2015-24-2512
Published 09/06/2015

doi:10.4271/2015-24-2512
saeeng.saejournals.org

Particle Emission Measurements from L-Category Vehicles

Barouch Giechaskiel, Alessandro Zardini, and Giorgio Martini
Joint Research Centre, EC

ABSTRACT

In 2011 a particle number (PN) limit was introduced in the European Union's vehicle exhaust legislation for diesel passenger cars. The PN method requires measurement of solid particles (i.e. those that do not evaporate at 350 °C) with diameters above 23 nm. In 2013 the same approach was introduced for heavy duty engines and in 2014 for gasoline direct injection vehicles. This decision was based on a long evaluation that concluded that there is no significant sub-23 nm fraction for these technologies. In this paper we examine the suitability of the current PN method for L-category vehicles (two- or three-wheel vehicles and quadri-cycles). Emission levels of 5 mopeds, 9 motorcycles, 2 tricycles (one of them diesel) and 1 quad are presented. Special attention is given to sub-23 nm emission levels. The investigation was conducted with PN legislation compliant systems with particle counters measuring above 23 nm and 10 nm. In addition other approaches using catalytic strippers and counters from 3 nm or particle sizers were used to confirm the nature of the particles. The results showed that there is a significant portion of solid particles not counted with the current PN method. On the other hand, the high amount of volatile material can lead to artifacts below 23 nm, and thus great care has to be taken when measuring the PN of this category.

CITATION: Giechaskiel, B., Zardini, A., and Martini, G., "Particle Emission Measurements from L-Category Vehicles," *SAE Int. J. Engines* 8(5):2015, doi:10.4271/2015-24-2512.

INTRODUCTION

Mopeds (combustion engine with displacement <50 cm^3 and speed <45 km/h) and motorcycles (displacement >50 cm^3, speed >45 km/h) are widespread means of transport in some regions such as southern Europe and in countries of East and South Asia. In Europe (EU27) more than 37 million were registered until 2013 [1], and according to the latest data available, in 2014 more than 1 million were registered in the EU. Italy is the leading manufacturer of motorized 2-wheel vehicles in Europe. The production in 2011 was 414.000 vehicles, more than half of the European output. The country has the largest number of powered two-wheelers on the road in Europe: 8.6 million vehicles in 2011 (2.2 million mopeds and 6.4 million motorcycles) [2].

Urban air pollution can be strongly influenced by mopeds and motorcycles' emissions, which are not negligible when compared with those of modern passenger cars [3, 4]. Two stroke mopeds emit significant amounts of primary organic aerosol (POA), aromatic volatile organic compounds (VOC) and also produce significant secondary organic aerosol (SOA) [5, 6]. The relative contribution of mopeds and motorcycles to particulate matter (PM) emissions started to increase after 2011. The reason is the introduction of diesel particulate filters (DPF) in both passenger cars and heavy duty vehicles at Euro 5/V and Euro 6/VI levels, which significantly decreased emissions from these vehicle categories. Although the contribution of mopeds and motorcycles to total road transport PM emissions will probably remain small (~5%) by 2020, their contribution could increase to ~20% of when focusing on urban emissions [7]. These values could be even higher when particle number (PN) is considered because of the high number of nuclei particles formed from the unburnt fuel and lubricant.

PN measurements of mopeds and motorcycles have been conducted by some researchers (e.g. [8, 9, 10, 11, 12]) but for the latest Euro 3 the data are limited (e.g. [10]). The emission levels are usually much higher than the current emission limits for passenger cars (6×10^{11} p/km for solid particles >23 nm), in some cases at levels close to diesel vehicles without DPF [3, 4]. Sub-23 nm solid PN measurements are rare [13]. It has been mentioned that the PN measurements of mopeds are prone to artifacts due to the high concentration of volatile materials [14, 15].

Regulation (EU) No 168/2013 sets out environmental requirements for two stages with the second stage (Euro 5) being mandatory for new types of vehicles as of 01 January 2020. An Environmental Effect Study stipulated in its Article 23(4) and 23(5) will provide additional underpinning through experimental testing, modelling, technical feasibility and cost-effectiveness analysis based on the latest available data. In addition, this study will assess (see Recital 12) the feasibility of in-service conformity testing requirements, off-cycle (i.e. real driving) emission requirements and a particulate number emission limit for certain (sub-) categories.

Objective of this study is to give the PN emission levels of various L-category vehicles (two- or three-wheel vehicles and quadri-cycles) following the legislation applied to passenger cars. The geometric mean diameter of the emitted size distribution will also be given.

However, due to the particular nature of their emissions (i.e. high percentage of unburnt fuel and lubricant) the sampling protocol and the sampling location will be investigated. Topics like appropriate dilution and thermal pre-treatment and their effect on the results are discussed, especially for sub-23 nm measurements. Finally, a correlation between the PN emissions of the current type approval cycles with the future world harmonized motorcycle testing cycles (WMTC) is conducted for the first time according to our knowledge. The present study is not an output of the above mentioned Effect Study, but a preliminary feasibility study that may serve as an input to the Effect Study.

EXPERIMENTAL

Set-up

The tests were conducted in the Vehicle Emissions Laboratory (VELA 1) of the Joint Research Centre (JRC) in Ispra, Italy. VELA 1 is a climatic emission test cell with a single axis roller dynamometer used mainly for motorcycles. The exhaust of the vehicles was connected to a full dilution tunnel with constant volume sampling (CVS) (Figure 1). Typical flow rates that were used in the dilution tunnel were 4-6 m^3/min. In the case of 2-stroke mopeds, where high amounts of unburnt fuel and lubricant are expected, a cyclone was used at the exhaust line to remove big droplets which can harm the instrumentation, without affecting the number of fine particles. The diameter with 50% penetration, which depends on the exhaust flow rate of the vehicles, was >10 µm. The exhaust flow rates of the 50 cm^3 mopeds were around 0.1-0.25 m^3/min, and >1 m^3/min at high speeds for the big motorcycles. They were estimated by the difference of the total CVS flow rate minus the dilution air entering the tunnel. The uncertainty of determining a small flow from two big flows may be high. For engines of 400 cm^3 we compared the estimated flow with an exhaust flow meter (Sensors, 1.5 inches) and we found a difference of only 10%.

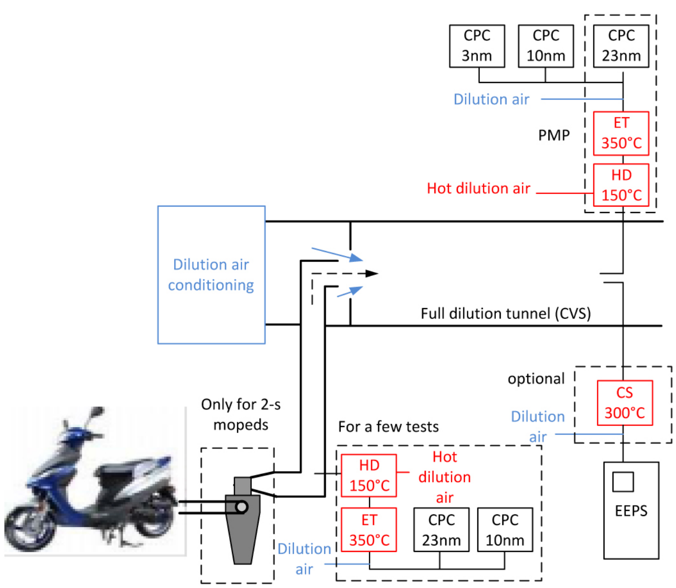

Figure 1. Experimental set-up.

From the dilution tunnel an Engine Exhaust Particle Sizer (EEPS) (TSI, 3090) was measuring the size distributions (5.6-560 nm) in real time [16]. A catalytic stripper (CS) at 300 °C (prototype from AVL) [17] was used in half of the tests (see Table 1) to remove the volatiles and measure only the non-volatiles (solids, from now on) size distribution. A short heated tube at 300 °C was included in the device upstream of the CS (residence time approximately 0.1 s). Dilution air was added at the exit of the CS to reach the flow required by the EEPS. This mixing resulted in a dilution of 10:1, approximately. The losses of the CS are 10% at sizes >30 nm, around 40% at 15 nm and 60% at 7 nm. The EEPS was compared with a Scanning Mobility Particle Sizer (SMPS) (model TSI 3080L with a TSI 3025 Condensation Particle Counter (CPC)) measuring soot particles from a propane diffusion flame generator (APG from AVL). The Geometric Mean Diameters (GMD) were within 5% for (EEPS) GMDs between 25 and 40 nm. For smaller or bigger sizes for every 10 nm the EEPS diameter should be increased 20%. The sizes presented in this paper are the EEPS sizes without any size correction. Recently TSI released an inversion algorithm that takes into account the different charging probabilities of fractal particles. We compared our corrections with the new algorithm and we found very good agreement (within 5-10 nm).

A PN measurement system compliant with the light duty vehicles (UN-ECE Reg. 83) and heavy duty engines (UN-ECE Reg. 49) regulations was used (AVL APC 489) at the dilution tunnel [18]. It consists of a hot dilution (HD) at 150 °C and an evaporation tube (ET) at 350 °C. The system was calibrated by the manufacturer and the dilution including the particle losses (as average of 30, 50 and 100 nm) is called Particle number Concentration Reduction Factor (PCRF). Typically, a primary PCRF of 1000 and a secondary of 10 were used for the mopeds and 100×10 for the rest vehicles. However, different settings were also investigated. We will use the term 'Hot dilution with evaporation tube' (HD+ET) to characterize the specific thermal pre-treatment system. The extra losses at 15 nm of this system are approximately +40%.

