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Particulate Emissions of Euro 4 Motorcycles and Sampling Considerations

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Abstract: The scientific literature indicates that solid particle number (SPN) emissions of motorcycles are usually higher than that of passenger cars. The L-category (e.g., mopeds, motorcycles) Euro 4 and 5 environmental steps were designed to reduce the emissions of particulate matter and ozone precursors such as nitrogen oxides and hydrocarbons. In this study the SPN emissions of one moped and eight motorcycles, all fulfilling the Euro 4 standards, were measured with a SPN measurement system employing a catalytic stripper to minimize volatile artefacts. Although the particulate matter mass emissions were <1.5 mg/km for all vehicles tested, two motorcycles and the moped were close to the SPN limit for passenger cars (6×10^{11} particles/km with sizes larger than 23 nm) and four motorcycles exceeded the limit by a factor of up to four. The measurement repeatability was satisfactory (deviation from the mean 10%) and concentration differences between tailpipe and dilution tunnel were small, indicating that performing robust SPN measurements for regulatory control purposes is feasible. However, steady state tests with the moped showed major differences between the tailpipe and the dilution tunnel sampling points for sub-23 nm particles. Thus, the measurement procedures of particles for small displacement engine mopeds and motorcycles need to be better defined for a possible future introduction in regulations.

Keywords: air pollution; powered two-wheelers; L-category; solid particle number (SPN); particulate matter (PM) mass; artefacts; tailpipe; dilution tunnel (CVS); WMTC; sub-23 nm

1. Introduction

Particulate matter (PM) is damaging to ecosystems and cultural sites, responsible for reduced visibility and an important global risk factor for human health [1]. Ultrafine particles (particles with diameter smaller than 100 nm) typically provide the greatest contribution to total particle count, especially in urban environments [2,3], but a very small contribution to total volume and mass [3,4]. Ultrafine particles have been associated with short-term cardiorespiratory and central nervous system adverse health effects [5]. Clinical and toxicological studies have shown that ultrafine particles can act through mechanisms that are not shared with larger particles [4]. For this reason, surface area or particle number concentrations may be better predictors of health effects than mass concentration [4,6]. The ultrafine particles in urban areas can either be primary particles from emission sources such as traffic [2,4,7], or secondary particles formed by gaseous precursors [8], with the internal combustion engines being a major source of these precursors [9].

Automotive exhaust PM, due to its important contribution to ambient PM [10], has been subject to continuously more stringent regulations worldwide. PM mass emissions are determined worldwide gravimetrically by collecting diluted exhaust gas on a filter [11]. In addition to the PM method, in the European Union (EU), a non-volatile (solid) particle number (SPN) method is enforced for light-duty and heavy-duty vehicles. Under this method, particles with diameter >23 nm surviving a thermal pretreatment stage at 350 °C are considered to be non-volatile particles [12]. The SPN limit value for passenger cars is 6×10^{11} particles per km (p/km from now on) [13]. The SPN regulation was initially applicable to light-duty diesel vehicles, but subsequently covered on-road and off-road heavy-duty engines and also gasoline direct injection light-duty vehicles, as well as inland navigation vessels. Recently, the European Commission decided to extend the lowest detection size of the SPN methodology to 10 nm [14], to cover cases that have a high fraction of particles in the 10 nm to 23 nm size range (e.g., some vehicles with spark ignition engines) [15–17].

One source of ultrafine particles are mopeds (engine displacement <50 cm^3) and motorcycles, collectively called powered two-wheelers (PTW). The registered PTW accounted for 33.8 million vehicles in EU-28 in 2016, about 10% of the passengers mobility fleet [18,19]. In Italy the registered PTW in 2016 were more than 9 million, or 27% of the EU-28 PTW fleet. The year 2018 closed with a 10% increase and a 31% decrease of motorcycles and moped new vehicle registrations, respectively, compared to 2017. During the first 3 months of 2019, the registrations of mopeds and motorcycles increased compared to the registration levels of the same period in 2018. This means that the EU PTW circulating fleet is increasing, as well as the share of motorcycles compared to mopeds [20].

In 1997, Directive 97/24/EC implemented Euro 1 standards to reduce air pollutant emissions from two- and three-wheel vehicles, which are referred to in later directives as Category L vehicles. Directive 2002/51/EC and Directive 2003/77/EC introduced the Euro 2 and 3 standards for motorcycles; the latter further tightened with a new driving cycle introduced by Directive 2006/72/EC. The Euro 3 package, in particular, included motorcycle emissions at cold engine start (cold start emissions, hereon) as part of the type-approval procedure. The cold start test was extended to the moped later in 2014. Regulation (EU) No 168/2013 in 2013 and supplemental technical Regulation (EU) 134/2014 in 2014 repealed previous EU legislation on L-category by implementing the Euro 4 (2016–2017) and Euro 5 (2020–2021) packages which among other provisions: 1) introduced a new emission test cycle for some vehicle types, 2) tightened the gaseous compounds emission limits, 3) expanded the number of L-subcategories, and 4) introduced a PM limit. The scope was to keep constant or reduce the share of total road-transport emissions from L-category vehicles as compared to other road vehicle categories with a focus on PM and ozone precursors such as nitrogen oxides and hydrocarbons. The PM mass limit was set for compression ignition (CI) and CI/hybrid vehicles at a lenient level of 80 mg/km in Euro 4 and reduced to 4.5 mg/km (the same as for passenger cars) in Euro 5 with extension to gasoline direct injection engines.

The relative contribution of mopeds and motorcycles to PM emissions started to increase as the levels from other vehicles started to decrease. The particulate emissions of two-stroke PTW have been studied by many researchers (e.g., references [21–37]) exceeding 100 mg/km and 10^{13} p/km in most cases. Two-stroke mopeds emit significant amounts of aromatic volatile organic compounds and also produce significant secondary organic aerosol [9,34]. Four-stroke mopeds [26,27,33,34,38,39] and motorcycles [23,29,35–37,40–43] have generally lower SPN emissions, but in most cases above the limit applicable for passenger cars. Data for the latest Euro 4 PTW are limited (e.g., reference [44]). Most importantly, there is neither a legislated nor a standardized procedure to measure particle number emissions for this category of vehicles. Regulation (EU) 168/2013 required an ex-post environmental effect study [45] which should inter alia assess the feasibility of a SPN limit for L-category [46]. In the absence of a standardized procedure, some researchers sample from the tailpipe (e.g., reference [24,26]), while others from the full dilution tunnel without specifying lengths and residence times in the tubing (e.g., reference [46]). Physical processes such as particle agglomeration, diffusion and thermophoresis can decrease the concentration from the tailpipe to the dilution tunnel [17,47,48]. Desorption of semi-volatile components from this tubing can also result in volatile artefacts, i.e. re-nucleation of volatile species downstream of the evaporation tube that are counted as solid particles [46,49]. The objective of this paper is to present particulate emissions of Euro 4 PTW in terms of PM mass and SPN. In addition, particles below the current lower size defined in the passenger cars regulation

(23 nm) will be investigated, because high sub-23 nm fractions have been reported for this category of vehicles [16,44,46]. Potential issues with SPN measurements for future regulations will also be discussed.

