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To cite this version:

Ines Belkacem, Ali Helali, Salah Khardi, Khalifa Slimi. Investigations on vehicle non-exhaust particle emissions: real-time measurements. International Journal of Environmental Science and Technology, 2022, 19 (12), pp.11749-11762. 10.1007/s13762-022-03955-w . hal-03659795

HAL Id: hal-03659795

https://hal.science/hal-03659795v1

Submitted on 16 May 2023

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Investigations on vehicle non-exhaust particle emissions: real-time measurements

I. Belkacem[1] · A. Helali[2,3] · S. Khardi[4] · K. Slimi[1]

Abstract

Despite the potentially harmful effects on health and environmental impacts correlated with non-exhaust emissions (e.g., brake, tire and road wear and resuspension), but very limited environmental research studies have measured the contribution of vehicle non-exhaust emissions in real-world measurements and at different road segment types. Therefore, to fill this gap in academic literature, the main purpose of this study is to collect the knowledge base required to orient towards more sustainable mobility. During July 2019, continuous real-world measurements of non-exhaust particles (NEPs) were recorded over three different road segment types (urban, rural and motorway) in the city of Bron, near Lyon (France). Data were obtained using a native algorithm based on the GRIMM analyzer, series 1.108 Portable Aerosol Spectrometer. Results have confirmed abundant fine/coarse non-exhaust particle emissions which increase with the average vehicle speed and during sharp acceleration/deceleration manoeuvers. Motorway area has recorded the highest particle number concentrations as compared to urban and rural areas, which reaches 1.85×10^7 cm^{-3} due to increased vehicle speed, pavement materials and abrupt vehicle acceleration and deceleration maneuvers. In addition, the highest PM ratio was registered on motorway area and the lowest PM ratio appeared on urban road due to vehicle speed. It has been concluded that NEPs depended on the changes in driving conditions and road pavement type.

Keywords Air quality · Non-exhaust emissions · Real driving conditions · Particle number concentration · Road traffic

Introduction

Road traffic is the main source in the degradation of the ambient air quality (Belkacem et al. 2020, 2022; Silva et al. 2020). The total non-exhaust PM (PM2.5 and PM10) induced by light-duty vehicles worldwide will increase by 53.5% along with transport demand in 2030 as compared to 2017 (OECD 2020). Road, tire and brake wear emissions have developed from 39% of UK PM10 road traffic emissions in 2000 to 73% in 2018 and from 26% in 2000 to 67% in 2018 for PM2.5 (COMEAP 2020). Diesel particle filters DPFs are considerably effective tools for assessing diesel particulate emissions. This is accounted for by the fact that vehicle exhaust PM emissions in developed countries have decreased abruptly; on the other side, vehicle non-exhaust emissions now strongly exceed vehicle exhaust emissions (AQEG 2019). Emissions from road traffic can be classified into three different classes: (1) primary and secondary particles induced from vehicle exhaust; (2) primary and secondary particles produced from the tire, brake and road wear; (3) primary particles engendered from resuspension due to vehicle-wheel turbulence (Schauer et al. 2006; Thorpe and Harrison 2008; Mehel and Murzyn 2015). Resuspension and wear parts can be considered as non-exhaust emissions. Atmospheric Particulate Matter PM2.5 or fine PM are considered to cause 412, 000 premature deaths per year, including 33, 200 in France (European Environment Agency

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2015). The particles induced from road dust, tire, road surface and brake wear are emitted with a diameter <10μm, that induces a significant health risk for the human body. Despite the important burden of non-exhaust particle emissions on public health and the environment, few regulations target them explicitly (OECD 2020). This is due to the lack of uniform technique/protocol of measurements. According to the UK National Atmospheric Emissions Inventory (NAEI), the NEPs are strongly higher than exhaust emissions for both PM2.5 and PM10. The impact on NEP emissions remains unclear, as the evolution of the advanced propagation of regenerative braking systems (e.g., the energy recovery mechanism employed in electric vehicles that makers resistance braking through the vehicle's engine acting as a generator to transform kinetic energy into electrical energy) will probably mitigate brake wear emissions. This is because these vehicles require conventional friction braking for abrupt deceleration when stationary and at very limited speeds. Then again, ICE vehicles tend to be lower than electric vehicles; this is leading to decrease in resuspension and tire wear emissions (Timmers and Achten 2016; AQEG 2019; Eddows and Harrison 2021). Coarse and fine particles from non-exhaust sources have been related to short-term morbidity and mortality (Ostro et al. 2011; Meister et al. 2012). Small particles less than 10μm can easily penetrate into the bloodstream, lungs and hearts (Environmental Protection Agency 2017). However, in order to contribute to a productive and healthy indoor air environment, vehicle ventilation systems should be equipped with filters that are able to remove PM1 particles, since the smallest particles are the most harmful to human health like pulmonary inflammation and asthma exacerbation (Shao et al. 2017; Niu et al. 2020). It has been demonstrated that regularly exposure to nanoparticles may harmfully affect human health (Feng et al. 2020). A comparative study by Zwozdziak et al. (2016) demonstrated that PM1 has a greater effect on the lung function parameters compared to PM2.5 for school children aged between 13 and 14 years.

In order to realize a sustainable environment and mobility, it is important to quantify not only particle mass concentration but also particle number concentration. Given the pronounced negative impacts of particulate matter on human public health, it is incumbent on authorities on to mitigate these emissions.

Disc brakes are the most frequent type of braking system for the recent technological vehicle generation, including an abradable brake pad, which works on the brake disc (Grigoratos and Martini 2015a). Particles are engendered from the frictional wear during the braking action, but the fraction of this PM (less than 10μm) is not yet fully mastered (Grigoratos and Martini 2014a). In fact, the composition of brake friction material is frequently proprietary/confidential and can be influenced by the manufacturer and the tire of brake system (e.g., ceramic, non-asbestos organic, semi-metallic, etc.) (Grigoratos and Martini 2014b, 2015b; Thiyagarajan et al. 2015). There is a diversity of commercial brake friction materials which exceeds 200 ingredients. Tire and road wear particle emissions are induced when tires associate with the road surface through abrasion and friction (Grigoratos et al. 2018a; Singh et al. 2020). These particles are internally comprising and mix both the embedded road materials, depending on the type of road surface (e.g., concrete/asphalt) and the tread rubber (Grigoratos and Martini 2014b). The tire compositions are multiple, and their proprietary data make it complicated to estimate the tire tread composition. They contained a mixture of synthetic and natural rubbers (40–60%), vulcanization agents (2–5%), fillers (20–35%), textile and metal reinforcements (5–10%), process), process oils (12–15%) and additives (5–10%) (Panko et al. 2019; Baensch-Baltruschat et al. 2020). Road vehicle dust resuspension emissions are engendered by different mechanisms: turbulent micro-eddies, subsequent and attachment of material from the tire and road surface due to high-speed airflows, and movement of the vehicle as air is expelled from the tire (AQEG 2019; Harrison 2020). Various sources participate in the composition of road dust resuspension, which makes quantifying and separating the different emission sources quite difficult (Harrison 2020; Furger et al. 2020). Nevertheless, particle size distribution of resuspension is over 10μm, of which crustal and soil material reveal the dominant components in road dust (Kasimov et al. 2019; Huang et al. 2020).