Downstream of the thermal pre-treatment system a TSI CPC 3790 with 50% counting efficiency at 23 nm ($d_{50\%}$=23 nm) was measuring. In parallel a TSI CPC 3772 ($d_{50\%}$=10 nm) and TSI CPC 3025A ($d_{50\%}$=3 nm) were used in order to investigate the presence of particles <23 nm. Note that HD+ET with a CPC $d_{50\%}$=23 nm is the protocol defined in the Particle Measurement Program (PMP) and used for the regulatory measurements [19].

For a few tests a PMP system was connected to the tailpipe to investigate the differences between the different sampling locations. A PCRF of 125×5 was used. The extracted flow was approximately 1.5 lpm, thus had only a negligible effect on the CVS results.

Vehicles

The vehicles are usually classified as mopeds, motorcycles and tricycles. With Directive 2002/24/EC and later Regulation (EU) No 168/2013 the vehicles are part of L-category. Details can be found in the Appendix (Table A2). In this paper the vehicles that were tested were classified as (see also Table A4 in the Appendix):

- L1e-B (2s) (Moped, <50 cm^3, 2-stroke)

- L1e-B (4s) (Moped, <50 cm^3, 4-stroke)
- L3e-A1 and A2 (Motorcycle, <140 km/h, 4-stroke)
- L3e-A3 (Motorcycle, >140 km/h, 4-stroke)
- L5e-A (Tricycle)
- L5e-B (Commercial tricycle, diesel)
- L7e-A1 (Quad)

The vehicles tested spanned from Euro 1 to Euro 3.

Test Cycles

The vehicles were tested according to their type approval driving cycle (UN-ECE Reg. 40, UN-ECE Reg. 47) (from now R40 and R47), but also according to the future World Harmonized Motorcycle Test Cycle (WMTC) depending on their class (details in Table A4 in the Appendix and references therein). PN measurements are in real time, thus it was possible to divide the emissions in parts of the cycles (e.g. cold start part, hot part and high speed part), even if the cold part was not required by the legislation for some of them. This way the emissions from the previous cycles can be correlated to the future WMTC results. Details of the cycles and their cold, hot and high speed parts can be found in the Appendix, Figures A1, A2, A3.

Some motorcycles were tested at constant speeds in order to investigate the effectiveness and robustness of the PN measurements. For these tests some parameters of the PN instruments were changed (e.g. PCRF).

Reference fuel with 5% ethanol content was used. The lubricant used was semi-synthetic.

Test Protocol

No pre-test condition is required for the R40 and R47 cycles, however all motorcycles were preconditioned by running the legislation cycle the day before to guarantee reproducible conditions. Prior to WMTC tests, all motorcycles were pre-conditioned with the WMTC the day before as stated in the regulation. At least two repetitions were conducted for each vehicle for the type approval cycle and the appropriate WMTC (Table 1). Although error bars will not be given for all cases the difference between two identical cycles were typically 10-15% for solid particles and 20-25% for total particles. Table A4 in the Appendix summarizes the tested vehicles, the relevant type approval cycles, their class and the future type approval WMTC.

RESULTS AND DISCUSSION

Initially, the exploratory results regarding the sampling location and sampling conditions will be given. Then, the measured emission levels will be presented. Finally, the correlation of the various cycles will be shown.

Table 1. Test protocol. Numbers are the repetitions conducted.

Code	R40 & R47	WMTC	Extra investigations
L1e-B (2s) #1	2	-	-
L1e-B (2s) #2	6	4	Repeatability, thermal treatment
L1e-B (4s) #3	6	1	Tailpipe
L1e-B (4s) #4	4	2	
L1e-B (4s) #5	3	3	Tailpipe
L3e-A1 #1	2	2	Tailpipe
L3e-A2 #2	4	4	
L3e-A2 #3	2	3	Thermal treatment
L3e-A2 #4	1	1	
L3e-A2 #5	2	3	
L3e-A2 #6	3	2	
L3e-A3 #7	2	2	
L3e-A3 #8	-	4	
L3e-A3 #9	-	3	
L5e-B (diesel)	9	3	
L5e-A (3-wh.)	1	1	
L7e-A1 (quad)	3	3	

Dilution Tunnel vs Tailpipe

Measurements from the dilution tunnel as required by the current legislation or directly from the tailpipe can have differences in particle number concentration due to various processes like thermophoresis, agglomeration, condensation, nucleation and diffusion [20, 21]. In addition, the exhaust flow rate used in the calculations can have a big effect. The contribution of these processes to the PN results was investigated by comparing two PMP systems one measuring at the tailpipe and one at the dilution tunnel (Figure 1). The results are shown in Figure 2. Initially, for some tests both PMP systems were connected to the dilution tunnel in order to confirm that they were measuring similarly. The difference was <5%. Then one of the systems was moved to the tailpipe. The mean differences ranged from −10% to +25%, with a standard deviation of 35%. It should be noted, that for the mopeds (L1e-B) the system at the tailpipe measured on average higher than the system at the dilution tunnel. The long residence time (>10 s at idle for example) in the tube between the tailpipe and the dilution tunnel probably resulted in diffusion losses and agglomeration that led to lower concentrations in the dilution tunnel. These results confirm that the results that will be presented from the dilution tunnel should be quite close to what would be measured at the tailpipe at least for solid particles >23 nm.

However, quite often mopeds and motorcycles emit particles <23 nm. In this size range the particle loss mechanisms are significant. In order to investigate the differences at sub-23 nm levels some steady state tests were conducted with the addition of a CPC with $d_{50\%}$=10 nm to the system connected to the tailpipe. The comparison of PN emissions >23 nm and >10 nm of a constant speed test can be seen in Figure 3.

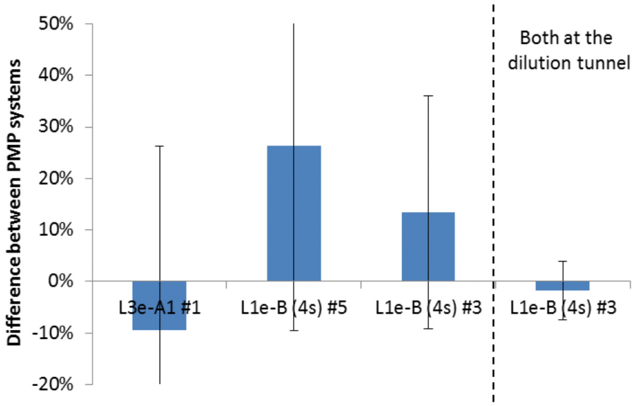

Figure 2. Difference of solid PN emissions >23 nm measured at the tailpipe compared to the full dilution tunnel system. Error bars indicate one standard deviation.

Although the agreement is very good for the >23 nm measurements (within 15%), the >10 nm measurements have differences. At the beginning of the test the system at the tailpipe is measuring almost 50% higher than the system at the dilution tunnel. The difference can be attributed to agglomeration, thermophoretic and diffusion losses. After the first 50 seconds, the PN system at the tailpipe is measuring approximately 50% lower than the system at the full dilution tunnel, which is in contrast to what would be expected. In this case the GMD (as measured at the dilution tunnel downstream of a CS with an EEPS) decreased from approximately 80 nm to 10 nm. One explanation of this unexpected behavior is that the system at the tailpipe does not count some particles because they are smaller than 10 nm. The particles when measured at the dilution tunnel are bigger due to growth from agglomeration in the tube between the tailpipe and the mixing point of the dilution tunnel. It is also possible that the condensed material on the particles is not completely removed from the PN system at the dilution tunnel; the system at the tailpipe does not have this issue because the sampling is conducted directly from the tailpipe, where the temperatures are still high and no condensation has occurred. Finally, the different penetrations of the PN systems and CPCs might have contributed, especially considering that the GMD was around 10 nm. For this test the exhaust gas temperature was less than 250 °C at the tailpipe sampling location, so no significant desorption is expected. Tests with CPCs with lower $d_{50\%}$ had even bigger differences (Figure not shown).

More detailed analysis of measurements at the dilution tunnel and the tailpipe has been conducted elsewhere [20]. There the researchers saw even bigger differences between tailpipe and dilution tunnel; the tailpipe system measuring higher. In their case the high temperatures and concentrations resulted in higher thermophoretic losses and decrease of concentration due to agglomeration. The low exhaust flowrate of the moped might also have resulted in high diffusion losses [21] due to the long residence time in the tube between the tailpipe and the dilution tunnel. This tube in many cases is corrugated and can further increase the losses. In any case, the message is clear: Particle measurements of L-category vehicles for legislative purposes need further investigation, especially for the small engines.

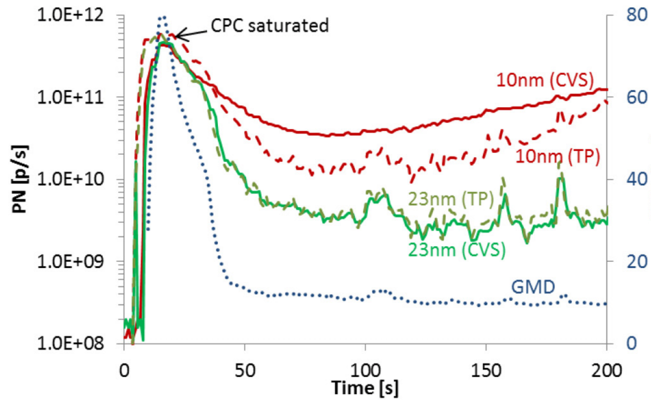

Figure 3. Comparison of measurements at the dilution tunnel (CVS) and the tailpipe (TP) (L3e-A1 #1) during a constant speed test.

Sampling Conditions

Target of these tests was to determine the minimum PCRF (dilution) for accurate measurements without interference of volatile artifact and at the same time to investigate the nature of the emitted particles. One moped and one motorcycle were tested at constant speed and the primary PCRF was changed from 15 to 1000.