2. Experiments

The tests were conducted in the Vehicle Emissions Laboratory (VELA 1) of the European Commission—Joint Research Centre (JRC) in Ispra, Italy. VELA 1 is a climatic emission test cell with a single axis roller dynamometer used for passenger cars and motorcycles. The exhaust of the vehicles was connected to a full dilution tunnel with constant volume sampling (CVS) (Figure 1). All connections were with stainless steel parts. No elastomers were used because at high temperatures they can release semi-volatile species that could affect the mass or number measurements and they are not allowed in the light-duty vehicles regulations. The flow rate of the CVS was 5.5 m^3/min (0.12 kg/s). The temperature of the cell was 23–25 °C.

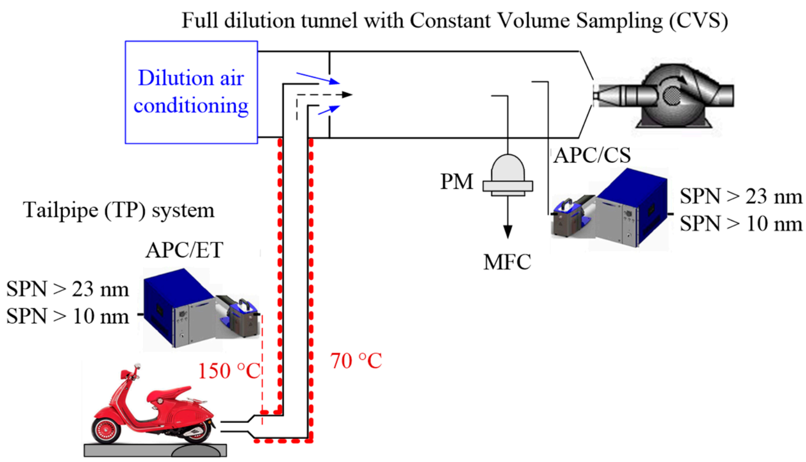


Figure 1. Experimental setup. SPN = Solid particle number; APC = AVL particle counter; ET = Evaporation tube; CS = Catalytic stripper; PM = Particulate matter; MFC = Mass flow controller.

The PM mass was determined with filter measurements, as described in the Regulation (EU) 2014/134. The flow rate through the filter was 50 L/min. TX40 filters of 47 mm diameter were used.

The SPN measurement system connected to the dilution tunnel was the AVL particle counter (APC) 489 (AVL, Graz, Austria), compliant with the light-duty vehicle regulations [50]. Previous studies suggest that both solid and volatile artefacts appear in SPN systems when 10 nm measurements are conducted and catalytic strippers are recommended for sub-23 nm measurements [51]. For this reason, the volatile particle remover (VPR) of the measurement system consisted of a hot diluter kept at 150 °C, a catalytic stripper at 350 °C [52], and a final porous diluter operating with room-temperature filtered air. The system was calibrated by the manufacturer. The so called particle number concentration reduction factor (PCRF) that expresses concentration reduction due to the combined effects of dilution and average particle losses at 30 nm, 50 nm and 100 nm, was approximately 250 (25 × 10). Downstream of the VPR a butanol condensation particle counter (CPC) (model TSI 3790) [53,54] with 50% counting efficiency at 23 nm and a butanol CPC (model TSI 3772) [55] with 50% counting efficiency at 10 nm were connected to measure solid particles. No additional particle losses for sub-23 nm particles were applied. The additional particles below 23 nm reported in this work (i.e. the difference of the 10 nm and 23 nm CPCs) would be 1.7 times higher with loss correction [17]. The additional particles that reside below 23 nm were calculated as:

$$\text{Additional sub-23 nm} = SPN_{10} / SPN_{23} - 1 \quad (2)$$

In order to investigate the differences between tailpipe and CVS measurements, an identical combination of instruments was connected to the tailpipe with a 0.5 m heated line at 120 °C for a few tests using moped #1 and motorcycle #8 (see details below). Due to limited instrument availability, instead of catalytic stripper, an evaporation tube was included as a VPR. In order to minimize artefacts [56], we used high primary dilution (200) with a total PCRF of the system at the tailpipe of 2000 (200 × 10).

The powered two-wheelers (PTW) that were tested are summarized in Table 1. Three of them (#6, #7, #9) were used in another study [44] where results had been averaged with older vehicles of the same category and presented in aggregated form. In this study we instead used disaggregated results, and a particle counting system with additionally a catalytic stripper. The following subcategories were covered (definitions according to Regulation 168/2013):

- 2-wheel mopeds (L1e-B) with engine displacement ≤ 50 cm^3, maximum speed ≤ 45 km/h, and power ≤ 4 kW.
- Low performance motorcycles (L3e-A1) with engine displacement ≤ 125 cm^3, power/weight ratio ≤ 0.1 kW/kg, and maximum power ≤ 11 kW.
- Medium performance motorcycles (L3e-A2) with power/weight ratio ≤ 0.2 kW/kg, and maximum power ≤ 35 kW.
- High performance motorcycles (L3e-A3) with power/weight ratio > 0.2 kW/kg, and maximum power > 35 kW.

Table 1. Characteristics of the Powered Two-Wheelers (PTW). All Euro 4 gasoline 4-stroke engines with port fuel injection and three-way catalyst as exhaust after-treatment. Fuel E5.

Code	Category	Power (kW)	Displ. (cm^3)	MY	TR	Max Speed (km/h)	Mileage (km)	Mass [1] (kg)	Power/Mass (kW/kg)
#1	L1e-B	2.4	50	2018	CVT	45	500	98	0.02
#2	L3e-A1	9.0	125	2016	MT	95	2350	142	0.06
#3	L3e-A2	11.0	155	2017	CVT	101	1000	157	0.07
#4	L3e-A2	15.6	278	2018	CVT	115	300	158	0.10
#5	L3e-A2	18.5	279	2016	CVT	128	1000	179	0.10
#6	L3e-A2	18.5	280	2015	CVT	128	3100	179	0.10
#7	L3e-A2	32.0	693	2016	MT	120	1000	162	0.20
#8	L3e-A3	103.0	798	2018	MT	>140	850	209	0.49
#9	L3e-A3	92.0	1170	2015	MT	>140	1150	254	0.36

[1] Mass in running order (including 10 kg for coolant, oil, fuel). MY = Model year; TR = Transmission; MT = Manual Transmission; CVT = Continuously Variable Transmission.

