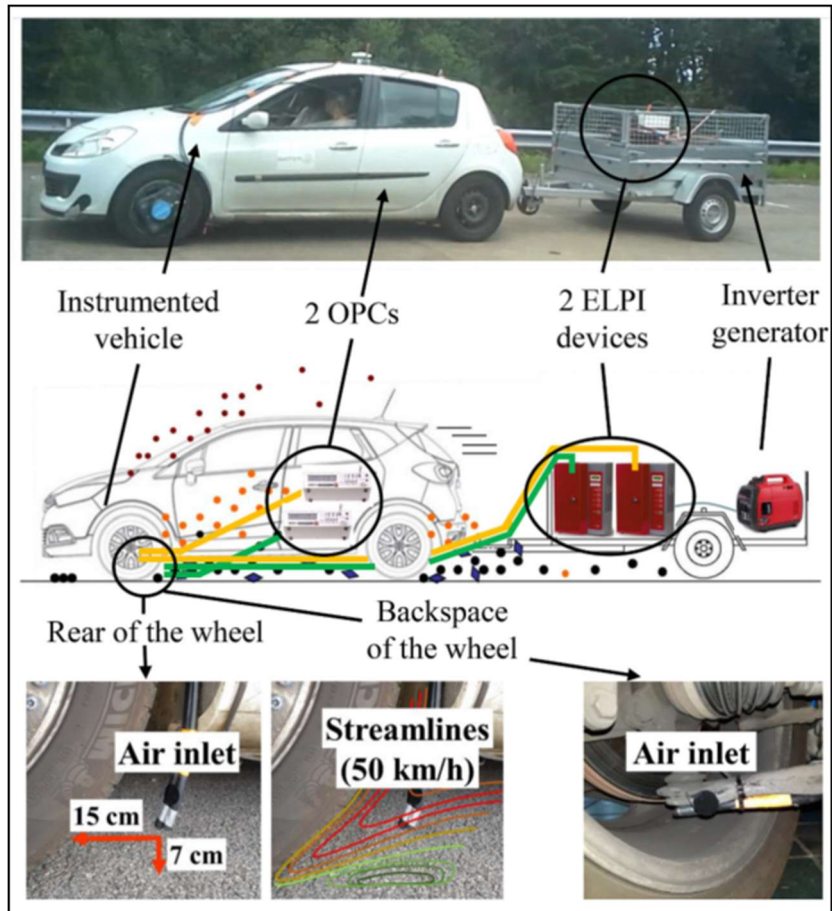


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655 **Figure 2**

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