4-Stroke Motorcycle

Figure 4 shows a test with a 4-stroke motorcycle at 100 km/h (L3e-A2 #3) after 5 min warm-up at 50 km/h. The EEPS was sampling directly from the dilution tunnel. The EEPS was saturated so only part of the cycle is shown. CPCs with $d_{50\%}$= 23 nm and $d_{50\%}$=3 nm were sampling downstream of the HD+ET.

At the beginning of the 100 km/h test the GMD was 10 nm and the concentration of solid and total particles was the same. After time 400 s the concentration of total particles was higher than the solid ones, indicating formation of volatile particles.

The concentration of particles >23 nm decreased over time. At time 500 s the concentration of particles >3 nm increased to very high levels. The PCRF changed between 15×15 and 200×15 (primary × secondary PCRFs). However the concentration (corrected for the PCRF) from the different CPCs remained relatively constant indicating that these were ‘solid’ particles and not an artifact due to re-nucleation downstream of the ET. At this point the EEPS was connected downstream of the HD+ET and the GMD of the solid particles was around 10 nm, justifying the high difference between the 3 nm and 23 nm CPCs. These tests also show that a low PCRF (dilution) around 15×15 is appropriate for 4-stroke engines at least at warmed up operation. Nevertheless, much higher PCRF was used in this paper (>100×10).

The difference between solid particles >23 nm and >3nm is very high. The tests with high PCRF or a CS showed that they are solid (i.e. do not evaporate at 350 °C). It was the first time that the specific motorcycle was operated at this speed for so long, thus desorption of solid particles from the tubes is possible. The high exhaust gas temperature might have resulted in pyrolysis of the volatiles that were desorbed (or emitted). These sub-23 nm particles could also be heavy molecular hydrocarbons that do not evaporate at 350 °C and thus are counted as solid particles. For example, in [22] the volatility analysis of particles from a 2-stroke engine showed that only 60% of the volume evaporated at a temperature of 350 °C. Finally, these particles could be metals originating from the fuel and lubricant: They partially vaporized during combustion and nucleated [23], especially in this case where the soot mode was low. This fraction could be 1% of the mass emissions [22]. Abrasion metals (e.g. Fe, Cr, Ni, Cu, Pb) from piston rings, valves and bearings are usually assumed to be low (ng/km) and in the µm range. Similarly for metals from the coatings of catalytic converters (e.g. Pt, Va). Filter analysis of exhaust gas particulate matter often finds high amount of residuals that can be ash [13, 23, 24].

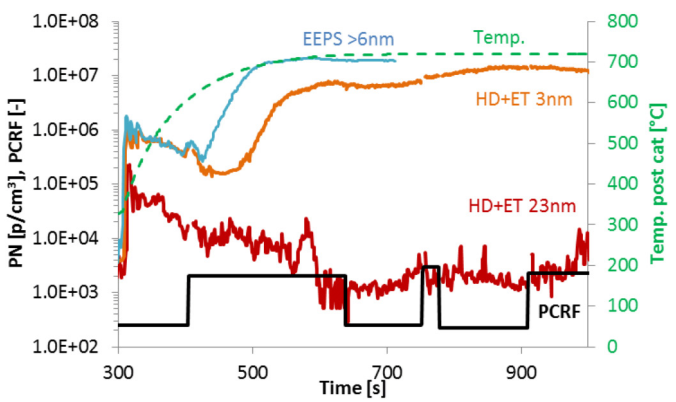

Figure 4. Investigation of PCRF effect on solid particle emissions for a 4-stroke motorcycle from the dilution tunnel (CVS) (L3e-A2 #3).

Although no re-nucleation artifacts were noticed during the hot operation of the engine in the previous example, it has to be mentioned that artifacts (i.e. re-nucleation downstream of the ET) depends on the availability of volatiles. The primary dilution affects directly the availability of volatiles, but the secondary dilution can also have an effect. The combustion process affects the absolute levels as well, thus during cold start tests and accelerations it is possible to have artifacts even with the maximum dilution. These effects were investigated with a 2-stroke moped.

2-Stroke Moped

Figure 5 shows an example of two different measurements of a 2-stroke moped (L1e-B (2s) #2). One was conducted in December 2013 (A) and the other in October 2014 (B). Although the emissions >23 nm are almost identical, the >3 nm emissions have a big difference at the beginning of the cycle. The CPC with $d_{50\%}$=3 nm was saturated during period (B) even though a 1000×10 PCRF (dilution) was used.

The nature of these particles was further investigated by using the EEPS (>6nm) at different sampling locations. Figure 6a shows the results: Sampling directly from the dilution tunnel with constant volume sampling (CVS) or the tailpipe (TP) with a catalytic stripper (CS) did not show this spike (see time around 20 s). Sampling from the CVS with a CS showed this spike which is much higher than the total particles measuring directly from the dilution tunnel (CVS). The size distributions showed a separate nucleation mode (Figure 6c). These results confirm that this high spike is re-nucleation downstream of the ET (Figure 5) or even the CS (Figure 6). Pyrolysis inside the ET or CS cannot be excluded but is highly unlikely at the 300-350 °C temperature range.

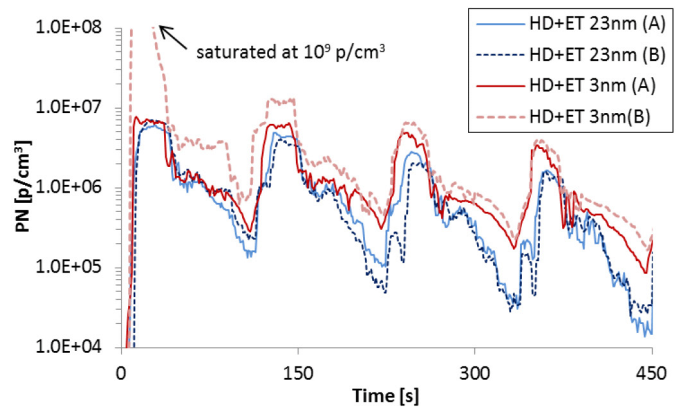

Figure 5. Investigation of artifacts for a 2-stroke moped (L1e-B (2s) #2). Measurements from the dilution tunnel (CVS).

The CS had this artifact at the dilution tunnel but not at the tailpipe. Note that the CS was used without primary but only with secondary dilution (x10) both at the tailpipe and the dilution tunnel. A possible explanation is that at the dilution tunnel the particles have grown by condensation and then the residence time inside the CS (0.1 s in this case) is not enough to completely evaporate and oxidize them.

Sampling from the tailpipe did not have this issue because the temperatures are already high. As it will be shown in the lab tests with atomized oil the concentration of hydrocarbons was at the limit of the specific CS.

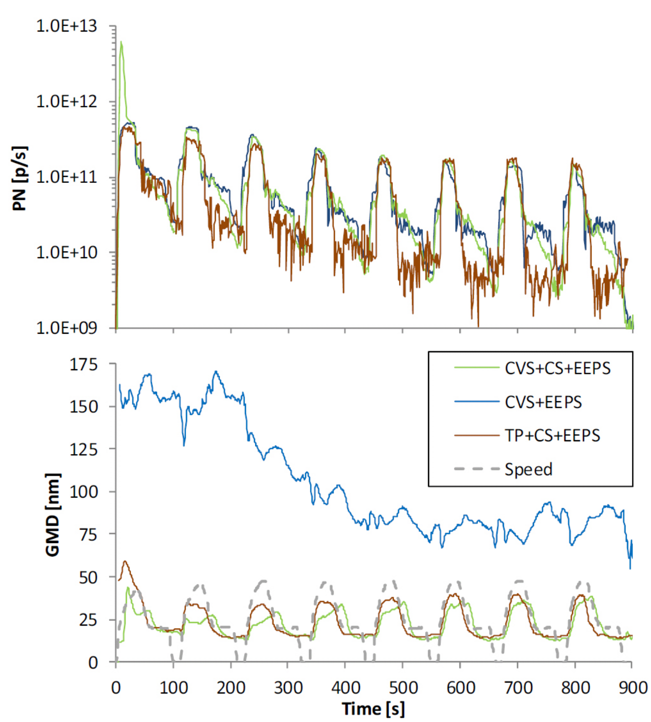

Figure 6. a. Real time emissions as measured with the EEPS with different configurations, b. GMD (average of 5 s) over time (L1e-B (2s) #2) c. example of size distributions at t=20 s.

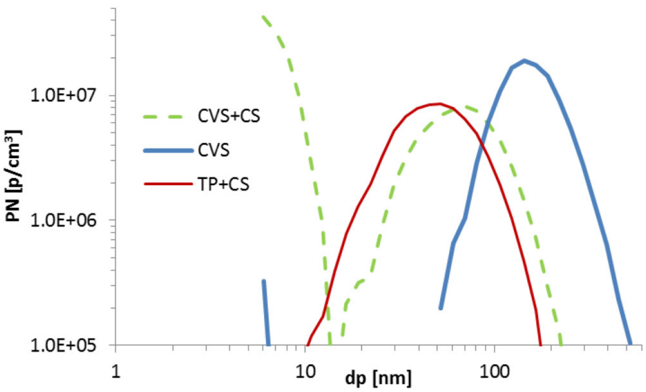

Figure 6 (cont). a. Real time emissions as measured with the EEPS with different configurations, b. GMD (average of 5 s) over time (L1e-B (2s) #2) c. example of size distributions at t=20 s.

In order to capture most of the size distribution which peaks at low sizes and to minimize the artifact of re-nucleation when measuring at 3 nm, a lower size of 10 nm was investigated. Figure 7 shows the emissions >10 nm with an EEPS sampling directly or via a CS from the tunnel (tests of Figure 6). A CPC with $d_{50\%}$=10 nm measuring via a HD+ET is also shown (tests of Figure 5). The results are almost identical and even the artifact from re-nucleation in the CS from the dilution tunnel case is minimum. Thus, when investigating emissions of mopeds, a CPC with $d_{50\%}$=10 nm is recommended.