Reference fuel with 5% ethanol content was used. The test cycle was the world-harmonised motorcycle test cycle (WMTC) applicable to Euro 4 motorcycles and from 2020 to all Euro 5 PTW. The WMTC consists of 5 different speed profiles depending on maximum vehicle speed and engine displacement and corresponds to the type-approval cycle for all vehicles in Table 1 except for the moped (L1e-B) which was type approved under the UNECE (United Nations Economic Commission for Europe) Regulation 47 procedure. The WMTC and its parts are plotted in Figure 2. Table 2 gives the applicable parts of the test cycle for each PTW. For example, PTW #4–7 were tested with part 1 (engine cold start) followed by part 2 (warm engine conditions). Details for the UNECE Regulation 47 cycle can be found elsewhere [44,46]. We used the weighting factors of the cold and hot phases (Table 2) for both Euro 4 and Euro 5 specifications in order to explore the impact of future provisions. The weighting factors are legislative prescribed percentages (sum equals 100%) that give different importance at the different parts of the test cycle (see Regulation EU 134/2014).

The PCRF corrected concentrations [p/m^3] of the CPCs of the system connected to the tailpipe were multiplied by the PTW exhaust flow rate [kg/s] (Appendix A) and divided by the exhaust gas density to calculate particles per second (p/s). The PCRF corrected concentrations of the CPCs of the system connected to the dilution tunnel were multiplied by the CVS flow rate (0.12 kg/s) and divided by the air density. The applied densities (1.29 kg/m^3) were at the same conditions that the CPCs concentrations were normalised to (0 °C, 101.3 kPa). The instantaneous values were integrated for each phase and divided with the respective distance. Details can be found elsewhere [17].

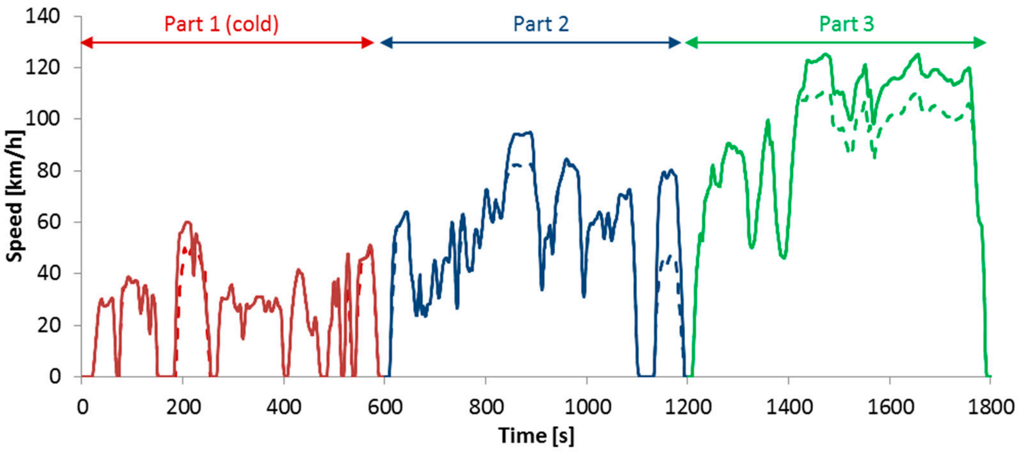


Figure 2. Test cycle (WMTC) and parts. Dashed lines show the reduced speed version.

Table 2. Test cycles for each PTW. P1-P3 refer to parts 1–3 of the driving cycle (Figure 2). Reduced = reduced speed profiles as in Regulation 2014/134.

Code	Category	WMTC	Parts	WF (Euro 4)	WF (Euro 5)
#1	L1e-B	1	P1 + P1 (reduced)	30-70	50-50
#2	L3e-A1	1	P1 + P1 (reduced)	30-70	50-50
#3	L3e-A2	2-1	P1 + P2 (reduced)	30-70	50-50
#4	L3e-A2	2-2	P1 + P2	30-70	50-50
#5	L3e-A2	2-2	P1 + P2	30-70	50-50
#6	L3e-A2	2-2	P1 + P2	30-70	50-50
#7	L3e-A2	2-2	P1 + P2	30-70	50-50
#8	L3e-A3	3-2	P1 + P2 +P3	25-50-25	25-50-25
#9	L3e-A3	3-2	P1 + P2 + P3	25-50-25	25-50-25

WF = Weighting factors.

3. Results

The PM mass emissions per vehicle are given in Figure 3. For PTW #5 no PM measurements were taken and for #4 and #8 only one filter for the complete cycle. Note that for the PTW specific to this study, no PM mass limit is applicable in Euro 4 or Euro 5 standards. All vehicles emitted <1.5 mg/km, which is even much below the future Euro 5 PM mass limit for diesel and gasoline direct injection L-category engines. The variability of the measurements expressed as difference of maximum value from the mean of two measurements was on average 28% (range 8–53%) or 0.25 mg/km.

Figure 4 summarizes the SPN emissions measured at the dilution tunnel of all vehicles with the weighting factors of Euro 4 or Euro 5 provisions. The SPN limit for passenger cars is used as a guide to the eye (dashed line) in order to put the PTW levels in context with the existing legislative framework. This level should not be taken as a future PTW limit value or as a threshold which qualifies or disqualifies the environmental performance of the vehicles in this study.

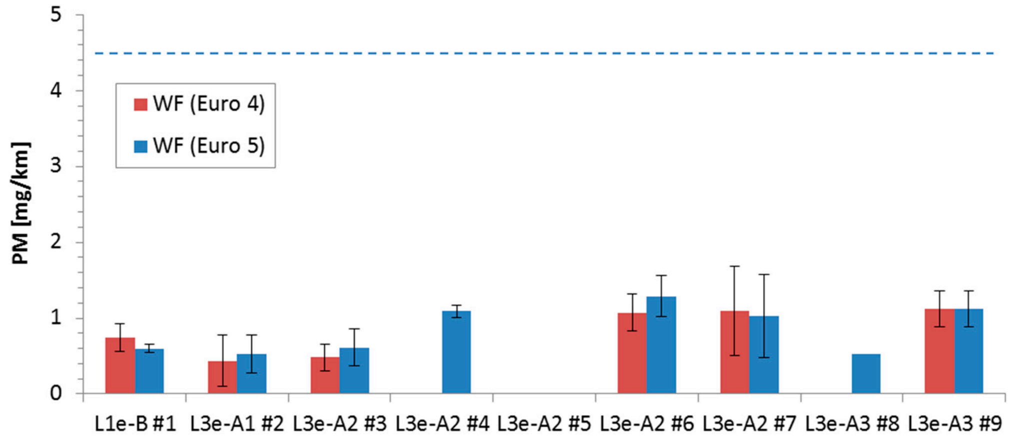


Figure 3. Particulate matter (PM) mass emissions. The cycle tested was the WMTC (Figure 2) with the weighting factors (WF) of Table 2. Exception: L1e-B Euro 4 test cycle was from UNECE Regulation 47. The dashed line shows the PM limit for Euro 5 diesel and gasoline direct injection PTW (and light-duty vehicles). Error bars show min-max values of two repetitions.