Even though highly developed vehicle technologies have been made for mitigating PM emissions from motor exhausts, no actions were taken to reduce the non-exhaust proportion of emissions, inducing a substantial increase of the total emissions. The relative contribution of road and tire wear particles is anticipated to gradually multiply at short-medium-long term (Vanherle et al. 2021). Tire wear particles can also be constituted as evaporative emissions, resulting in the tire followed by coagulation and condensation (Jekel 2019). The emissions of tire road wear particles (TRWPs) constitute a major non-exhaust particles source (Kwak et al. 2013; Grigoratos and Martini 2015a), including the road surface wear and tires as well as the resuspension of road dust. Practically, in road transport, the most primary fine particles are produced from the exhaust, whereas coarse particles are mainly induced from non-exhaust sources (Grigoratos and Martini 2014a). The change in particle emissions is due to many factors, such as traffic conditions, meteorological, ambient particulate pollution, variation in tire composition and texture, driving style and road surface features (Grigoratos et al. 2018a; Park et al. 2018).

In order to take complete and accurate information about particle measurements, both laboratory and real-time measurements can be considered as complementary tools. In fact,

in real-time measurements, all driving and traffic conditions (driver behavior, road dust, road signs, etc.) will be taken into account. However, in laboratory measurements, it could be less difficult to distinguish between the four non-exhaust sources (tire, road, brake wear and resuspension). For this reason, laboratory measurements have been enhanced through on-road-real driving emissions (RDE) in order to surpass the limitation of each technique (Belkacem et al. 2021). In addition, laboratory studies are not suitable to represent the entire vehicle fleet, as tires and brakes that can change significantly between the performance and manufacturers specifications. Meanwhile, there may be dissimilarities between real-world and simulations conditions, including emissions driving styles.

A number of studies have been conducted towards characterizing the non-exhaust particles (NEPs) on road (Harrison et al. 2012; Kwak et al. 2013) or in the laboratory measurements (Grigoratos et al. 2018b; Foitzik et al. 2018). In addition, some studies have focused on evaluating the effect of acceleration and deceleration maneuvers, without taking into account the real traffic conditions (real driving conditions) (e.g., Kwak et al. 2014) or with a predefined test cycle (e.g., Pelkmans and Debal 2006). However, these latter mentioned conditions may not reflect real particle number concentrations.

Nowadays, data related to vehicle non-exhaust emissions are still insufficient. In particular, few research studies accurately measured the contribution of vehicle non-exhaust emissions (brake, tire and road surface wear and resuspension) via real-world measurements taking into consideration the real traffic conditions and driver behavior (e.g., speed, acceleration, etc.) in different road types including urban, rural, national roads and motorway areas. These deficiencies engender the evaluation of climate and health impacts, accurate vehicular emission inventories and the establishment of efficient regulatory measures to reduce air pollution in different road types. In addition, real-world measurements allow to determine several parameters under a wide range of conditions, which is not the case in laboratory measurements. They provide continuous time-series data at the unit time scale.

Fundamentally, this study tends to measure real NEPs in different road segment areas of Lyon—France; urban, rural, and motorway, during July 2019. In fact, implementing similar measurements and sampling methodologies are needed to provide comparative results. The parameters that were changed from one to another sampling day were; road type, vehicle speed and acceleration/deceleration maneuvers, while keeping the same driver during all measurement days. Thus, instantaneous particle emissions are applied in individual level analysis because they provide accurate spatial and temporal analyses. Finally, this research measured the effect of real vehicle speed profile and acceleration/deceleration maneuvers on NEP concentrations in urban, rural and motorway areas. In this study, results have confirmed abundant fine/coarse non-exhaust particle emissions in all sampling days. Motorway area has recorded the highest PNCs compared to urban and rural areas, this is due to high vehicle speed and pavement materials.

Materials and methods

Study areas

Measurements took place during July 2019 in the vicinity of Lyon (France). Lyon is France's second largest conurbation and third largest city; it is located in central-eastern of France between Paris and Marseille, in the Auvergne-Rhône-Alpes Region. The National Institute of Statistics and Economic Studies (INSEE) has estimated the population at 515,695 as of 2016, with location coordinates of 45° 45′ 35″ North, 4° 50′ 32″ East. The total mileage traveled for all sampling day measurements was approximately 172 km, including roundtrip literary. This large population number underscores the importance of this research through exposing the risk to the human body to different types of road traffic air pollution (specifically for urban and rural roads). Non-exhaust particle concentrations including resuspension, brake, tire and road surface wear were collected during the morning or evening, depending on climate conditions (Table 1). Emission thresholds are identified for compounds regulated in the year that a vehicle category is introduced on European roads: pre-1992 (Euro 0), 1992–95 (Euro 1), 1996–99 (Euro 2), 2000–04 (Euro 4), 2005 – 08 (Euro 4), 2009/2011–13 (Euro 5a/b) and 2014-present (Euro 6). Measurements have mainly been obtained in urban (Bron-Décines-Meyzieu), rural (Corbas-Saint-Just Chaleyssin) and motorway (A 46) (Fig. 1). The mileage traveled was not the same on all sampling days, it depended upon the road type (urban, rural or motorway).