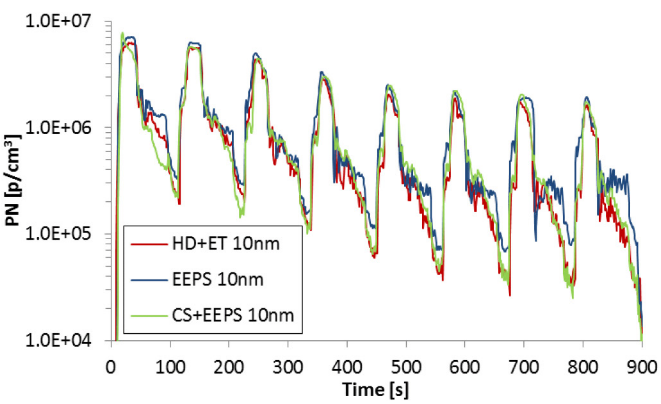

Figure 7. Real time emissions as measured with different instruments using similar $d_{50\%}$ (L1e-B (2s) #2) from the dilution tunnel (CVS).

Atomized Emery Oil

The artifact of re-nucleation downstream of the thermal pre-treatment was further evaluated in the calibration laboratory using atomized synthetic oil (Emery 3004 or PAO 4 cSt, a highly branched isoparaffinic polyalphaolefin (1-decene (tetramer) mixed with 1-decene (trimer), hydrogenated). Target of the experiment was to evaluate the various thermal pre-treatments in removing liquid oil particles, as those that could be produced by 2-stroke engines. Legislation requires >99% removal efficiency of tetracontane (alkane $C_{40}H_{82}$) which was met by all systems used in this study, even with one-two orders of magnitude higher concentrations than those prescribed by the legislation (>10000 p/cm^3). Thus we wanted to challenge the systems with more realistic two-wheelers aerosol.

A Scanning Mobility Particle Sizer (SMPS) was used to measure upstream (directly from the atomizer) and downstream of the HD+ET thermal pre-treatment. For some tests a CS was also added. The standalone CS was also evaluated. In all cases a secondary dilution of 10 was used. The results corrected for the PCRF can be seen in Figure 8. Note that the PCRF takes into account losses from 30 nm, thus the results <30 nm are underestimated. The HD+ET had the re-nucleation artifact, which was bigger with the low primary dilution. The addition of the CS completely removed the volatile particles even with the lowest dilution.

The tests were repeated by increasing the temperature from ambient to 350 °C (only for the HD+ET case). Up to 200 °C the size distribution was shifted to the left (from 190 nm to 100 nm), at 250 °C a small nucleation mode appeared which became dominant at 300 °C. In the cases examined here the mean size of the nucleation mode was bigger than 23 nm. Thus a PMP system would be affected by this artifact. However the examined concentration was extremely high. We have seen artifact at PMP systems (>23 nm) only once: it was a non-preconditioned 2-stroke moped and the PMP was sampling from the tailpipe. In all other cases examined we have never seen again such an artifact for PMP systems with real exhaust.

More tests were repeated at different inlet concentrations and/or dilutions in order to find the hydrocarbons levels that could be efficiently removed by the thermal pre-treatment systems. The HD+ET+CS could remove all concentrations examined (up to 3.4×10^7 p/cm^3, size 190 nm and PCRF 10×10). The HD+ET could remove up to 1.5×10^6 p/cm^3, size was 190 nm and PCRF 25×10). The standalone CS (with secondary dilution of 10) could remove volatiles up to up to 1.5×10^6 p/cm^3, size 190 nm (no higher concentration was examined).

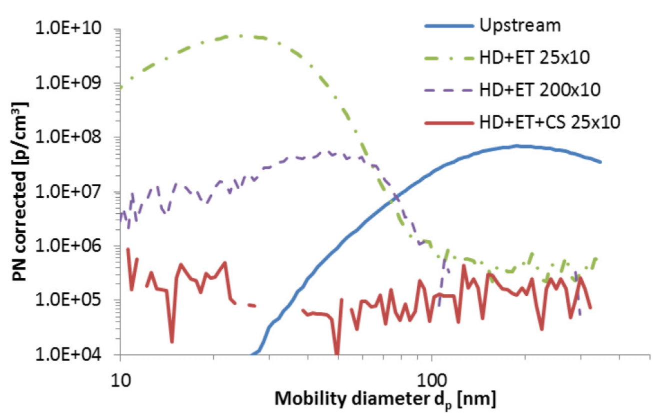

Figure 8. Laboratory investigation of oil removal efficiency from PN systems.

Theoretical Considerations

The concentration of the lab tests was 3.4×10^7 p/cm^3 and the size was 190 nm (Figure 8). Using a density of 0.815 kg/m^3, the estimated mass was approximately 290 mg/m^3. This mass could be oxidized even with the lowest PCRF (dilution) of 10×10 at which the HD+ET+CS system was tested. The standalone CS could remove approximately 15 mg/m^3 of liquid oil.

The mass concentration of the volatiles at the dilution tunnel for the moped tests (Figure 6b) was >30 mg/m^3 assuming that all particles of this vehicle are originating from lubricant and are spherical (165 nm, 6×10^6 p/cm^3). During this test re-nucleation was observed downstream of the standalone CS. During the second testing period the size was around 130 nm and the mass concentration 15 mg/m^3 and no re-nucleation was observed (with the CS or with the ET and PCRF 1000×10). These results show that the specific CS was capable of removing the volatiles up to 15 mg/m^3, but not higher concentration. This value is still much higher than the value of 0.2 mg/m^3 that has been shown in laboratory studies that the CSs can handle (see references in [26]), and in agreement with our lab tests.

Thermal pre-treatment without CS (i.e. HD+ET) couldn't handle the mass of 290 mg/m^3 even with a PCRF of 1000×10. Actually even a mass of 1.5 mg/m^3 resulted in small particles <10 nm with the same PCRF. A mass of 15 mg/m^3 resulted in re-nucleation artifact (>10 nm) with PCRF of 10×10, but not 25×10. These results show that re-nucleation can happen at values lower than theoretical mass required for homogeneous nucleation of hydrocarbons (3 mg/m^3 [25]).

During our moped experiments with a primary PCRF of 1000 an artifact occurred at the cold start (Figure 5) with an inlet mass was 30 mg/m^3 but not with 15 mg/m^3. The re-nucleation happened at mass close to or lower than those measured during the lab tests.

At the moped tests the sulfur might have assisted the re-nucleation. Assuming a sulfur content of 10 ppm for the fuel and 5000 ppm for the lubricant, as well as an oil consumption equivalent to 1% of fuel, one estimates an engine-out SO_2 concentration in the range of 2 ppm.

Measurements with a Fourier Transform Infra-Red (FTIR) Spectrometer (AVL SESAM) showed SO_2 peaks of 60 ppm at the beginning of the cycle. Reported SO_2 to SO_3 conversion efficiencies for the exhaust temperatures that were measured (300-400 °C) lie in the range of 30-100% for platinum based oxidation catalysts, but much less for palladium based catalysts. Thus the SO_3 concentration at the exit of the evaporation tube could be around 0.006 ppm (assuming a dilution in the tunnel of 10 and a primary dilution of 1000) or approximately 6 µg/m^3. This value is still higher than the one required for nucleation 0.7-3.5 µg/m^3 (details in [26]) and thus the contribution from sulfur is very probable.

Sampling Recommendations

Generally, the current United Nations legislative procedures for light-duty vehicles and heavy-duty engines (i.e. measurement of >23 nm with hot dilution and evaporation tube) seem robust for L-category vehicles as well, but dilution of at least 100×10 is recommended (even higher for 2-stroke engines). A catalytic stripper is recommended when lower dilutions have to be used (e.g. for size distribution measurements) or sub-10 nm measurements. In this case, the high losses at sub-10 nm sizes have to be considered. The standalone CS of this study could remove volatiles up to 15 mg/m^3, while the CS in a PMP configuration could remove 20 times higher. A PMP system (without CS) can handle 2-3 orders of magnitude lower hydrocarbons mass concentration at the inlet of the ET (depending on the lower size of the CPC).

PN EMISSION LEVELS

In the following sections the emissions of the L-category vehicles tested measured from the dilution tunnel (CVS) will be given. As mentioned in the 'Dilution vs. Tailpipe' section the >23 nm results should be similar (within 25%) to those that would be obtained from the tailpipe. For the sub-23 nm results differences of 50% could be expected (smaller for bigger engines). The emissions will be compared with the current limit of passenger cars in Europe (6×10^{11} p/km). This does not imply that the L-category will ever be subject to the same PN limit value as passenger cars (or to a PN limit at all), but can give an idea of where the emissions stand.

Mopeds

Figure 9 summarizes the PN emission levels of mopeds for the cold part (4 first elementary modes) of the R47 cycle (details in Figure A1). The sub-23 nm emissions are also given. For all tests a PCRF (dilution) of 1000×10 was used.

All mopeds emit much higher than the current PN limit for light-duty vehicles of 6×10^{11} p/km, by a factor of 3-20. The higher factors are for the 2-stroke mopeds. The particles between 10 and 23 nm are 10%-60% of the >23 nm emission levels (see ratio of blue to red bars). Losses below 23 nm in the PN system were not considered; this correction factor is around 1.6 [26] (see also experimental setup). The solid sub-10 nm fraction was given only for the cases that the measurements were considered reliable.