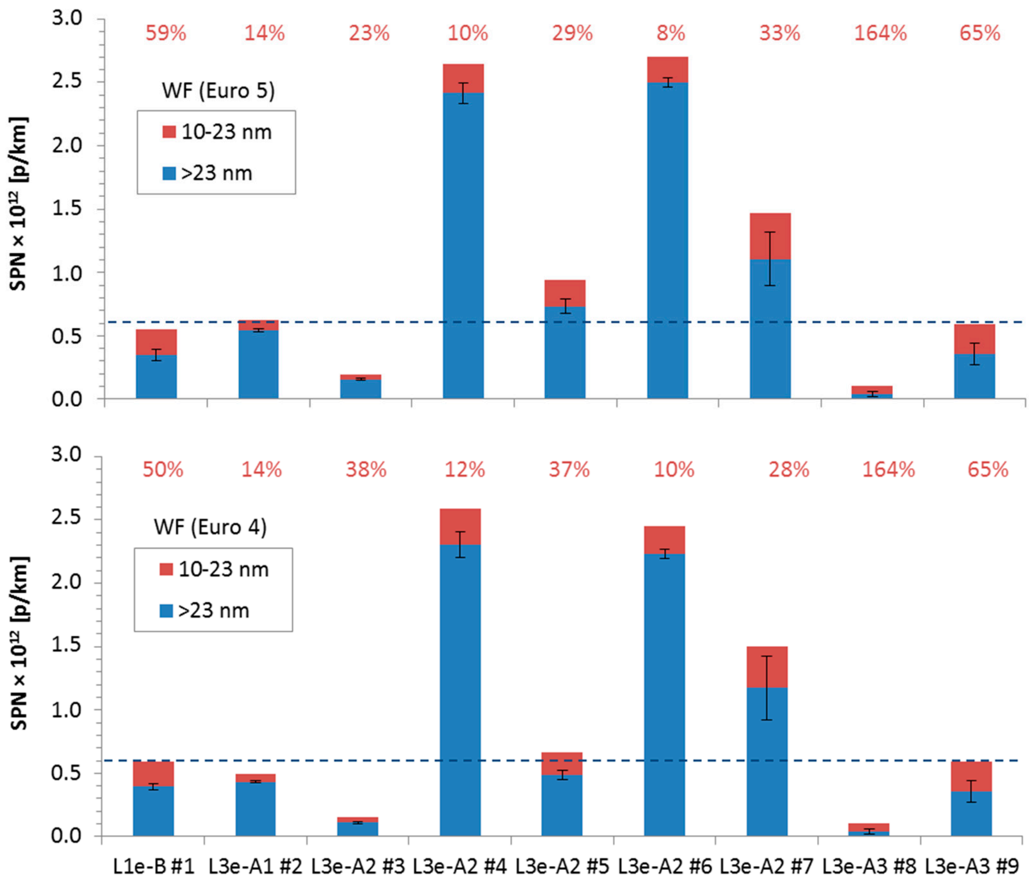


Figure 4. Solid particle number (SPN) emissions. The cycle tested was the WMTC (Figure 2) with the Euro 5 (upper panel) and Euro 4 (lower panel) weighting factors (WF) of Table 2. Exception: L1e-B Euro 4 test cycle was from UNECE Regulation 47. The dashed line shows the SPN > 23 nm limit for diesel and gasoline direct injection passenger cars. Percentages on top show the additional particles that reside below 23 nm (Equation (1)).

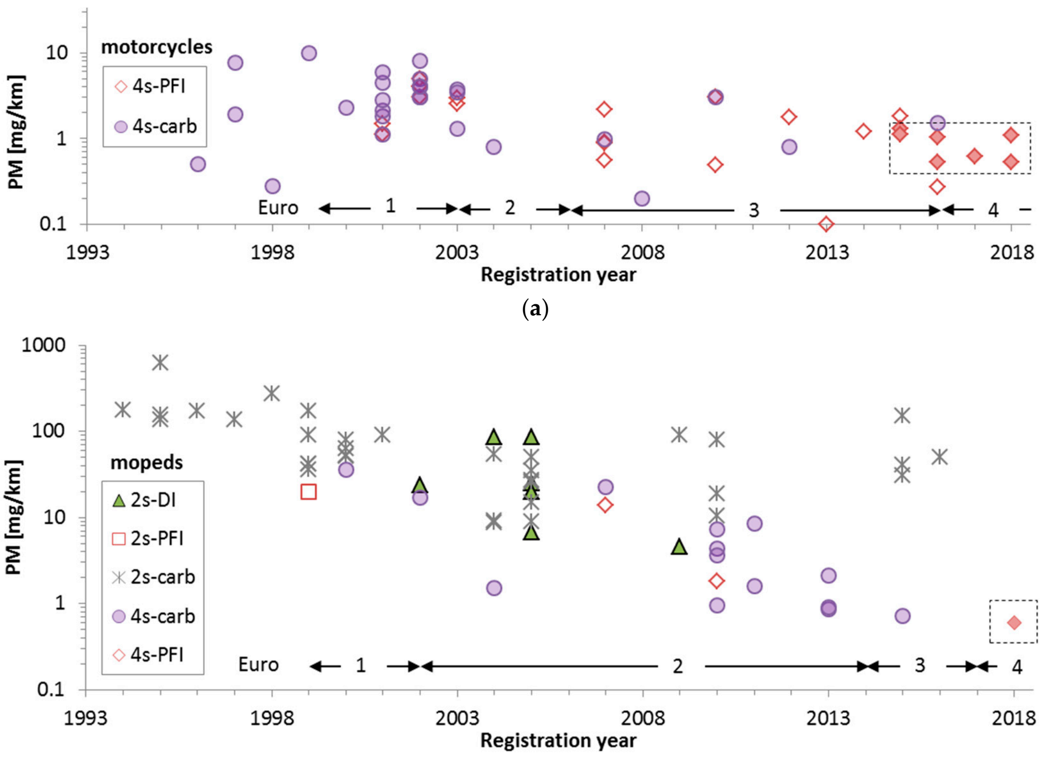
By applying the Euro 5 weighting factors (upper panel), 4 out of 9 exceed the SPN > 23 nm limit for passenger cars. Three more PTW were close to the limit when the sub-23 nm particles were also considered. The contribution of sub-23 nm particles was 8–65%, with one exception (164%) for a low emitting vehicle (L3e-A3). The SPN > 23 nm emission levels varied from 1.5 × 10^{11} p/km to 2.5 × 10^{12} p/km. There was no particular trend in terms of model year, motorcycle manufacturer, maximum power or engine capacity. Applying the Euro 4 weighting factors (lower panel) the results were similar, indicating that the cold start contribution was small for these PTW. For SPN > 10 nm, the first part was on average 80% higher than the second part excluding the L3e-A2 #5 (6 times higher) and the moped (3 times higher).