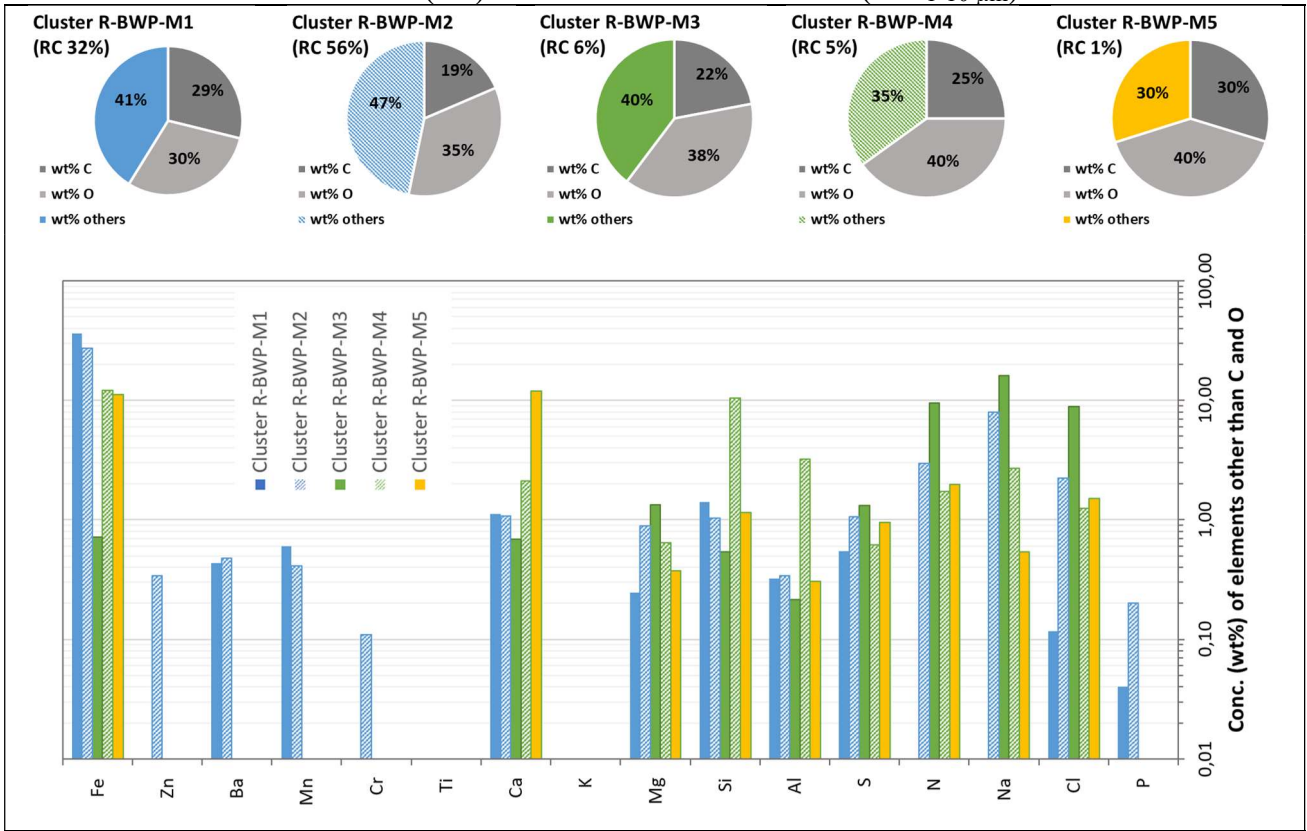


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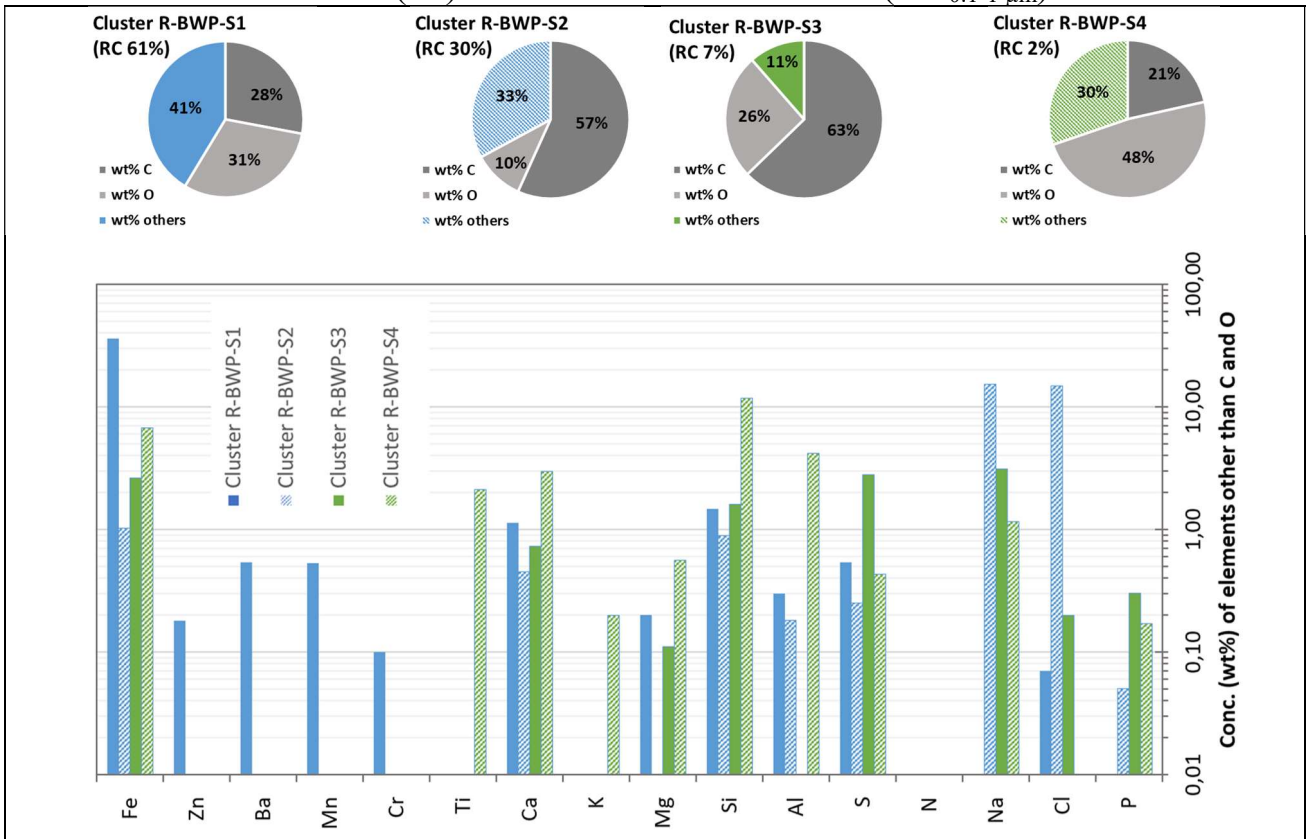
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