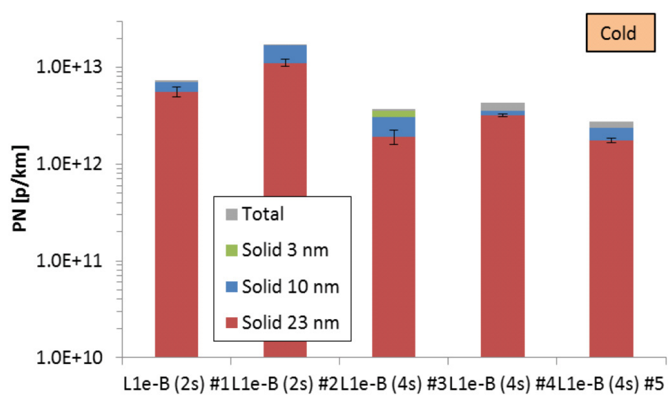

Figure 9. Emission levels of mopeds for the cold part (4 elementary modes) of the R47 cycle. Error bars show min-max values.

The emissions at the hot part (4 last elementary modes) of the R47 cycle are shown in Figure 10 (details in Figure A1). The 2-stroke mopeds were approximately 5.5 times higher than the passenger cars number limit. One moped (4-stroke) had emissions lower than 6×10^{11} p/km and the other 4-stroke was close to the limit. At the hot part the sub-23 nm fraction was high (70-420%), indicating that the PMP methodology misses a big part of solid particles (blue to red bars). The solid particle emissions >10 nm were all higher than 1×10^{12} p/km.

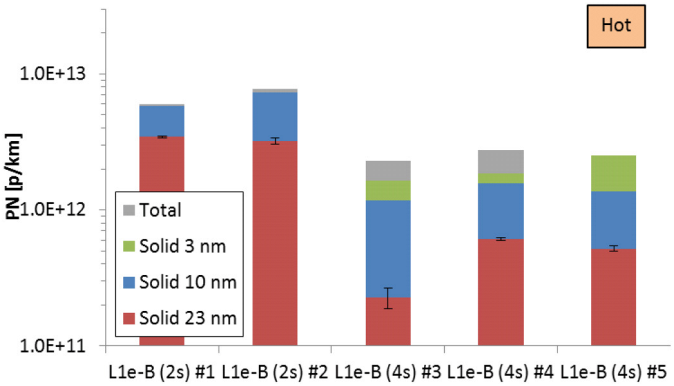

Figure 10. Emission levels of mopeds for the hot part (4 last elementary modes) of the R47 cycle. Error bars show min-max values.

For Euro 2 vehicles only the hot part is considered for determining the emission levels (all mopeds of Figure 9 and 10). However, for Euro 3 the total emissions of the cycle would be the weighted average of cold (30%) and hot (70%) parts and all mopeds would be >6×10^{11} p/km even with the PMP protocol. In this case, even though the PMP protocol would miss much more than 50% of the solid particles, a high emitter would be still detected.

In general, the results are in agreement with the literature where emission levels on the order of 10^{12} p/km or higher have been found [3, 4, 27, 28]. Two-stroke engines emit more than four-stroke engines due to the piston scavenging losses. Especially the volatile part is higher due to the higher amount of unburnt fuel and lubricant [8, 11].

The cold part emissions are higher than the hot part due to the more rich operation, higher hydrocarbons emitted and even blow out of particles in some cases [8]. However the opposite has also been observed [13].

Motorcycles

Figure 11 summarizes the particle emission levels of the motorcycles for the cold part (2 first elementary modes) of the R40 cycle (see Table A4 in the Appendix which was the relevant type approval cycle for each vehicle). The sub-23nm particle emissions are also given. All motorcycles emit higher than the current PN limit of 6×10^{11} p/km, by a factor of 2 to 4. The particles between 10 and 23 nm are 15-80% of the >23 nm emission levels (blue to red bars). Losses in the PN system were not considered; this factor is around 1.6. The ratio of particles between 3 and 23 nm is between 10 and 110% (blue and green to red bars).

The emissions at the hot part (4 last modes) of the R40 cycle are shown in Figure 12. More than half of the motorcycles had emissions lower than 6×10^{11} p/km. The sub-23nm fraction of the 10 to 23 nm fraction was 20-120%. There is one exception (L3e-A1 #1) with even higher percentage which was presented separately in Figure 3. This motorcycle was emitting particles with GMD around 10 nm, so the absolute emissions >23 nm were very low (and the sub-23 nm fraction seems high). Note that the motorcycle of Figure 4 didn't show any high percentage of sub-23 nm particles because the test cycle is still the hot part of R40. At the EUDC (high speed part) the sub-23 nm emissions were very high compared to the >23 nm. Actually, the emissions at the high speed part (EUDC) were higher than 6×10^{11} p/km (Figure not shown) for all (but one) motorcycles reaching 2×10^{12} p/km. The sub-23 nm fraction was 15-65% with the few exceptions mentioned previously.

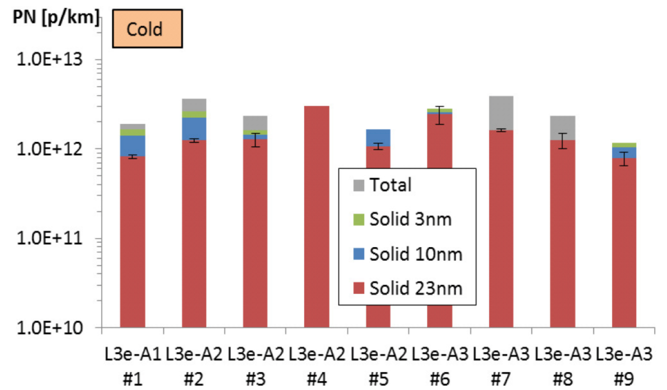

Figure 11. Emission levels of motorcycles for the cold part (2 first elementary modes) of the R40 cycle. Error bars show min-max values.

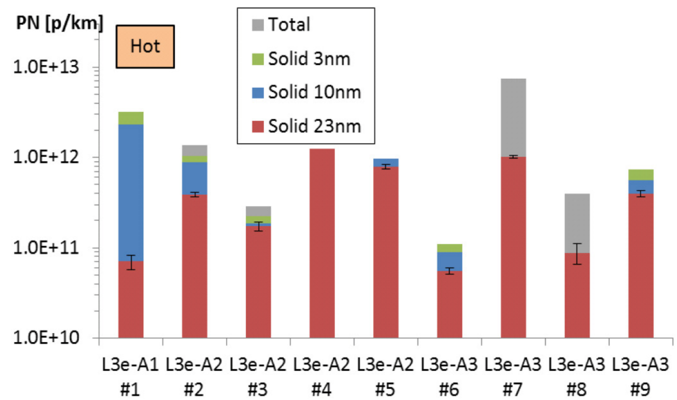

Figure 12. Emission levels of motorcycles for the hot part (4 last elementary modes) of the R40 cycle. Error bars show min-max values.

3- and 4-Wheelers

The emissions of a diesel tricycle, a 3-wheeler and a quad for the cold and hot parts of the tested cycles are given in Figure 13. The emissions of the diesel vehicle are close to the 10^{14} p/km. The other 3-wheeler has emissions similar with the motorcycles as its engine technology is similar. The quad has emissions >10^{13} p/km.

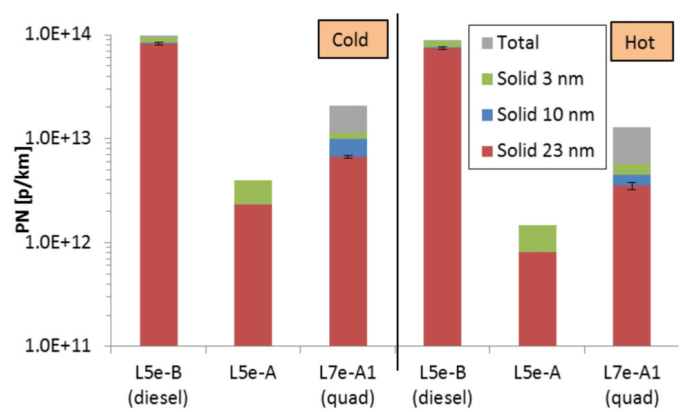

Figure 13. Emission levels of 3- and 4-wheelers for the cold and hot part of the R40 cycle. Error bars show min-max values.

Comparison with the Literature

The measured emission levels are similar to those reported in the literature, where a wide range of emissions has been measured [10, 29]. The higher emissions for some of them have been attributed to the rich operation of the engine. Previous researchers compared the emissions of mopeds or motorcycles with passenger cars of the same period (e.g. 3, 4). Here we compared with the current PN limit of 6×10^{11} p/km and the limit was exceeded from all mopeds. Regarding motorcycles, only one big motorcycle did not exceed the limit and those that had emissions that peaked <23 nm. These results confirm that L-category vehicles are a significant PN pollution source. It was also shown that the sub-23 nm fraction is high (>70%), especially considering that this fraction is <40% for passenger cars and even lower for DPF equipped vehicles [15].

Euro 4 L-category vehicles will be introduced in 2017. The Euro 4 limits will require the extensive use of three way catalysts and stoichiometric combustion for motorcycles, while larger catalysts and overall better strategies will be requested for mopeds [29]. In particular, the introduction of a cold-start means that better thermal management will be required for faster catalyst light off. Euro 4 is not expected to require any technological breakthroughs to achieve, rather normal engineering improvements over the previous stage. Euro 5 however will require significant technological investments to materialize. This is not only the consequence of the reduced emission limit values but also the combined impacts of the enhanced durability and on-board diagnostics (OBD) requirements. For gasoline vehicles, this will require strict enforcement of stoichiometric combustion and an efficient three way catalyst, optimally positioned to reach the limits [29]. How these measures will affect the PN emissions is not clear at the moment and studies with future technologies are necessary. However, because all these measures focus on gaseous pollutants, their effect on solid particle emissions is expected small. Nevertheless, total particle emissions are expected to decrease due to the decreased amount of unburnt fuel and lubricant. It should be also noted that the share of the high emitters (2-stroke mopeds) decreases over time.