The variability of the measurements expressed as difference of maximum value from the mean of 2 measurements was on average 10% (range 1–24%), with the exception of L3e-A3 #8 (50%) where the emissions were very low at 2 × 10^{10} p/km.

4. Discussion

4.1. Emission Levels

Figures 5 and 6 summarize the PM mass and SPN (with different lower sizes) emissions respectively reported in the literature for motorcycles (upper panel) and mopeds (lower panel), with 2-stroke (2s) or 4-stroke (4s) engines, with carburettor (carb), direct injection (DI) or port fuel injection (PFI). The emissions are given as a function of the registration year. When the year was not available, it was assumed to be two years before the published year of the specific paper. When the Euro standard was given, the year was adjusted to match the specific Euro period.



(**a**)

(**b**)

Figure 5. Particulate matter (PM) mass emissions from the literature (details in text) for (**a**) motorcycles and (**b**) mopeds with 2-stroke (2s) or 4-stroke (4s) engines with carburettor (carb), direct injection (DI) or port fuel injection (PFI). The vehicles of this study are in dotted boxes.

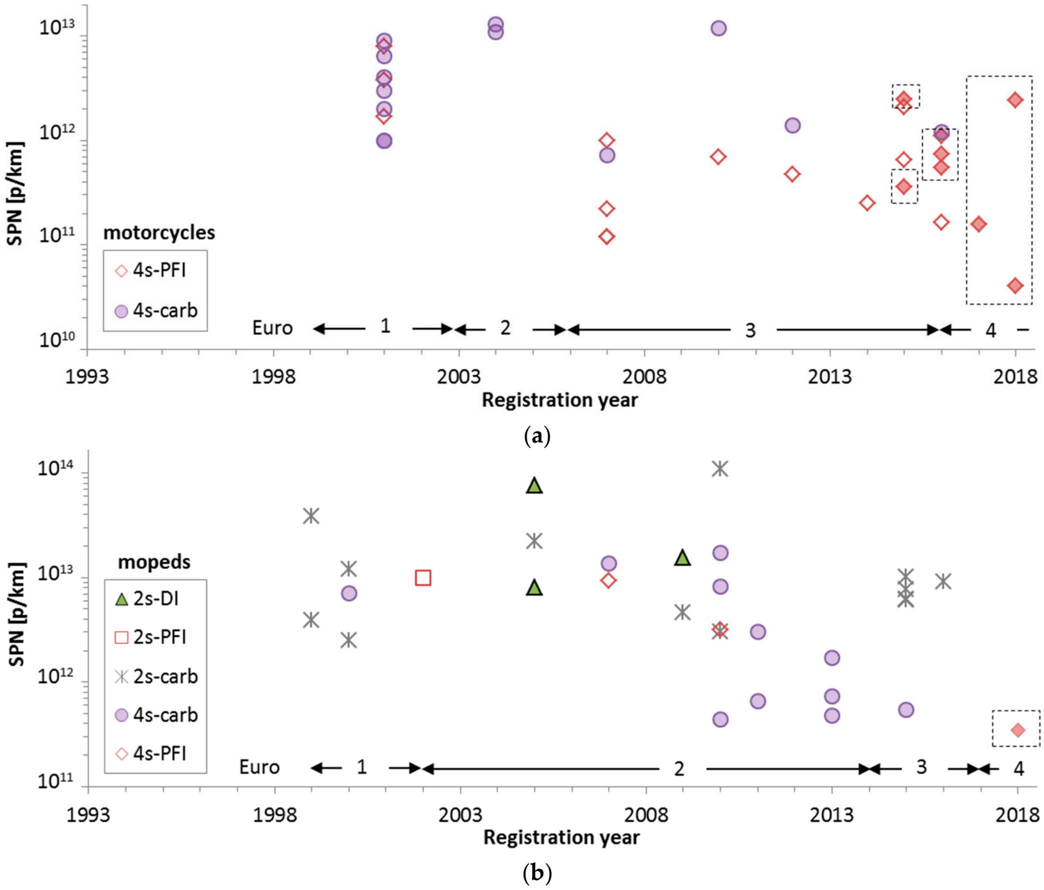


Figure 6. Solid particle number (SPN) emissions from the literature (details in text) for (**a**) motorcycles and (**b**) mopeds with 2-stroke (2s) or 4-stroke (4s) engines with carburettor (carb), direct injection (DI) or port fuel injection (PFI). The vehicles of this study are in dotted boxes.

The PM emission levels of the Euro 4 PTW that we examined were below <1.5 mg/km (Figure 5). As far as the authors are aware, there are no literature data on Euro 4 mopeds and very limited data on Euro 4 motorcycles [44], which were included in this paper. Comparing with older type approved mopeds (Euro 2) (Figure 5), the PM mass levels for 4-stroke mopeds, as the one in our study, reported in the literature show large variations: From less than 4.5 mg/km [26,27,34,44] to higher values [38,39] reaching even 36 mg/km [33]. The emissions though are much lower than two-stroke mopeds with carburettor [21–23,25–36,44], direct injection [24,27,30–32,36], or port fuel injection [35,36] that can exceed 100 mg/km in many cases. There is also no clear difference among the different technologies (direct injection, carburettor and port fuel injection) for 2-stroke engines raising concerns that future PM limit will be applied only to positive ignition direct injection engines. However, it is expected that the 2-stroke mopeds market share will be significantly reduced in the Euro 5 step due to their demanding costs to comply with hydrocarbons emission limits [44,45]. The PM mass levels for 4-stroke motorcycles reported in the literature vary in a smaller range: they are typically less than 4.5 mg/km [35–37,40–44] but with a few older models with a carburettor [23,37,42] reaching up to 10 mg/km.

The reported SPN emission of 4-stroke mopeds (Euro 2 or before) (Figure 6) range from 4×10^{11} p/km to 1.7×10^{13} p/km [27,33,39,44], thus the moped of our study (3.5×10^{11} p/km) was slightly below the low end. The 2-stroke engines have on average higher emissions [21,27,32,33,35,44]. The reported SPN emission of 4-stroke motorcycles range from 10^{11} p/km to 1.3×10^{13} p/km [33,35,37,41,43,44]. SPN emissions of the Euro 4 motorcycles in our study ranged from 4×10^{10} p/km to 2.5×10^{12} p/km, indicating that emissions have decreased with technology improvements. The likely cause is the reduction in total hydrocarbons from Euro 2 to Euro 4 [44] that also requires better control of fuel enrichment during transients. It should also be mentioned that in some literature instances the reported emissions were without any thermal pre-treatment, thus emission levels might have appeared to be higher due to the presence of the volatile nucleation mode. In addition, in our tests we used a catalytic stripper which is less prone to artefacts, while other studies with evaporation tube and lower size limit below 23 nm overestimate the emissions due to artefacts [44,46].