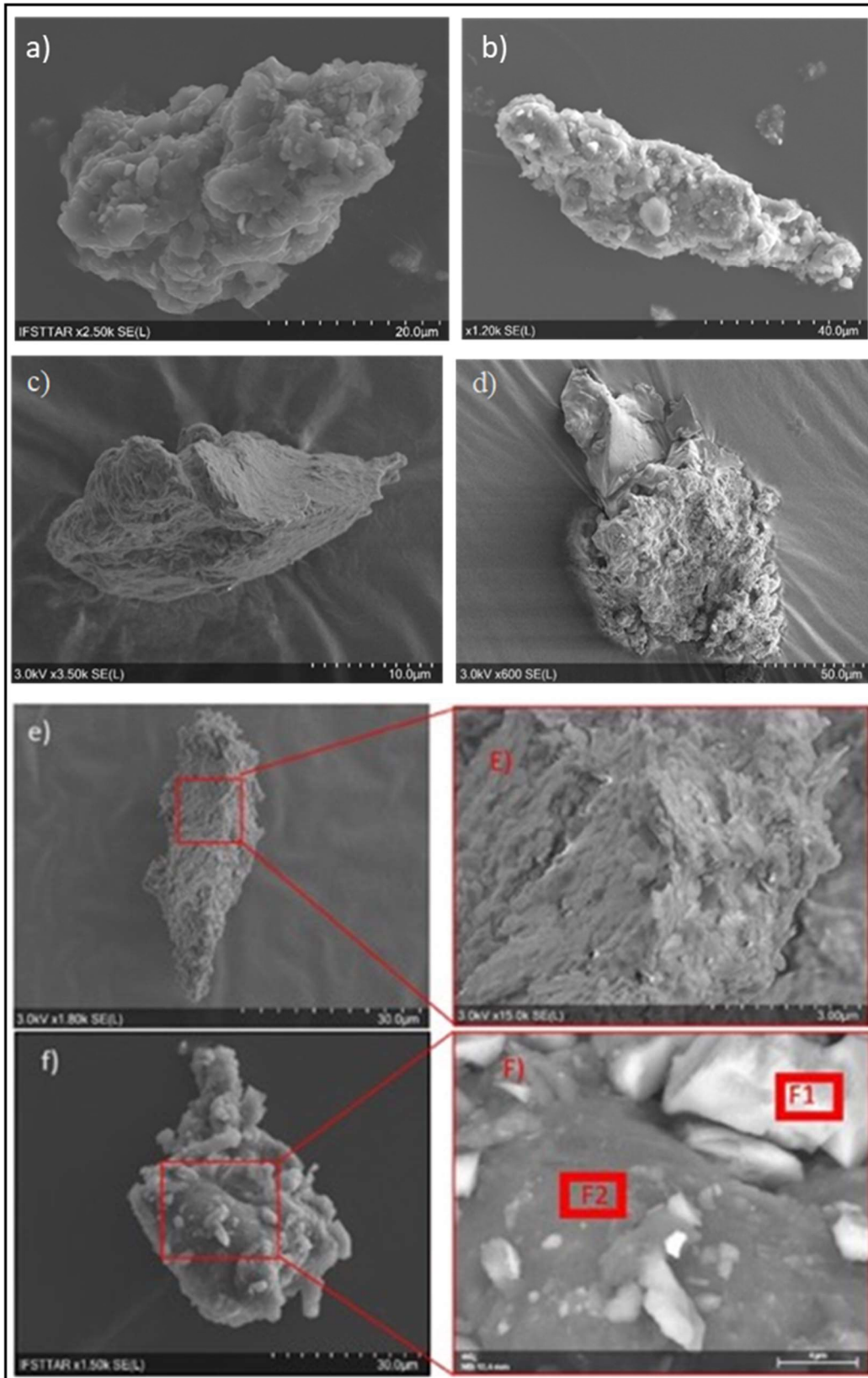
659 **Figure 3**

**On-road (R-) BWP - Micron fraction (PM<sub>1-10 μm</sub>)**



**On-road (R-) BWP - Submicron fraction (PM<sub>0.1-1 μm</sub>)**



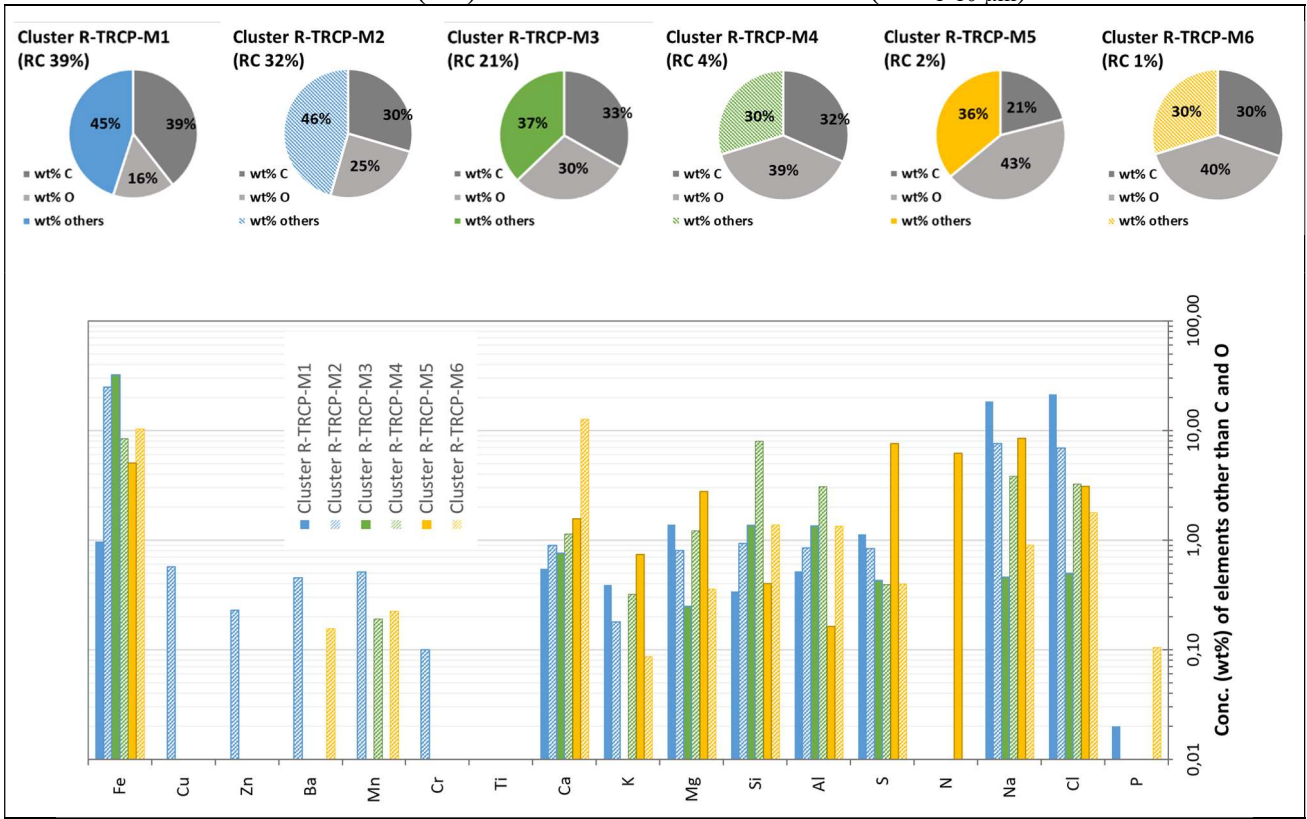


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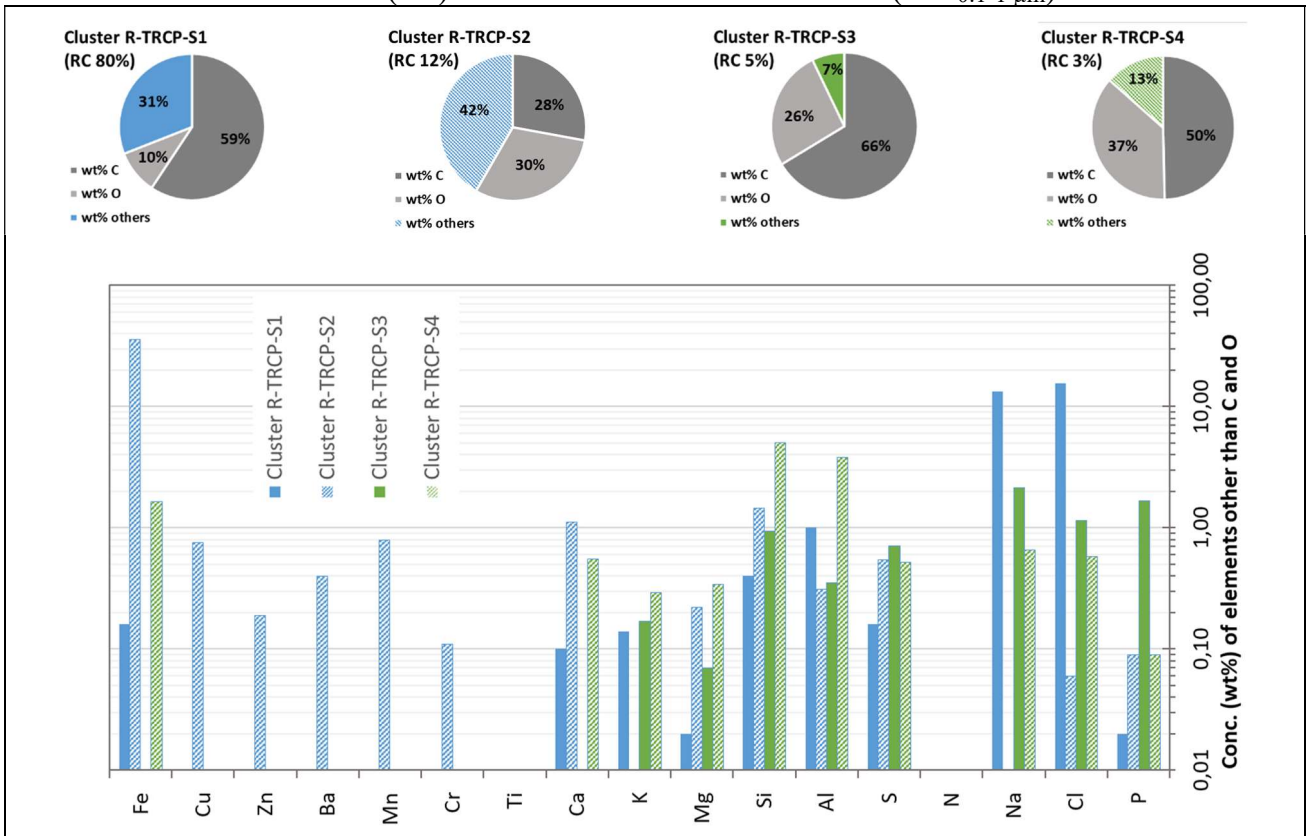