Figure 1a depicts the first day's itinerary of mobile sampling measurements on an urban road. The operating mode was adjusted according to the speed, idle acceleration and time via the global positioning system (GPS) under real-world monitoring with a $1-s$ resolution. The itinerary was extended from Bron to Meyzieu. Figure 1b illustrates the rural itinerary (Corbas-Saint-Just Chaleyssin). Figure 1c represents the third day's mobile sampling itinerary along the *A*46 motorway. According to the official website of France's Ministry for the Ecological and Inclusive Transition (http://www.dir.centre-est.developpement-durable.gouv.fr/donnees197de-trafic-r87.html), the average traffic volume traveling on the *A*46 amounted to 85,760 vehicles per day, with 19% composed of Heavy Duty Vehicles (HDVs). In all sampled measurements, the current study has taken into

Table 1 Related data for all sampling measurement days

Measurement day	Direction	Road type	Distance (km)	Min. temp. (°C)	Max. temp (°C)	Mean temp. (°C)	Av. wind speed (km/h)	Precipitation (mm)	Av. vehicle speed (km/h)
D1	Forward	Urban	33	17	30	20	14	No	34
	Backward		32						
D2	Forward	Rural	15	17	31	21	8	No	40.00
	Backward		16						
D3	Forward	Motorway	35	18	32	24	3	No	89.82
	Backward		39.6						

account roundtrip itinerary. Table 1 lists detailed information on all the mobile measures, including time, road type, mileage traveled and direction. Three days of measurements were processed in order to evaluate non-exhaust particle concentrations for the three tested road types, again in both directions. Trip duration varied according to road type. One sample had been gathered for each direction route (two-samples a day). In fact, climate conditions (ambient temperature, humidity, wind direction and wind speed, etc.) could be changed, which might influence particle number concentration and particle mass concentration.

Instrumentations

Non-exhaust PM concentrations (PM1, PM2, PM10 and PM2.5/PM10) are measured using a light-scattering method because a real-world technique is always more suitable to assess rapid changes in PM levels. An optical particle counter (OPC, Grimm™, ref. EDM 108) was applied to measure PM concentrations at a flow rate of 1.2 L min^{-1} and time resolution of 6 s. A series of real-world measurements of particles were then taken with an optical diameter ranging from 0.35 to 22.5 µm size channels). This device had been calibrated by its manufacturer using dolomite dust. The instantaneous vehicle speed profiles have been recorded using the global positioning system (MOUCHARD GPS747 Pro). Before starting sampling measurements, GPS time and OPC time were synchronized.

Sampling and measurement strategies

Non-exhaust particle emissions (resuspension, tire, brake and road surface wear) were investigated under real-time driving conditions (continuous speed profiles, with different mileages varying between 32 up to around 75 km). The same tires have been used during all sampling measurement days. The registration year of the light utility vehicle used for sampling days was 2001, corresponding to Euro 3 class. It is a diesel-fueled utility vehicle.

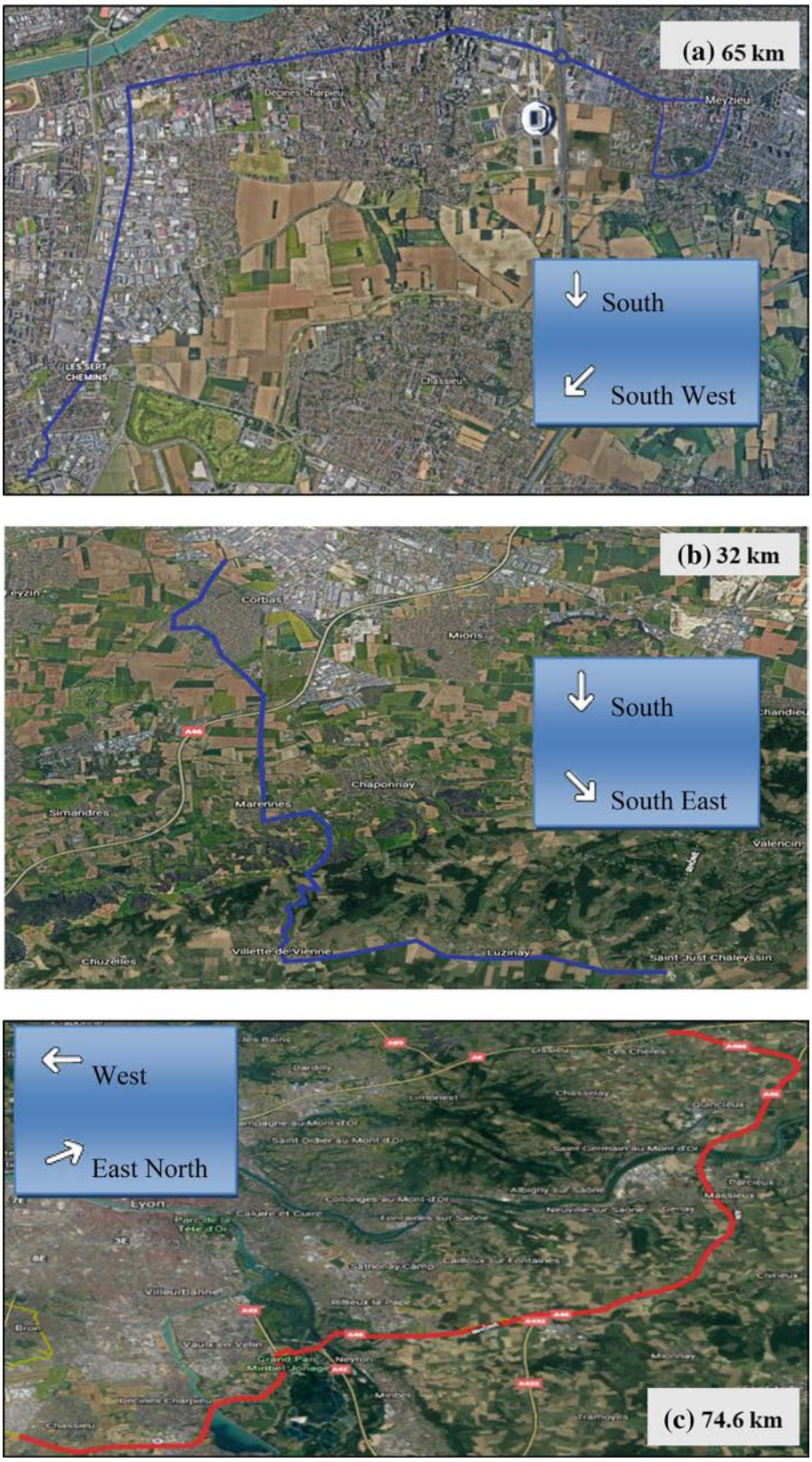
The summer tire (dimension $185/75R16C$-Michelin.) was chosen to study variation in wear and particle emission between different tires and roads under real-time conditions. Sampling measurements have been taken under dry weather conditions ($T = 17$–32 °C with 23–67% humidity) and moderate wind speed (<30 km h^{-1}).