4.2. Correlation PM–SPN

Figure 7 shows the correlation between integrated PM mass and dilution tunnel SPN > 23 nm over the different parts and total duration of WMTC. Considering only the data from the first two parts, the slope is 1.2×10^{12} p/mg which is at the low end of the range reported for passenger cars and heavy-duty vehicles ($1–4 \times 10^{12}$ p/mg) [12,57]. The low value indicates that the PM mass comprises a significant fraction of volatile species, originating either from the PTW emissions or the sampling system as such. The so called "filter artefact" for TX40 filters is well known and has been reported to be around 1 mg/km [12,58,59]. It is unlikely that the low slope was due to large particles, typically seen with 2-stroke engines, because it is not common for 4-stroke engines [46]. The high SPN emitting vehicles (#4 and #6) lie above the correlation line. The point of the 3rd phase shows a high mass compared to the number of solid particles. The high mass could be attributed to released material from the sampling lines or incomplete combustion at the high speed (and exhaust gas temperatures) part of the cycle.

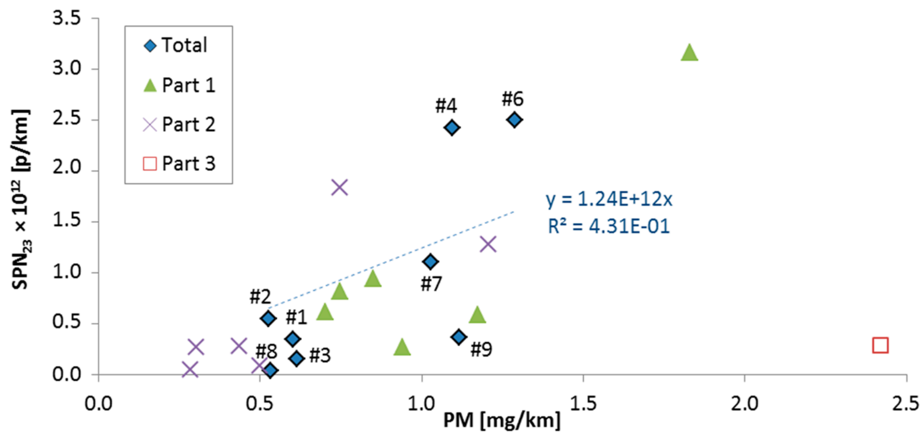


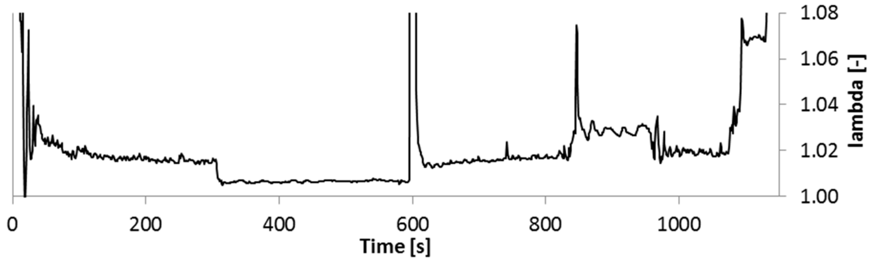
Figure 7. Correlation of particulate matter (PM) mass and solid particle number (SPN) emissions (>23 nm). The cycle tested was the WMTC (Figure 2) with the Euro 5 weighting factors of Table 2.

Using the 1.2×10^{12} p/mg value, a SPN limit of 6×10^{11} p/km translates to a PM mass limit of approximately 0.5 mg/km which is much lower than the 4.5 mg/km limit for Euro 5 diesel and gasoline direct injection L-category engines. In addition, the 0.5 mg/km level is close to the background levels of the facilities of our study. Finally, the scatter of the points is high ($R^2 = 0.43$), which makes it difficult to draw a clear conclusion regarding a possible PM limit that could also ensure low SPN emissions (e.g., less than 6×10^{11} p/km). Thus, for L-category vehicles, as with the rest vehicle categories (light-duty vehicles, heavy-duty engines), PM mass and SPN should be treated separately.

4.3. Sub-23 nm Fractions

The additional particles below 23 nm (8–65%) was given in Figure 4. For Euro 4 vehicles, this was within the range reported for older L-category vehicles [46]. Generally, spark ignition vehicles exhibit higher ratios of sub-23 nm particles, compared to vehicles with compression ignition engines. This indicates that efficient control of particle number emissions for L-category vehicles should be extended to smaller particle sizes (e.g., >10 nm).

Some steady state tests were conducted to further investigate whether the fraction of particles below 23 nm depends on tailpipe and operation conditions. Figure 8 plots emission rates of an L3e-A3 vehicle (#8 in Table 1), with particle samples being collected at the tailpipe.



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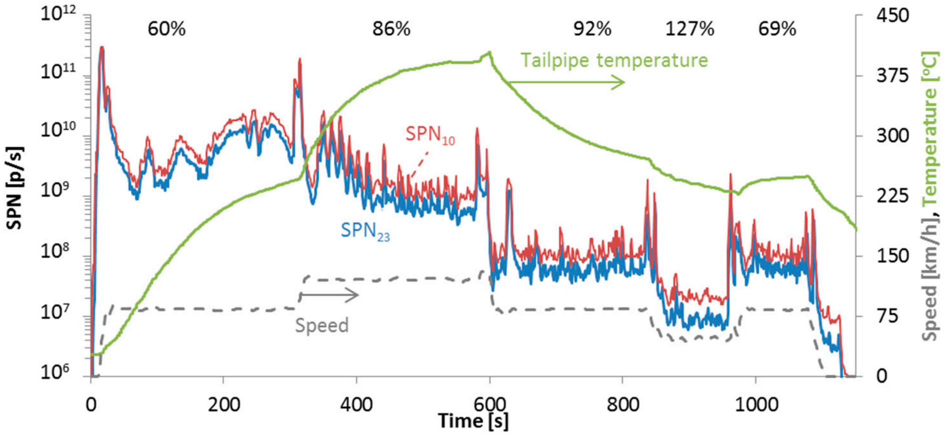


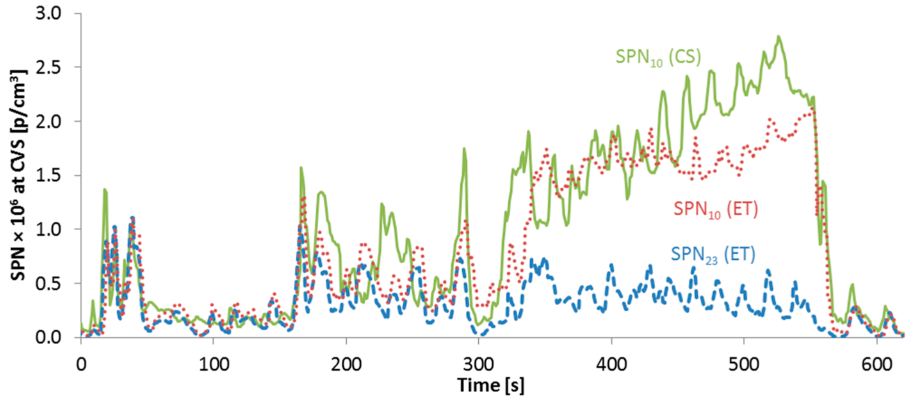
(**b**)

Figure 8. (**a**) Lambda; (**b**) solid particle number (SPN) emissions > 23 nm and > 10 nm measured at the tailpipe for L3e-A3 #8. Percentages give the additional particles < 23 nm. Speed and exhaust gas temperature are also shown.