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On-road (R-) TRCP - Micron fraction (PM<sub>1-10 μm</sub>)



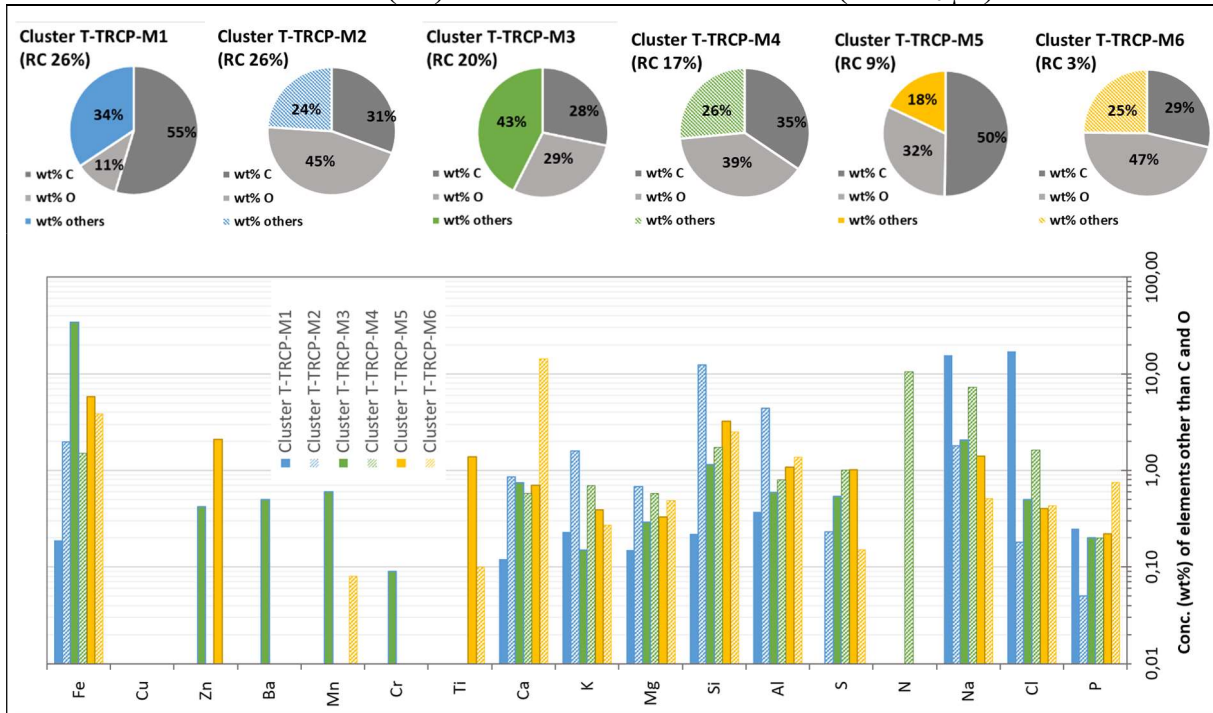