The iso-kinetic sampling has been considered during all measurement days. The same driver was kept and maintained for all the experimentation in order to maintain the same driving style and conditions throughout all sampling days. Instantaneous speed profiles and instantaneous acceleration profiles were recorded at 1 Hz frequency regardless of driving conditions. The scientific instrument was installed behind the utility car. The GRIMM was chosen due to its small size and light weight compared to other atmospheric particle instruments (for example, PEMS, FMPS). In fact, heavy instruments may provide inaccurate data due to their weight on vehicle engine efficiency. A GRIMM did not require to power generators due to the built-in battery that lasts between six- to eight-hours continuous operations. Furthermore, the highest TRWPs are generally recorded in accumulation and coarse modes (Kim and Lee 2018; Beji et al. 2020). In addition, sampling measurements were registered under real-time driving characterized by high acceleration and deceleration maneuvers.

The inlet sampling probe was fixed in the axis of the wheel 5 cm from the ground, 10 cm behind the tire and with a diameter of 1 cm. PM could be divided into PM1.0, PM2.5 and PM10 based on the optical diameter smaller than 1 µm, 2.5 µm and 10 µm, respectively. The GRIMM efficiency for radial symmetric sampling is influenced by wind speed. INRS (2012) conducted a comparative study of GRIMM1.108 response against 6 other devices, namely TEOM1400, spectrometer TSI APS 3321, GRIMM1.109, LIGHTHOUSE HH3016IAQ, GLA 5000PVC and GLA 5000PVC. High suitability between GRIMM results and the six tested devices had been obtained.

Measurements were taken on three different road segments in the vicinity of Lyon (France). Thirty minutes were required before starting the trip in order to load all necessary

Fig. 1 Road map of the various study areas



tools inside the light utility vehicle. All staff members exercised caution not to exceed five hours of charging, which would have caused the battery to discharge. Moreover, before initiating each sampling measurement, zero calibrations were regulated on both the GRIMM1.108 aerosol spectrometers and the GPS. Next, a blank test was run for a 10-min duration using a filter in order to eliminate any stale lingering particle in the GRIMM pipe. During this process, one team member ensured that the standby button was activated before taking measurements.

Results and discussion

Particle number distributions under various driving conditions

Studies have reported the generation of ultrafine particles with diameters of 30–60 nm and particle with diameter sizer lower than 30 nm for studded and non-studded tires, respectively (Park et al. 2017; Foitzik et al. 2018), equally with the emission of a coarse fraction (Kwak et al. 2013; Kim and Lee 2018). The vehicle of the actual study was fitted with summer tires. Figure 2 presents the PNCs on various road segments (urban, rural and motorway). The particle number was characterized by a high concentration level with a diameter less than 1 m, which reaches up to 1.85×10^7 cm^{-3} on motorway. Whenever the particle diameter exceeded 1.3 m, the PNs decreased rapidly. It is worth pointing out that this trend stems from large particles being eliminated faster. This is because non-exhaust particles are essentially characterized by fine/coarse particles. We shall point out that during all measurement days, PNCs were characterized by a bimodal distribution with 0.35 and 1.3 m, respectively. It was found that cold start emissions (about the first 2 km of the trip) were composed of fine. In fact, we expect that cold tires can cause different brake and road wear than 2 km. The high temperature in the brake/rotor interface favors high fine particles. As demonstrated by Niemann et al. (2020), the high temperature can engender high brake particles. In addition, they outlined that the number of particles emitted showed a clear increase with brake temperature. In fact, in the beginning the brakes/tires are generally in a cold state, and then the temperature gradually increases due to the friction and the rise of acceleration/deceleration maneuvers.

However, in other available published studies when dealing with measurement of PNCs with an optical diameter ranging from 6 nm to 22.5 m, it was shown that bimodal distribution centered at approximately 200 nm and a coarse peak at 2 m (Beji et al. 2020). This slight difference in modal size could be explained by several factors including the difference in sampling methods, traffic conditions and instrumental properties. In fact, the current study has taken into account all real driving and traffic conditions (engendered

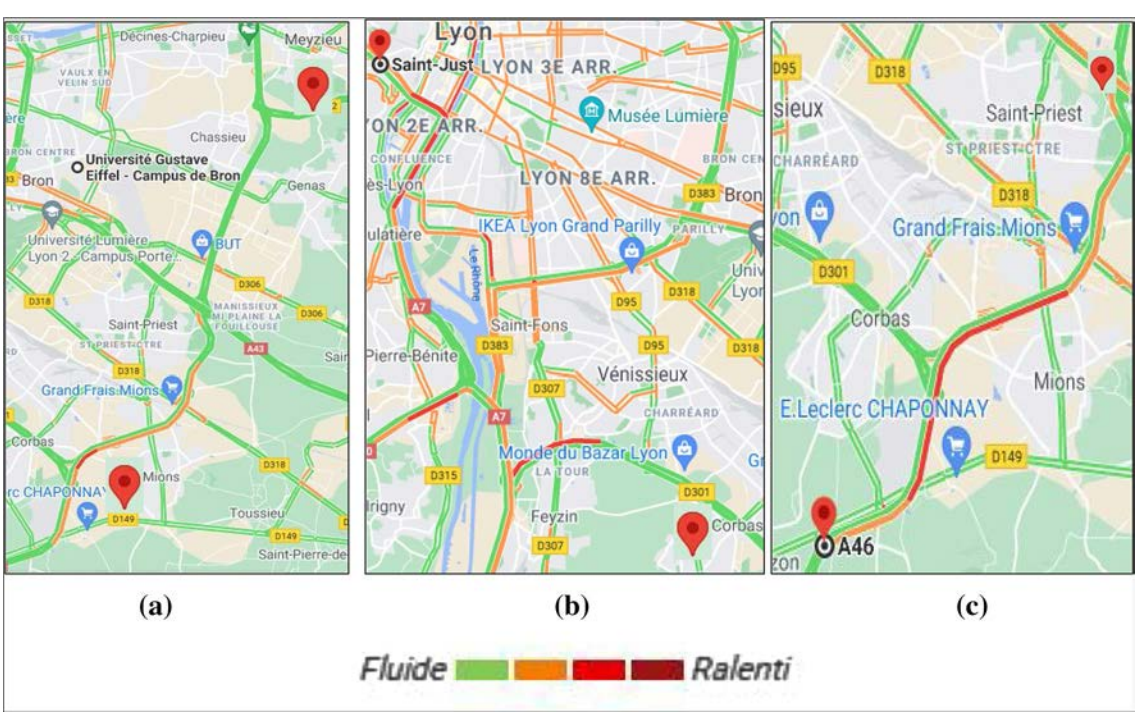


Fig. 2 corresponding road traffic maps

traffic (Fig. 2), road geometry, driver behavior (acceleration/deceleration maneuvers)).