The additional particles below 23 nm, for the last minute of each speed, range from 60% to 127% of the >23 nm emissions, depending on the point considered. The differences of the fractions and the absolute levels and can be justified by the slightly different engine operations (see lambda values at 120, 85 and 45 km/h, which were however always >1), i.e., the engine was running lean with small excess of air that assists the full oxidation of combustion products. For the speed that was tested three times (85 km/h) under different tailpipe temperature conditions, that fraction ranged between 60% and 92%. In the three cases the lambda remained the same, indicating that the exhaust gas temperature affected the sizes of the particles and consequently the fraction below 23 nm.

Figure 9 (upper panel) shows the SPN concentrations as measured at the CVS for an L3e-A2 vehicle (#4 in Table 1). For the two first speed points shown (75 km/h and 95 km/h) the concentration of particles above 23 nm and 10 nm, as measured with a sampling system employing and evaporation tube (ET), are at the same levels (additional particles < 23 nm around 35%). At the max speed of this motorcycle (115 km/h), the concentration of particles above 10 nm was found more than 3 times higher compared to that of particles above 23 nm.

This finding was observed regardless of whether an evaporation tube or a catalytic stripper were used to thermally treat the aerosol samples. Hence, this cannot be considered as a volatile artefact of the measurement system. It is unlikely that the rich operation of the motorcycle for the specific speed and the incomplete combustion increased the small particles (Figure 9, lower panel). They are probably a non-volatile artefact, as will be discussed in the next section.



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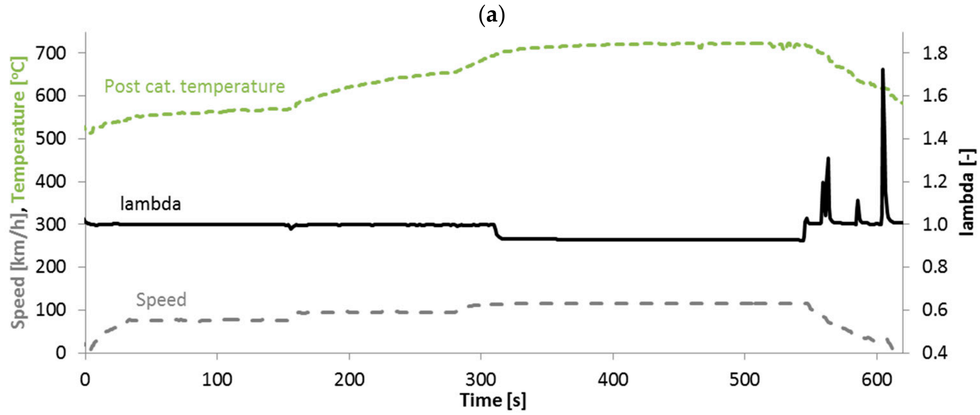

(**b**)

Figure 9. Solid particle number (SPN) concentrations at the dilution tunnel during a constant speed test with L3e-A2 #4 using a system with evaporation tube (ET) or a system with catalytic stripper (CS). Small differences at the traces are because the tests were conducted on different days.

4.4. Tailpipe vs. Dilution Tunnel

The SPN methodology sampling from the dilution tunnel was initially developed for diesel passenger cars based on the general configuration of existing test facilities [12]. However, measurements directly at the tailpipe are still crucial in assessing exhaust emissions both for research activities and for type-approval. For instance, real-driving emission measurements from the tailpipe are conducted with portable emissions measurement systems (PEMS). Additionally, laboratory tailpipe measurements are allowed for small gasoline utility engines type approval and are under discussion for heavy-duty engines type approval in EU. Recent studies with light-duty vehicles showed the equivalency of the two sampling locations with small differences due to particle losses or exhaust flow inaccuracies [17,48]. On the other hand, it was also shown that big differences can be seen, especially for mopeds, due to volatile [15,46,49] or non-volatile artefacts [60]. Thus, it is necessary to further investigate the topic for PTW.

Figure 10 plots the SPN > 10 nm from the tailpipe and the full dilution tunnel (CVS) for constant speed tests of the L3e-A3 #8 vehicle; the same one presented in Figure 8. The CVS background level is around 2×10^8 p/s (equivalent to 8×10^8 p/km) and interferes with actual emission levels at 45 km/h, which are low, resulting to a big difference (500%) between measured emissions levels at the CVS and the tailpipe. For the two first speeds, where the concentration is 10 times higher than the background, the difference between CVS and tailpipe is 16–80%. Such a range can typically be attributed to instrument and exhaust flow rate measurement uncertainties. For this 800 cm^3 motorcycle, the exhaust flow rate measurement should be accurate within 10% and the typical measurement uncertainty between different particle counters is also within 10%. Processes such as thermophoresis, diffusion and agglomeration would further decrease the CVS results [17,47,48]. Condensation on particles with an original size at tailpipe conditions below 10 nm may take place within the transfer tube to the CVS and the CVS and bring them within the size range of the measuring instrumentation. This would be reflected to higher number counts at CVS compared to the tailpipe.

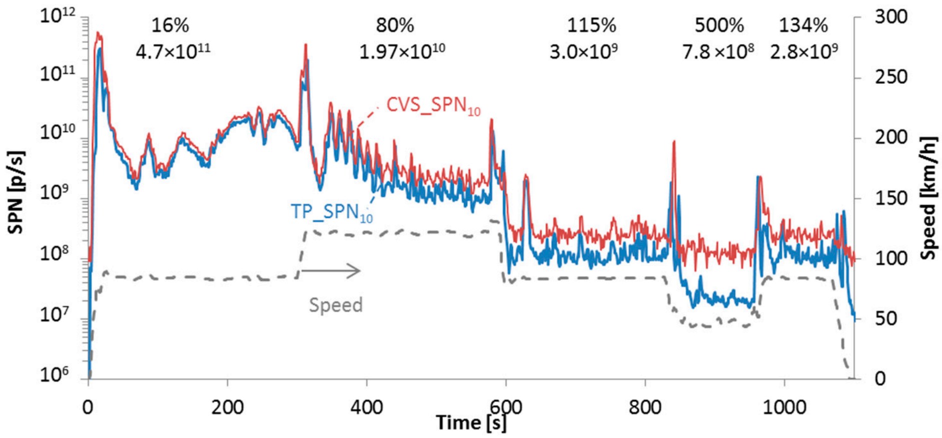

Figure 10. Solid particle number (SPN) emissions >10 nm measured at the tailpipe (TP) and the full dilution tunnel (CVS) for L3e-A3 #8. Speed and exhaust gas temperature is also shown. Numbers give SPN >10 nm emissions determined from the tailpipe instrument at the different speeds. Percentages give the differences of the dilution tunnel (CVS) instrument compared to the tailpipe one.