On-road (R-) TRCP - Submicron fraction (PM<sub>0.1-1 μm</sub>)



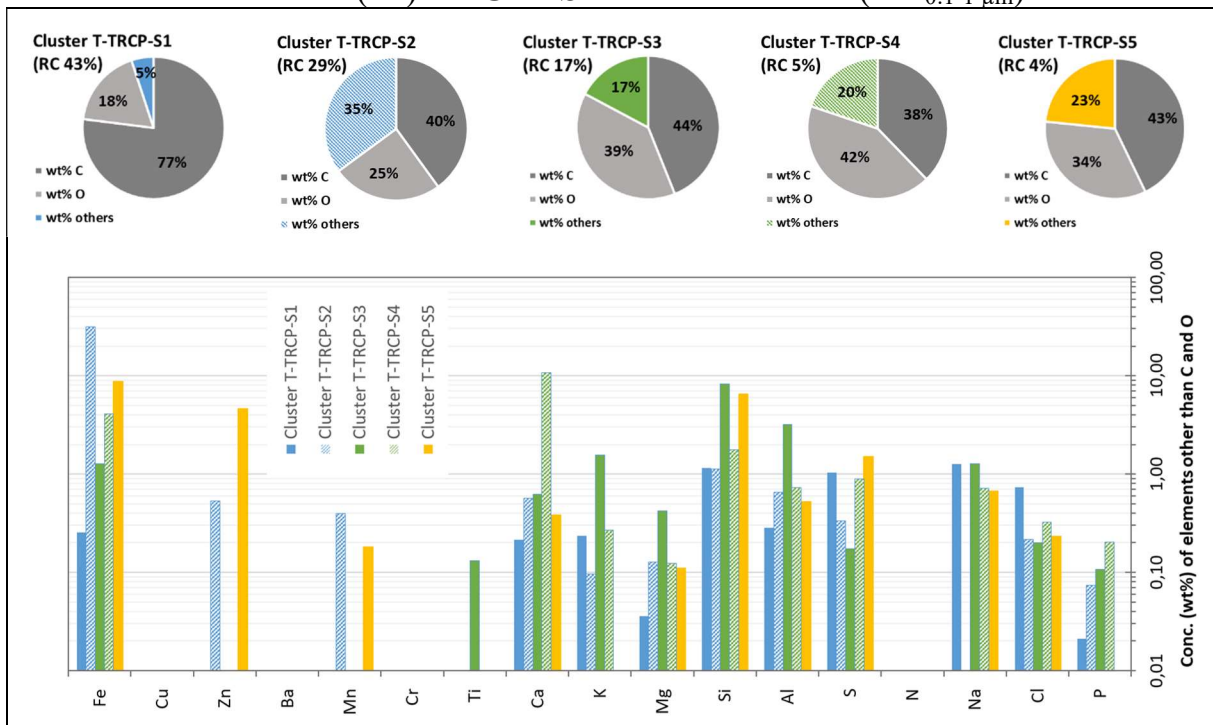
664 **Figure 6**

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**Test track (T-) TRCP - Micron fraction (PM<sub>1-10</sub> μm)**



**Test track (T-) TRCP - Submicron fraction (PM<sub>0.1-1</sub> μm)**



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