Figure 3a reveals that on the urban road, the majority of sampled particles have diameters smaller than 0.35 m and extend to 1.9×10^6 cm^{-3}, followed by a second light peak at 1.3 m that reaches 1.49×10^5 cm^{-3}. The same trends are shown in Fig. 3b. The highest particle concentrations appeared at 0.35 μm with 3.4×10^6 cm^{-3} in rural area. The

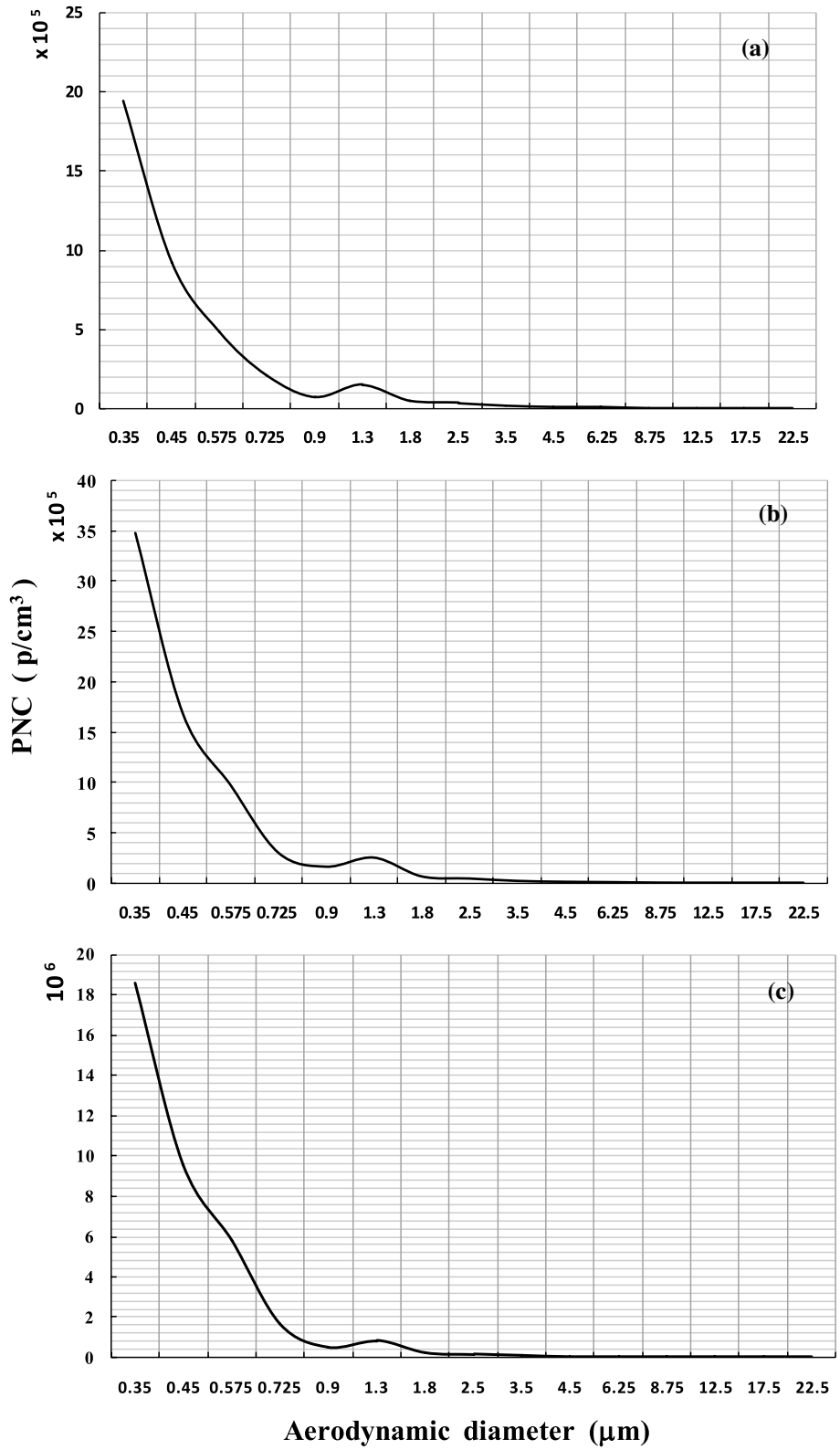


Fig. 3 Non-exhaust particle size distributions under real driving conditions in urban (**a**), rural (**b**) and motorway (**c**) areas

high concentration on rural road as compared to urban road can be explained by the high vehicle speed. Figure 3c illustrates particle size distributions on motorway. The maximum motorway PNCs were higher than both obtained in urban and rural zones, which reached as high as 1.8×10^{7} cm^{-3} due to high speed, pavement materials and abrupt vehicle acceleration and deceleration maneuvers.

Generally, concrete roads (motorway) are more pollutant than asphalt roads (urban–rural), as verified by Rogula-Kozłowska et al. (2014). They demonstrated that concrete surfaces cause more tire abrasion than asphalt surfaces; PM emissions are 1.4–2 times higher for concrete roads than for asphalt roads. However, this result remains relative and depends upon the tire type, drive behavior and climate conditions. In addition, a study conducted by Penkala et al. (2018) demonstrated that asphalt surface causes less tire abrasion than concrete. Moreover, the motorway area is characterized by high speed which favors the change of resuspension emissions, especially in dry road surface conditions, which favor the increase of vehicle induced turbulence (road dust resuspension).

Effect of average vehicle speed on PM concentrations

In real-time measurements, different instantaneous speed profiles depending on road type (urban, rural and motorway) were taken into account to investigate the effect of vehicle speed on PM mass. Figure 4 shows the average PM10 and PM2.5 concentrations. It is worth noting that the increase of PM concentrations was related to the average driving speed conditions. In fact, the highest PM ratio appeared on the motorway due to high vehicle speed ($V_{m1}{}^{5} = 89.82$ km h^{-1}). In contrast, the lowest PM ratio was found on urban road ($V_{m2}{}^{6} = 34.92$ km h^{-1}) as validated by several studies (i.e., Grigoratos et al. 2018; Kim and Lee 2018; Beji et al. 2020). The relative contribution of PM2.5 to PM10 (the ratio PM2.5/PM10) varied from 0.31 to 0.435. However, Kim and Lee (2018) reported lower values compared to our obtained results, where they reported 0.24 up to 0.32 as the contribution of PM2.5 to PM10. This is because particulate matter from road traffic is also induced from resuspension in addition to tire, brake and road wear, which is not the case in laboratory measurements. Indeed, particulate matter resuspension could be defined as freshly produced particles from abrasion and stress as well as older located road dust refreshed and transported into the atmosphere.

The results show that PM concentrations were positively correlated with the average vehicle speed. Particles occur through volatilization and by shearing Kreider et al. (2010) and friction forces. In fact, the shearing forces mechanism practically induces coarse particles, whereas the volatile mechanism produces smaller fine particles via evaporation (Kim and Lee 2018).