Particle Size

The Geometric Mean Diameters (GMD) of the different parts of the cycles will be given in this section. No error bars will be given because the size was changing as the engine was getting warmer (see e.g. Figure 6b). The mean cycle GMDs had variability similar to the PN emissions variability (see e.g. Figures 9, 10, 11, 12, 13). In many cases only one repetition was available.

Mopeds

The GMDs of the cold part (4 first modes) and the hot part (4 last modes) of the R47 cycle for mopeds are shown in Figure 14. The GMDs directly from the dilution tunnel (CVS) of the 2-stroke mopeds are around 150 nm, while for the 4-stroke mopeds are around 70 nm. Similar sizes were measured also for Euro 1 and Euro 2 mopeds [28, 30], but smaller GMDs (70-100 nm) have also been measured for 2-stroke mopeds [9]. The existence or not and the effectiveness of the oxidation catalyst plays an important role. In addition, for CVS diameters the sampling set-up is important. Long tubes between the vehicle and the dilution tunnel will increase condensation and agglomeration and thus the final size. As it has also been shown different lubricants or engine strategies can significantly affect the final GMD [e.g. 9].

After thermal pre-treatment at 300 °C in a CS, the GMDs are between 20 and 40 nm. Note that these sizes refer to tests that no volatile artifact was observed. Similar sizes (around 40 nm) were found by others [11]. This solid core could be either heavy molecular hydrocarbons not evaporated at 300 °C, small soot cores or metal oxides from the additives [12, 13, 15, 24]. This small GMD will result in underestimation of the emissions using the PMP protocol (HD+ET+CPC 23nm) as discussed in the previous section.

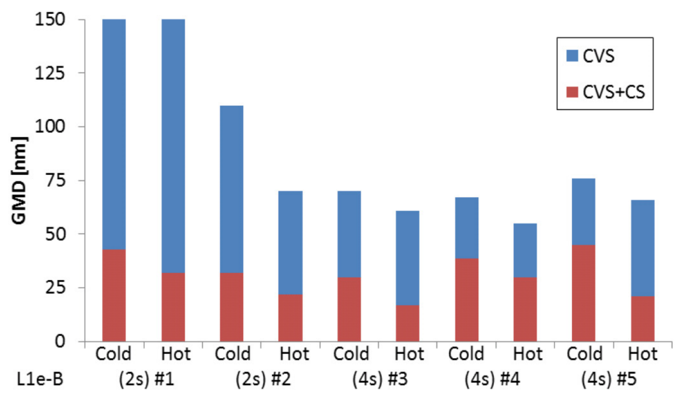

Figure 14. Geometric Mean Diameter (GMD) of mopeds for the cold part (4 first) and hot part (4 last elementary modes) of the R47 cycle.

Motorcycles

The GMDs of the motorcycles can be seen in Figure 15 for the R40 cycle. The GMDs after thermal-pretreatment with a CS are between 25 and 55 nm, slightly bigger compared to the mopeds. The GMDs as measured directly from the full dilution tunnel (CVS) range between 20 and 50 nm, sometimes smaller than the solid diameter, due to a separate (volatile) nucleation mode. The GMDs for the hot part are quite similar to the cold part. The GMDs for many of the motorcycles are much smaller than those measured by diesel vehicles or gasoline direct injection (where PN limits apply) [31]. Gasoline port fuel injection usually have smaller sizes but still bigger than those measured from the motorcycles. This raises concerns regarding the suitability of the PMP method to be extended to L-category vehicles as it is.

3- and 4-Wheelers

The GMDs of the 3- and 4-wheelers can be seen in Figure 16. The GMDs are around 20 nm for the spark ignition vehicles and around 65 nm for the diesel one. The GMDs for the hot part are quite similar to the cold part. The GMD after thermal pre-treatment with the CS was measured only for the diesel tricycle and it was found similar to the GMD without thermal pre-treatment (Figure not shown). This is what was expected for diesel particles.

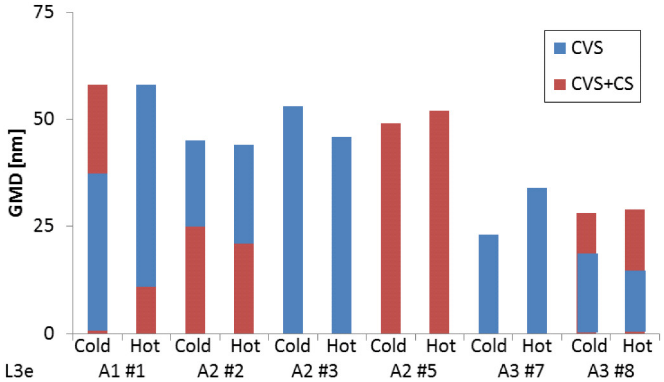

Figure 15. Geometric Mean Diameters (GMD) of motorcycles for the R40 cycles.

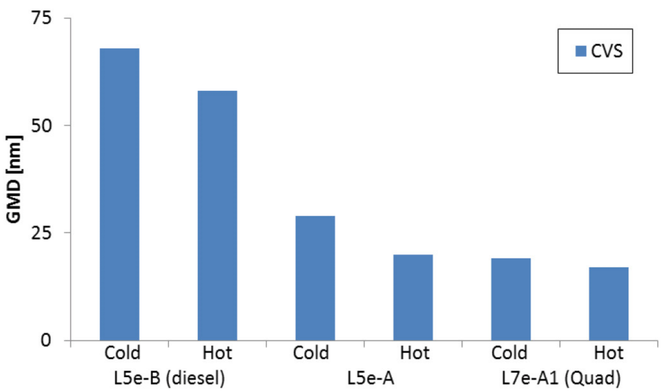

Figure 16. Geometric Mean Diameters (GMD) of 3- and 4-wheelers.

Correlation of Cycles

For most cases examined both the current type approval and the future type approval WMTC were used for the determination of the particle emissions. The following figures compare the cold, hot and the high speed parts of the cycles for particle emissions >23 nm (Figure 17) and >10 nm (Figure 18). Details for the different parts of the cycles can be found in the Appendix.

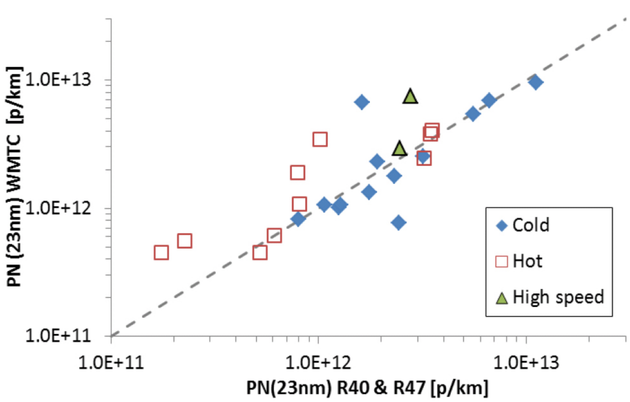

Figure 17. Correlation of WMTC with current type approval cycles (>23 nm).

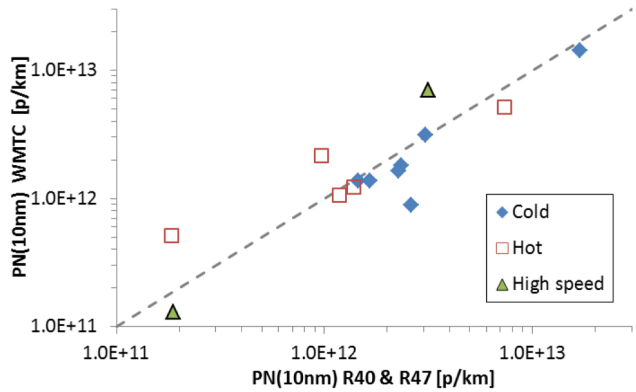

Figure 18. Correlation of WMTC with current type approval cycles (>10 nm).

In general, the agreement of the two cycles is good especially at the cold and high speed parts. The hot part has slightly bigger differences. One reason is that typically the hot part of the WMTC has higher speeds than the R40 and R47. These results indicate that the WMTC is slightly more severe. A vehicle fulfilling the emission limits with the WMTC is expected to fulfil the same limits with the older cycles. Similar results were found for gaseous pollutants in other studies with Euro 3 vehicles [10, 32].

SUMMARY/CONCLUSIONS

L-category vehicles (two- or three-wheel vehicles and quadri-cycles) are a widespread means of transport and their contribution to urban particulate emissions has become significant especially after the drastic decreases of particulate emissions from light duty vehicles. In this study 5 mopeds, 9 motorcycles, 2 tricycles (one of them diesel) and 1 quad were tested regarding their Particle Number (PN) emissions.

Initially the differences between tailpipe and dilution tunnel were examined. The tailpipe emissions are typically higher because agglomeration, thermophoresis and diffusion decrease the particle concentration in the transfer tube between tailpipe and dilution tunnel. For >23 nm emissions the differences were around 10-20% and noticeable mainly for the small engines (low exhaust flow rates). For sub-23 nm measurements the differences were higher, reaching 50%. There were also some interesting cases where the sub-23 nm emissions at the tailpipe were lower at the tailpipe than at the dilution tunnel. This occurred when the Geometric Mean Diameter (GMD) of the particles was around 10 nm, thus agglomeration or efficiency of thermal pre-treatment played an important role.

Then the appropriate sampling setup was investigated. At steady state conditions for 4-stroke motorcycles the typical dilutions used for light duty vehicles can be used. However, for 2-stroke engines or generally at cold starts and/or accelerations the high amount of unburnt fuel and lubricant can result in artifacts, i.e. formation of volatile nucleation mode particles downstream of the thermal pre-treatment section of the PN systems that will be counted as solids. This artifact was found in a few cold starts with 2-stroke engines even with very high dilutions or even when using a catalytic stripper. These particles are typically smaller than 23 nm or even 10 nm and the current legislated PN measurement protocol is not prone to this artifact.