Figure 11 plots the SPN emissions for the moped L1e-B at maximum speed (45 km/h) as measured at the tailpipe and at the CVS. There is a good agreement between the two SPN > 23nm measurements. The SPN > 10 nm, as determined at the tailpipe are two times higher than the SPN > 23 nm (after cold start), in agreement with the previously reported fractions (e.g., Figure 10), indicating that the size distribution peaks below 23 nm. However, the SPN > 10 nm concentration at the dilution tunnel starts to deviate from approximately time 250 s (exhaust gas temperature at the tailpipe around 250 °C). These particles are not a volatile artefact because the instrument had a catalytic stripper and, in addition, a change of the PCRF from 250 to 1500 did not change the measured concentrations.

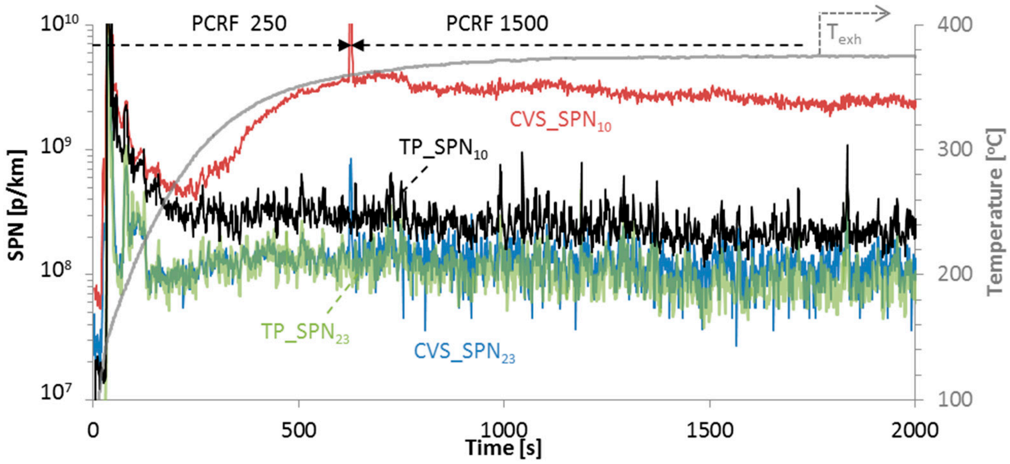

Figure 11. Solid particle number (SPN) emissions > 10 nm measured at the tailpipe (TP) and the full dilution tunnel (CVS) for the moped L1e-B. The particle number concentration reduction factor (PCRF) changed from 250 to 1500 at 600 s. Speed and exhaust gas temperature is also shown. The measurement system had a catalytic stripper.

As was discussed in another study [60] there are two plausible explanations: (i) non-volatile particle formation in the tube from the vehicle to the dilution tunnel (e.g., due to pyrolysis during the 15 s residence time), or (ii) homogeneously or heterogeneously nucleated and condensed heavy molecular species that cannot evaporate in the system at the dilution tunnel due to the short residence time (around 0.25 s) rending the catalytic stripper less effective [52]. This could also explain the high increase of sub-23 nm particles with L3e-A2 #4 (Figure 9). Why this was not seen with the motorcycle L3e-A3 #8 (Figure 10) is not clear. It seems that the long residence time in the tubing to the dilution tunnel of the moped (15 s) or L3e-A2 #4 (3.5 s) favored the non-volatile formation via pyrolysis or due to the low flowrates the heavy molecular species (emitted by the PTW or desorbed from the transfer tube) had time to grow. When the test of the moped was repeated with open tubing (i.e. ambient air entering and diluting directly at the tailpipe) this difference was not seen and the exhaust gas temperature was <130 °C. Thus, for moped, and in general for small engine displacement L-category vehicles, better definition of the sampling requirements is necessary before introducing SPN measurements in the regulations.

5. Conclusions

Particulate mass and number emissions of one moped and eight motorcycles equipped with 4-stroke engines, type-approved as Euro 4, were determined over the recently introduced world-harmonised motorcycle test cycle (WMTC). Particulate matter (PM) mass emissions were below 1.5 mg/km, well below the 4.5 mg/km limit introduced for Euro 5 powered two-wheelers (PTW) equipped with diesel or gasoline direct injection engines.

Solid particle number (SPN) emissions were determined from the full dilution tunnel using a sampling system equipped with a catalytic stripper to eliminate volatile and semi-volatile interference (artifacts). SPN could be determined with an average repeatability of 10% (range 1–24%) over two repetitions per vehicle. Four vehicles were found to exceed the 6×10^{11} p/km level (particles > 23 nm), applicable as a limit for passenger cars. For 3 more vehicles, emissions were close to the level when including particles down to 10 nm.

Compared to older PTWs, emissions of Euro 4 vehicles in this study were at the low end of measured ranges for both the PM mass and number, indicating that technology improvements to achieve HC and CO levels were also effective in decreasing particulate emissions. However, there was no clear PM level that would ensure low SPN levels and consequently the two metrics should be considered separately in future regulations. The fact that several Euro 4 vehicles are at or close to the limit level value means that monitoring of SPN emissions for PTWs needs to continue, especially as technology further improves towards Euro 5.

Comparisons of tailpipe and CVS measurements were in relatively good agreement for one motorcycle, but not for the moped. Much higher particle numbers in the 10–23 nm size range were observed following the CVS method compared to measurements at the tailpipe. Semi-volatile material condensation and particle growth might explain this. This is a clear indication that more targeted studies in that direction are required before introducing a measurement protocol for any future SPN regulation of such vehicles.

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Appendix A

The exhaust flow rates used for the constant speed tests are given in Table A1. For completeness the average exhaust flow rates of the WMTCs are also given. The exhaust flow rates were calculated with the CO_2 tracer method.

Table A1. Average exhaust flow rates [m^3/min] normalised to 0 °C and 101.3 kPa over various tests.

Code	WMTC	1	2-1	2-2	3-2	Constant Speeds		
	Speed [km/h]	**22.8**	**36.8 km/h**	**39.5**	**57.8**	**45.0**	**85.0**	**120.0**
#1	L1e-B	0.10				0.20		
#2	L3e-A1	0.10						
#3	L3e-A2		0.15					
#4	L3e-A2			0.20				
#5	L3e-A2			0.19				
#6	L3e-A2			0.17				
#7	L3e-A2			0.19				
#8	L3e-A3			0.31	0.47	0.33	0.54	1.03
#9	L3e-A3			0.26	0.39			

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