Under real-time measurements, the shear stress acting on tire tread was wide, mainly on the motorway due to high speed and the state of the tire. Indeed, the used tire in this experience is not put into circulation for the first time. Contrary to what was found by Kim and Lee (2018), limited shear stress was acting on tire tread with low PM10 particles. This can be explained by the difference in experimentation as in this current study, we took into account all real driving conditions including road dust emissions induced by mechanical vibration sieve Wang et al. (2012), which is not the case for laboratory measurements. In this study, non-exhaust PM10 concentration presents 64.58 µm cm^{-3}. The pronounced volatilization process related to high speed was produced on the motorway as well as on rural roads

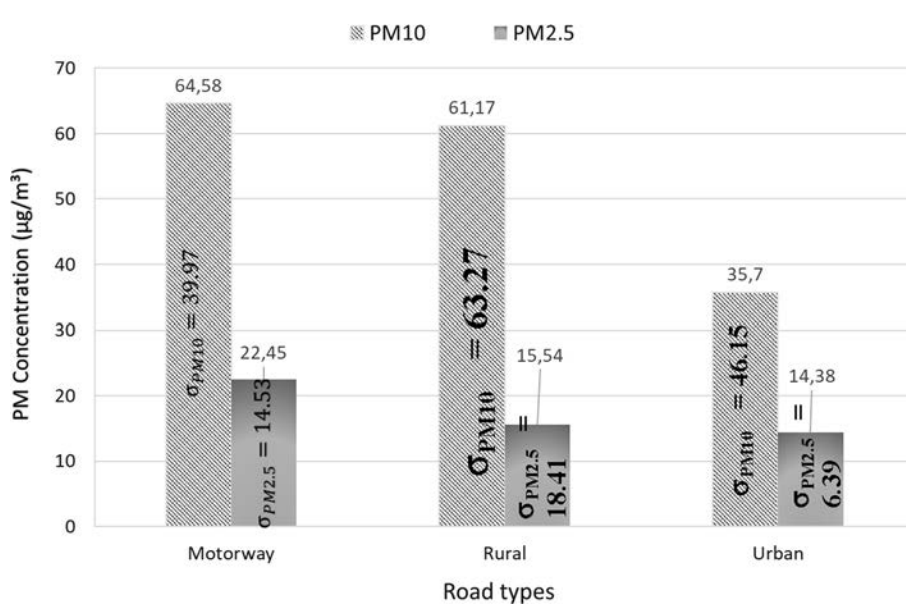


Fig. 4 Average particulate PM10 and PM2.5 concentrations and standard deviations

(ring). In fact, the selected rural road geometry features a curvature that requires more power from the engine and higher speed in order to ensure equilibrium in the middle of the roadway. Moreover, it is characterized by high traffic density, especially by the heavy vehicle category. Here, we notice that the increase in non-exhaust PM concentration is strongly related to road pavement material (concrete/asphalt) and to the increase of the average vehicle speed vice versa as validated by several studies (i.e., Grigoratos et al. 2018b; Kim and Lee 2018; Beji et al. 2020). This might be due to turbulence air streams, suspension, increasing road wear of accumulated particles and a high proportion of heavy-duty vehicles (HDVs). In fact, Wagner et al. (2018) conducted a review paper where they outlined that HDVs produced approximately ten times more TWP than passenger cars and light duty vehicles (LDVs).

Figure 5 shows that the particulate mass concentration is significantly correlated with the average vehicle speed, as demonstrated in OECD (2020). The coefficients of determinations were 0.83 and 0.85 for PM10 and PM2.5, respectively.

Vehicle speed effect on particle number concentrations

In order to investigate the effect of vehicle speed on the evolution of particles (in terms of number concentration) induced from non-exhaust in the range of 0.35–22.5 m, simultaneous assessment is taken out applying the GPS for vehicle speed on different road surface types (urban, rural and motorway). The variation in the total number of non-exhaust concentrations versus vehicle speed in urban, rural and motorways is provided in Fig. 6a–c, respectively. The maximum PNCs were measured on motorway 1.8×10^7 cm^{-3}, while le minimum PNCs were gathered on urban area 1.9×10^6 cm^{-3}. These findings may be explained by the high speed on motorway resulting in a substantial increase of PNCs as outlined by Béji et al. (2020). Obviously, this result highlights an increase in the coarse particles at high speed. This is because more shear stresses and turbulent air streams developing at the road tire pavement interface induced an increase in particle concentrations. Consequently, a remarkable change took place in the super-micron fraction of the wheel rear ambient aerosol. This current work and other available published studies have confirmed that vehicle speed is an important parameter to be considered to accomplish strategies to mitigate non-exhaust particle emissions from road traffic (i.e., Foitzik et al. 2018).

Positive and negative vehicle acceleration effects on non-exhaust particle concentrations

In order to evaluate the influence of vehicle speed on non-exhaust particle concentrations, it is important to include acceleration and deceleration (A/D) maneuvers in the analysis. In specific road geometry (curvature with sharp radius, speed bumps, etc.), traffic conditions (congested traffic, accident, etc.) and driver behavior (aggressive driving) (Luhana et al. 2004), both acceleration and deceleration maneuvers can engender a pronounced effect on non-exhaust emissions. Significant non-exhaust particle concentrations were registered in coarse mode during A/D cycles (Fig. 7). Figure 7a shows NEP concentrations versus positive and negative acceleration in an urban area. It demonstrates several negative acceleration maneuvers due to speed bumps, pedestrian crossing and traffic light. Abrupt positive vehicle acceleration [10–38 ms^{-2}] induced abundant NEP concentrations. This significant increase in particles rate that varies from 1.79×10^4 to 1.07×10^5 cm^{-3} may be explained by differing generation mechanisms like