Experiments with atomized oil showed that the current PMP systems are prone to re-nucleation artifact at mass concentrations of 15 mg/ m^3: A PCRF (dilution) of 25×10 could keep the re-nucleation mode below 10 nm, but >1000×10 was necessary to keep it below 3 nm. The addition of a catalytic stripper (CS) removed the need of any primary dilution for this mass concentration. The general recommendation is that for PMP systems a dilution of at least 100×10 should be used, and even higher for 2-stroke engines (10 times more). When lower dilutions are necessary (e.g. for size distribution measurements) a catalytic stripper is highly recommended.

The (solid) >23 nm PN emission levels of mopeds were 3-20 times higher than the current light duty vehicles limit of 6×10^{11} p/km, especially for the 2-stroke mopeds during cold start. At the hot part of the cycles the 4-stroke mopeds had emissions close to the limit, while the 2-stroke approximately 5.5 times higher. The particles between 10 and 23 nm were 10-60% more than the >23 nm during cold start but 7-420% higher during hot engine operation. The reason is that the GMD decreased to 23 nm as the engines got hotter.

The motorcycles had 2-4 times higher emissions compared to the PN limit of light duty vehicles. The 10-23 nm particles were 10-120% more than the >23 nm emissions. The GMD of solid particles was 25-55 nm, while the GMD without any thermal pretreatment was much smaller, indicating the existence of small volatile particles.

The quad had 12 times higher PN emission than the PN limit and GMD close to 20 nm. The diesel tricycle was >3 orders of magnitude higher but GMD around 65 nm.

The solid emissions of many of the L-category vehicles examined have sizes that peak close to this 23 nm diameter. This can result in underestimation of the true solid emissions of L-category vehicles. It was shown in the paper that a good compromise for measuring below 23 nm and avoiding artifacts is to measure above 10 nm.

Although the PMP protocol fails to measure a significant part of the L-category solid emissions (>70% for motorcycles, vs <40% for passenger cars), there were not many cases in which the PMP protocol could not identify a high emitter. Nevertheless, this topic should be further addressed, especially when a sufficient number of Euro 4 models will be on the market.

Finally, the PN correlation of current type approval cycles with the new WMTC was very good.

REFERENCES

1. European Association of Motorcycle Manufacturers. Powered Two Wheeler Registrations in EU and EFTA Countries: 2014 Statistical Release. February 2015. http://www.acem.eu/
2. U.S. Commercial Service Resource Guide for the European Motorcycle Industry. Motorcycles: European Market Briefs 2013-2014. Available at: http://www.export.gov/build/groups/public/@eg_main/@byind/@autotrans/documents/webcontent/motocycles066908.pdf
3. Ntziachristos, L., Giechaskiel, B., Pistikopoulos, P., Fysikas, E. et al., "Particle Emissions Characteristics of Different On-Road Vehicles," SAE Technical Paper 2003-01-1888, 2003, doi:10.4271/2003-01-1888.
4. Prati, M., and Costagliola, M., "Emissions of Fine Particles and Organic Compounds from Mopeds," *Environ. Engin. Sci.* 26:111-121, 2009, doi:10.1089/ees.2007.0206
5. Platt, S., Haddad, I., Pieber, S., et al., "Two-Stroke Scooters are a Dominant Source of Air Pollution in Many Cities," *Nature Communications* 5:3749, 2014.
6. Zardini, A., Platt, S., Clairotte, M., et al., "Effects of Alkylate Fuel on Exhaust Emissions and Secondary Aerosol Formation of a 2-stroke and a 4-stroke Scooter," *Atmospheric Environment*, 94:307-315, 2014
7. Ntziachristos, L., Geivanidis, S., Samaras, Z., et al., "Study on Possible New Measures Concerning Motorcycle Emissions," Final Report - Revised Version. Report No: 08.RE.0019.V4 Thessaloniki, Greece, September 2009
8. Czerwinski, J., Comte, P., Napoli, S., and Wili, P., "Summer Cold Start and Nanoparticulates of Small Scooters," SAE Technical Paper 2002-01-1096, 2002, doi:10.4271/2002-01-1096.
9. Czerwinski, J., Comte, P., Astorga, C., Adam, T. et al., "Combinations of Technical Measures for Reduction of Particle Emissions & Toxicity of 2-S Scooters," SAE Technical Paper 2009-01-0689, 2009, doi:10.4271/2009-01-0689.
10. Favre, C., Bosteels, D., May, J., De Souza, I. et al., "An Emissions Performance Evaluation of State-of-the-Art Motorcycles over Euro 3 and WMTC Drive Cycles," SAE Technical Paper 2009-01-1841, 2009, doi:10.4271/2009-01-1841.
11. Czerwinski, J., Comte, P., Makkee, M., and Reutimann, F., "(Particle) Emissions of Small 2-& 4-Stroke Scooters with (Hydrous) Ethanol Blends," SAE Technical Paper 2010-01-0794, 2010, doi:10.4271/2010-01-0794.
12. Seggiani, M., Prati, M., Costagliola, M., et al., "Bioethanol-Gasoline Fuel Blends: Exhaust Emissions and Morphological Characterization of Particulate from a Moped Engine," *J. Air & Waste Management Association* 62:8:888-897, 2012, doi:10.1080/10962247.2012.671793
13. Czerwinski, J., Comte, P., Larsen, B., Martini, G. et al., "Research on Particle Emissions of Modern 2-Stroke Scooters," SAE 2006-01-1078, 2006, doi:10.4271/2006-01-1078.
14. Giechaskiel, B., Chirico, R., DeCarlo, P., et al., "Evaluation of the Particle Measurement Programme (PMP) Protocol to Remove the Vehicles' Exhaust Aerosol Volatile Phase," *Sci. Total Environ*. 408:5106-5116, 2010, doi:10.1016/j.scitotenv.2010.07.010
15. Giechaskiel, B., Manfredi, U., and Martini, G., "Engine Exhaust Solid Sub-23 nm Particles: I. Literature Survey," SAE 2014-01-2834, 2014, doi:10.4271/2014-01-2834
16. Johnson, T., Caldow, R., Pöcher, A., Mirme, A. et al., "A New Electrical Mobility Particle Sizer Spectrometer for Engine Exhaust Particle Measurements," SAE Technical Paper 2004-01-1341, 2004, doi:10.4271/2004-01-1341.
17. Amanatidis, S, Ntziachristos, L, Giechaskiel, B, et al. "Evaluation of an Oxidation Catalyst ("Catalytic Stripper") in Eliminating Volatile Material from Combustion Aerosol," *J. Aerosol Sci.* 57:144-155, 2013, doi:10.1016/j.jaerosci.2012.12.001
18. Giechaskiel, B., Cresnoverh, M., Jörgl, H., and Bergmann, A., "Calibration and Accuracy of a Particle Number Measurement System," *Meas. Sci. Techn*. 21:045102, 2010
19. Giechaskiel, B., Dilara, P., and Andersson, J. "PMP Light Duty Interlaboratory exercise: Repeatability and Reproducibility of the Particle Number Method," *Aerosol Sci. Technology* 42:528-543, 2008
20. Czerwinski, J., Comte, P., Mayer, A., and Reutimann, F., "Investigations of Changes of the 2-Stroke Scooters Nanoparticles in the Exhaust- and CVS-System," SAE 2013-24-0178, 2013, doi:10.4271/2013-24-0178.
21. Giechaskiel, B., Arndt, M., Schindler, W., Bergmann, A. et al., "Sampling of Non-Volatile Vehicle Exhaust Particles: A Simplified Guide," *SAE Int. J. Engines* 5(2):379-399, 2012, doi:10.4271/2012-01-0443.
22. Ålander, T., Antikainen, E., Raunemaa, T. et al. "Particle Emissions from a Small Two-Stroke Engine: Effects of Fuel, Lubricating Oil, and Exhaust Aftertreatment on Particle Characteristics," *Aerosol Sci. Technol*. 39:2, 151-161, 2005 doi:10.1080/027868290910224
23. Mayer, A., Czerwinski, J., Kasper, M., Ulrich, A. et al., "Metal Oxide Particle Emissions from Diesel and Petrol Engines," SAE 2012-01-0841, 2012, doi:10.4271/2012-01-0841
24. Etissa, D., Mohr, M., Schreiber, D., and Buffat, P., "Investigation of Particles Emitted from Modern 2-StrokeScooters," *Atmospheric Environment* 42:183-95, 2008
25. Giechaskiel, B. and Drossinos, Y., "Theoretical Investigation of Volatile Removal Efficiency of Particle Number Measurement Systems," SAE *Int. J. Engines* 3(1):1140-1151, 2010, doi:10.4271/2010-01-1304.

26. Giechaskiel, B. and Martini, G., “Engine Exhaust Solid Sub-23 nm Particles: II. Feasibility Study for Particle Number Measurement Systems,” *SAE Int. J. Fuels Lubr.* 7(3):935-949, 2014, doi:10.4271/2014-01-2832.
27. Ntziachristos, L., Pistikopoulos, P., and Samaras, Z., “Particle Characterization from Two-stroke Powered Two-Wheelers,” Int. *J. Engine Res*. 6:263-275, 2005
28. Clairotte, M., Adam, T., Chirico, R., et al., “Online Characterisation of Regulated and Unregulated Gaseous and Particulate Exhaust Emissions from Two-Stroke Mopeds: A Chemometric Approach,” *Anal Chim Acta* 717:28-38, 2012.
29. Ntziachristos, L., Galassi, M., & Dilara, P., Emission Factors for New and Upcoming Technologies in Road Transport. EU report 26952, 2014
30. Martini, G., Astorga, C., Thomas, A., et al., “Physical & Chemical Characterization of emissions from 2-Stroke motorcycles: Comparison with 4-stroke engines,” EUR 23999 EN.
31. Giechaskiel, B., Mamakos, A., Andersson, J., et al., “Measurement of Automotive Non-volatile Particle Number Emissions within the European Legislative Framework: a Review,” *Aerosol Sci. Technol*. 46:719-749.2012
32. Bonnel, P., Martini, G., & Krasenbrink, A., “Report on EURO 3 Stage for motorcycles: Derivation of equivalent limits for the WMTC driving cycle,” EU report 2005.