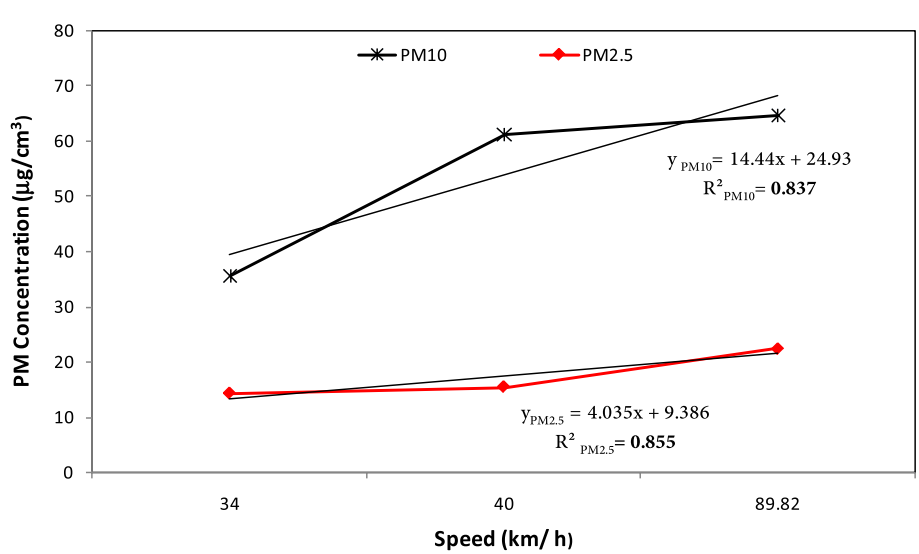


Fig. 5 PM concentration versus average vehicle speed

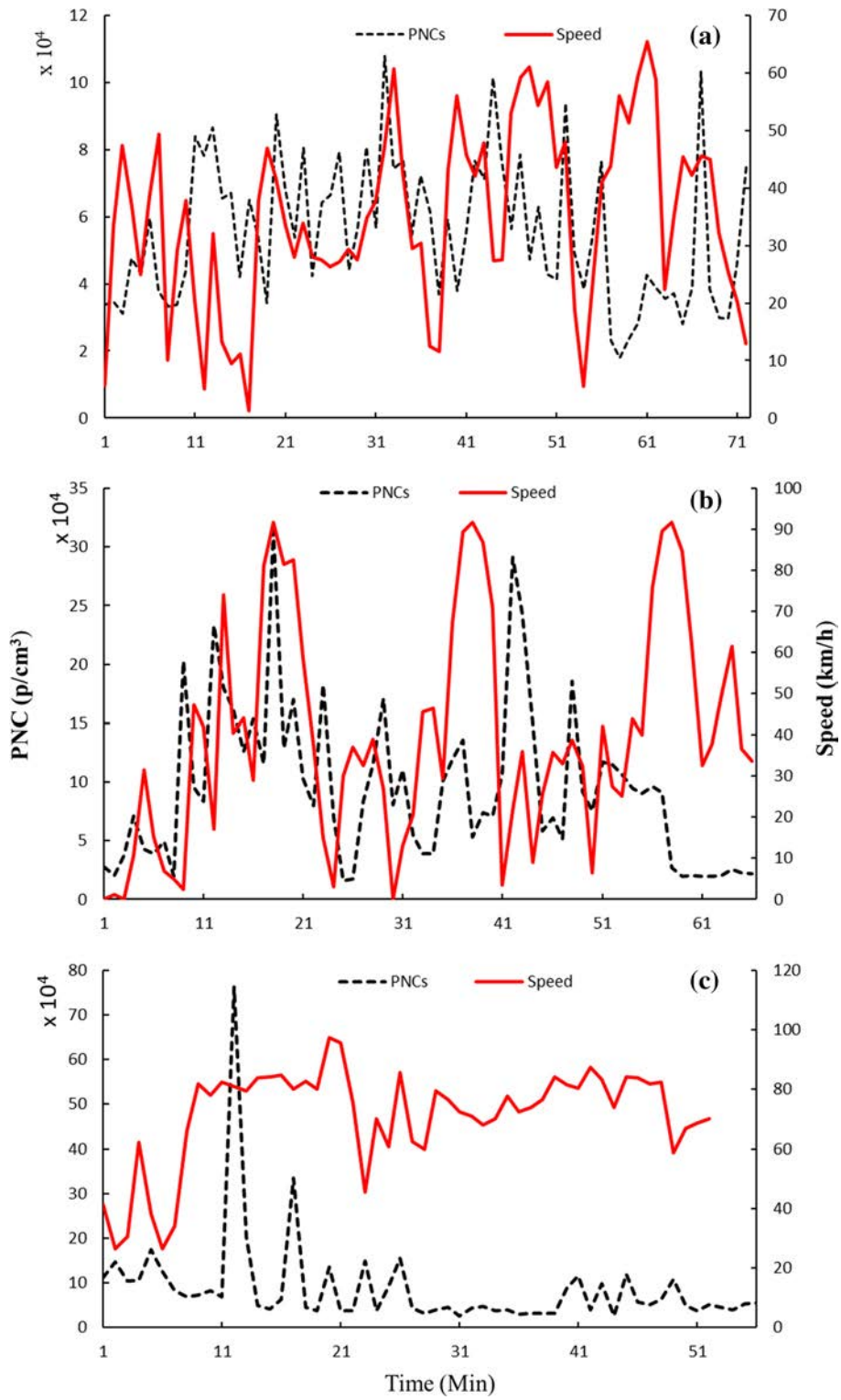


Fig. 6 Vehicle speed versus total number of concentrations recorded in urban, rural and motorway areas

tire wear under elevated temperature or related with a more abundant road dust fragmentation. Figure 7b illustrates NEP concentrations versus positive and negative acceleration in rural area. The geometry of the rural road is generally characterized by a high curvature change radius, thus requiring more A/D maneuvers. The rural NEP concentrations were 3 times higher when comparing the positive vehicle acceleration passing from (−24) to (+57.13) ms^{-2}. In contrast, with stable speed where the positive and negative vehicle acceleration were around zero, it showed a significant decrease

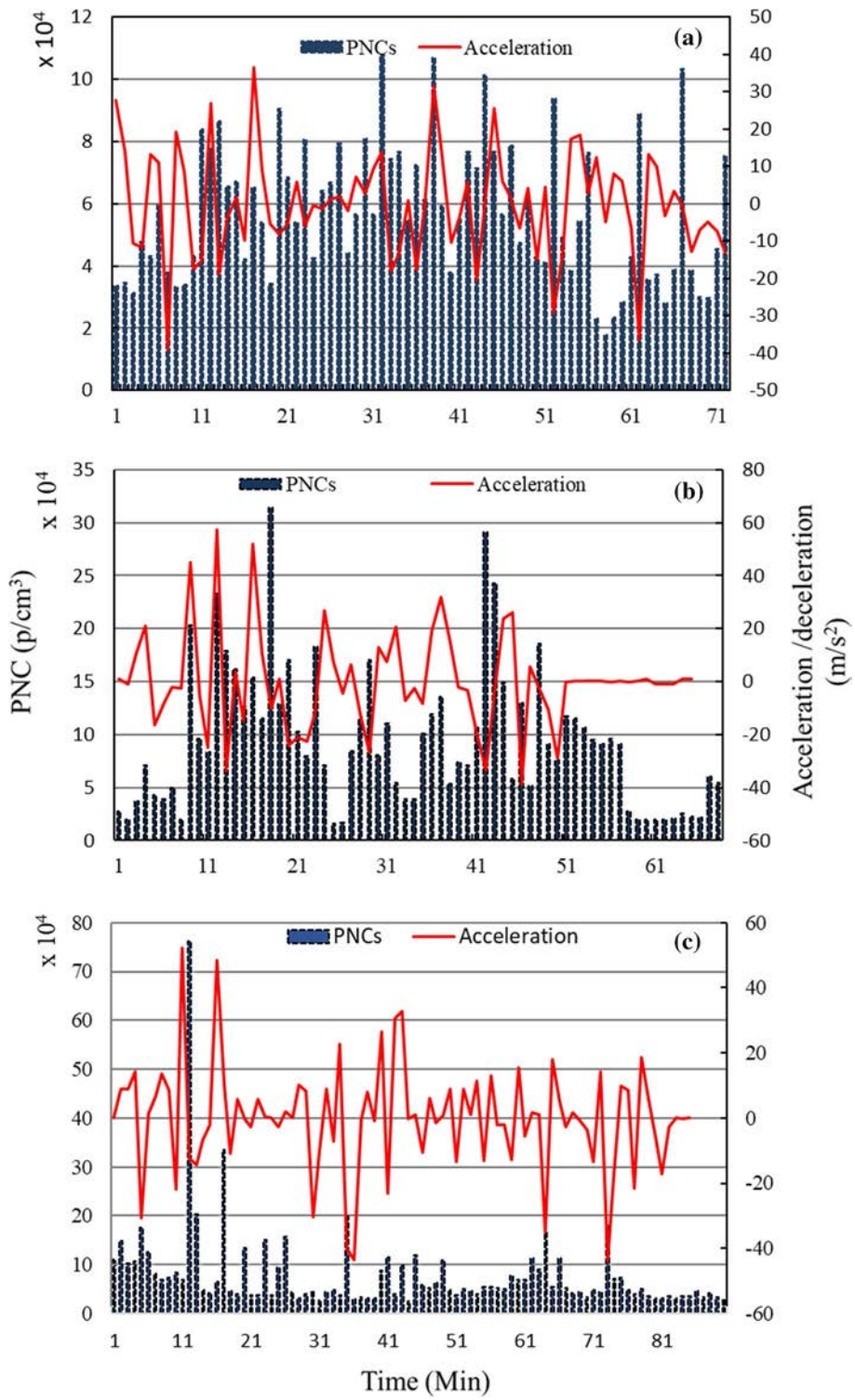


Fig. 7 Evolution of non-exhaust particle concentrations versus positive and negative accelerations in urban (**a**), rural (**b**) and motorway (**c**) areas

in NEP concentrations. Rural road is characterized by sharp rate of positive and negative vehicle due to road geometric (curvatures) and road maintenance during measurement days. Figure 7c indicates motorway NEP concentrations versus positive and negative acceleration maneuvers. The NEP concentrations were 11 times higher when comparing the negative vehicle acceleration passing from (+52) to (−12) ms^{-2}. The significant increase in NEP concentrations with sharp positive and negative vehicle acceleration maneuvers suggests that aggressive driving produces more abundantly tire road wear particles than with an economical driving style (Boulter 2005; Kwak et al. 2013). Despite that, the

urban area is distinguished by a high rate of vehicle A/D maneuvers, while not admitting the highest particle emissions. This is because in the urban area, generally the speed does not exceed 50 km/h^{-1}, which cannot engender a sharp vehicle A/D maneuvers. Unlike to motorway and rural roads, with a sudden vehicle A/D maneuvers can engender extreme A/D rates.

Conclusion

Three different road segment types have been controlled in real-time measurements, using the same equipment and sampling protocol, which allow to obtain complementary knowledge of vehicle speed effect on non-exhaust particle emissions (resuspension, tire, brake and road wear). On motorway real-time driving conditions, the NEP concentrations are higher in comparison with particles induced in rural and urban areas due to high speed, pavement materials and abrupt vehicle acceleration and deceleration maneuvers. NEP concentrations were characterized by a bimodal distribution at coarse modes with 0.35 and 1.3 μm ranges, respectively, within the three selected measurement days. Large coarse NEP concentrations were formed from the road dust resuspension, under stress of the tire with the pavement. Information gathered on the key parameters assessing non-exhaust particles in real-time measurements can be employed to issue recommendations considered to mitigate non-exhaust particle emissions and ensure a sustainable mobility. The speed, sharp positive and negative vehicle acceleration maneuvers have a pronounced effect on NEP concentrations. The relative contribution of PM2.5 to PM10 (the ratio PM2.5/PM10) varied from 0.31 to 0.435. The abundant increase in NEPs with abrupt positive and negative vehicle acceleration maneuvers propounds that irrational driving generates more significantly non-exhaust particles than with rational (economic) driving style. Therefore, road users must be made aware of the importance of Eco-Driving (Training and Education). In addition, a green infrastructure is applied, which tends to mitigate pollution with suspended particles by filtration and absorption. Moreover, NEP concentrations can vary with driving style and conditions. In addition, it has been demonstrated that tire road wear can engender substantial particles with respect to mass and/or number concentration. Furthermore, NEPs could be significant contributors to particles in motorway areas. Further researches on real-time measurements should be conducted to definitively define the effects of NEPs on human health, climate change and environment impact. In fact, this study presents some limitations related to the ability to differentiate between the four sources (tire, road, brake wear and resuspension) of non-exhaust emissions.

Measuring non-exhaust PNC and PMC in real-time measurements, taking into account real traffic conditions, makes it possible to distinguish which variable has the greatest impact on non-exhaust particles. Other parameters could be taken into consideration in future studies such as weight and climate conditions, etc. This gives more reflections in research in order to improve the ambient air and human health, ensuring a sustainable environment and mobility.

Acknowledgements The authors gratefully acknowledge the University of Monastir and the National Engineering School of Monastir for having sponsored periods of residence in France to conduct this research. Thanks are also extended to the University of Gustave Eiffel (Ex- IFSTTAR) for its technical and logistical supports.

Authors' contribution IB was involved in the conceptualization, methodology, data curation, visualization and writing—original draft. AH contributed to the supervision, visualization, investigation and validation. SK helped in the supervision, investigation, writing—review and editing, validation. KS was involved in the supervision, investigation, validation, writing—review and editing.

Declarations

Conflict of interest The authors hereby declare that they have no known competing financial interests or personal relationships that in any way could have influenced the work reported in this paper.

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