CONTACT INFORMATION

Barouch Giechaskiel, PhD
Sustainable Transport Unit
Joint Research Centre of the European Commission
I-21027 Ispra (VA), Italy
Barouch.Giechaskiel@jrc.ec.europa.eu

ACKNOWLEDGMENTS

The authors would like to thank Gaston Lanappe and Andrea Bonamin for their help with the experimental work.

DISCLAIMER

The opinions expressed in this manuscript are those of the authors and should in no way be considered to represent an official opinion of the European Commission.

DEFINITIONS/ABBREVIATIONS

CI - Compression Ignition

CPC - Condensation Particle Counter.

CS - Catalytic Stripper

CVS - Constant Volume Sampler

DPF - Diesel Particulate Filter

EC - European Commission

EEPS - Engine Exhaust Particle Sizer

ET - Evaporation Tube

EU - European Union

EUDC - Extra Urban Driving Cycle

FTIR - Fourrier Transform Infra-Red

GMD - Geometric Mean Diameter

HD - Hot Dilution

JRC - Joint Research Centre

OBD - On-Board Diagnostics

PCRF - Particle number Concentration Reduction Factor

PI - Positive Ignition

PM - Particulate Matter

PMP - Particle Measurement Program

PN - Particle Number

POA - Primary Organic Aerosol

R40 - UN-ECE Regulation 40

R47 - UN-ECE Regulation 47

SOA - Secondary Organic Aerosol

SMPS - Scanning Mobility Particle Sizer

TP - Tailpipe

VELA - Vehicle Emissions Laboratory

VOC - Volatile Organic Compounds

WMTC - World Harmonized Motorcycle Test Cycle

APPENDIX

Table A1 summarizes the emissions regulations timetable. 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 (Table A2). Directive 2002/51/EC (and Directive 2003/77/EC) amended Directive 97/24/EC in 2002 and implemented standards Euro 2 and 3 for motorcycles. Regulation (EU) No 168/2013 in 2013 and supplemental Regulation (EU) 134/2014 in 2014 expanded the number of L-categories and established implementation dates for Euro 4 and 5 in order to keep constant or reduce the share of total road-transport emissions from L-category vehicles as compared to other road vehicle categories. The Euro 4 and 5 environmental steps are such measures designed to reduce emissions of particulate matter and ozone precursors such as nitrogen oxides and hydrocarbons. A considerable reduction in hydrocarbon emissions from L-category vehicles is necessary to improve air quality and comply with limit values for pollution, not only directly to significantly reduce the disproportionately high hydrocarbon tailpipe and evaporative emissions from these vehicles, but also to help reduce volatile particle levels in urban areas and possibly also smog.

Euro 1 standards for mopeds had emission limits for CO and HC+NO_x. Euro 2 standards reduced those limits. Euro 3 standards included the cold start emissions (the entire R47 cycle is sampled). From Euro 4 on mopeds are included in the L1 category with separate emission limits for CO, HC and NO_x.

Euro 1 standards for motorcycles had emission limits for CO, HC and NO_x which were different for 2-stroke and 4-stroke engines. Euro 2 limits were tighter and depended on the engine capacity (<150 or ≥150 cm^3). Euro 3 kept the Euro 2 classification, tightened the limits and included the cold start emissions. Euro 3 gave also the possibility to use the new WMTC cycle for type approval (with different emission limits). From Euro 4 on motorcycles are included in the L3 category. The limits depend on their class, which is determined from the engine capacity and the maximum rated speed (Table A3). A Particulate Matter (PM) limit for Compression Ignition (CI) and CI/hybrid vehicles (80 mg/km) was also added.

The test cycles prescribed in the previous regulations can be seen in Figures A1, A2, A3. Sampling of emissions is conducted on different parts depending on the Euro level, engine capacity etc. Details can be seen in the figures. The appropriate parts of the WMTC for the type-approval test can be found based on the class of the vehicle according to Table A3.

Table A1. Emission regulations timetable. Vehicle categories in Table A2. WMTC classes in Table A3. Details of the test cycles can be found in Figures A1, A2, A3.

Standard	Class	Effect	Regulation	Cycle (modes sampled)	Comments
Euro 1	Moped Motorcycles	1999	Directive 97/24/EC	Reg. 47 (4 last of 8) Reg. 40 (4 last of 6)	Higher limits for 3-wheel vehicles Motorcycles limits for 2-s and 4-s
Euro 2	Moped Motorcycles Tricycles	2003	Directive 2002/51/EC	Reg. 47 (4 last of 8) Reg. 40 (4 last of 6) Reg. 47 (4 last of 8)	Motorcycles limits for <150 or ≥150 cm^3 Tricycles limits for PI or CI
Euro 3	Moped Motorcycles <150 cm^3 Motorcycles ≥150 cm^3	2006	Directive 2013/60/EU Directive 2002/51/EC	Cold Reg. 47 (4 + 4)* Cold Reg. 40 (all 6) Cold Reg. 40 + EUDC (all)	Possibility for WMTC type approval (based on speed classification)
Euro 4	L1e, L2e, L6e L5e, L7eB, L7eC L3e, L4e, L7eA	2017 2016 2016	Reg. (EU) 168/2013 and 134/2014	Cold Reg. 47 (4 + 4) Cold Reg. 40 + EUDC** WMTC, Stage 2	Different limits for PI or CI Different limits for PI or CI Diff. for speeds <130 or ≥130 km/h or CI
Euro 5	L1e – L7e	2020	Reg. (EU) 168/2013 and 134/2014	WMTC, revised	See vehicle classes for WMTC. Different weigh factors

* 30% and 70% weighing factor for Euro 3, no weight factors for Euro 4

** 1 cold R40 + 5 R40 + EUDC for Euro 4

Directive 2002/24/EC classified the vehicles of L category (Motor vehicles with less than four wheels) (Table A2). Later Regulation (EU) No 168/2013 expanded the vehicles of this category as in Table A2. It should be mentioned that in ECE Regulation 47 moped was considered a two-wheeled or three-wheeled vehicle with an unladen weight of less than 400 kg, a maximum design speed not exceeding 50 km/h and a cylinder capacity not exceeding 50 cm^3. Mopeds are now classified as L1 and the maximum speed is 45 km/h. In ECE Regulation 40 motorcycle was considered a two-wheeled or three-wheeled vehicle with an unladen weight of less than 400 kg having a maximum design speed exceeding 50 km/h and/or cylinder capacity exceeding 50 cm^3.

Table A2. Vehicle types according to Directive 2002/24/EC and Regulation (EU) No 168/2013.

	Type	Wheels	C [cm³]		Speed [km/h]	Power [kW]	Mass [kg]	Examples	
L1e-A L1e-B	Powered cycle Two-wheel Moped	2	≤50	+	≤25 ≤45	≤1 ≤4			
L2e	Three-wheel Moped	3	≤50	+	≤45	≤4	≤270		
L3e-A1 L3e-A2 L3e-A3	Motor-cycle (also depending on power/weight ratio)	2	≤125	or	>50	≤11 ≤35			
L4e	Motor-cycles with sidecars	3 asym.	>50	or	>45				
L5e-A L5e-B	Tricycles	3 sym.	>50	or	>45				
L6e-A L6e-B	Light quad Light mini car	4	≤50	+	≤45	≤4 ≤6	≤425		
L7e-A L7e-B L7e-C	On-road quad All-terrain vehicles Heavy mini car	4			 ≤90 ≤90	≤15 ≤15 ≤15	≤450 (600 for goods)	 	

Table A3. WMTC appropriate parts for the type approval based on vehicle class (P=Part).

Class	Speed [km/h]	Capacity [cm^3]	WMTC parts
1*	<100	<150	P1+P1(hot) (both reduced speed)
2-1	<115	any	P1+P2 (both reduced speed)
2-2	<130	any	P1+P2
3-1	<140	any	P1+P2+P3 (last part reduced speed)
3-2	>140	any	P1+P2+P3

* Categories L1e-A, L1e-B, L2e, L5e-B and L6

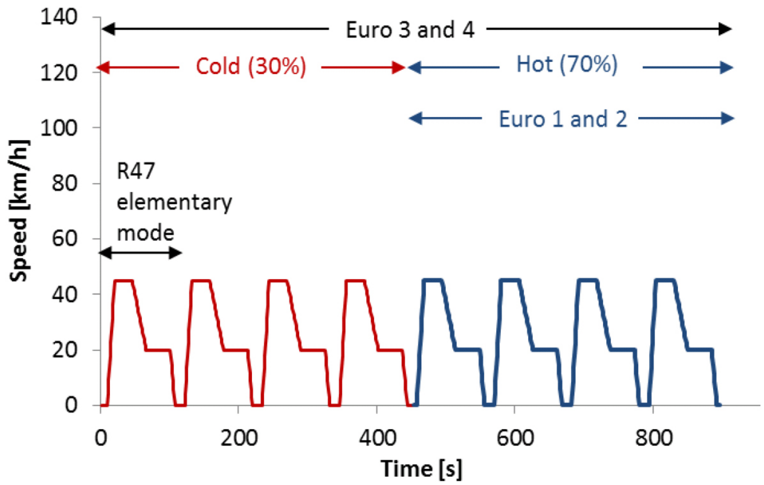

Figure A1. Driving cycles for mopeds (Euro 1 to 3) or L1e, L2e and L6e categories (Euro 4), based on R47 cycle. Note that mopeds until Euro 3 had to reach their maximum speed (up to 50 km/h).

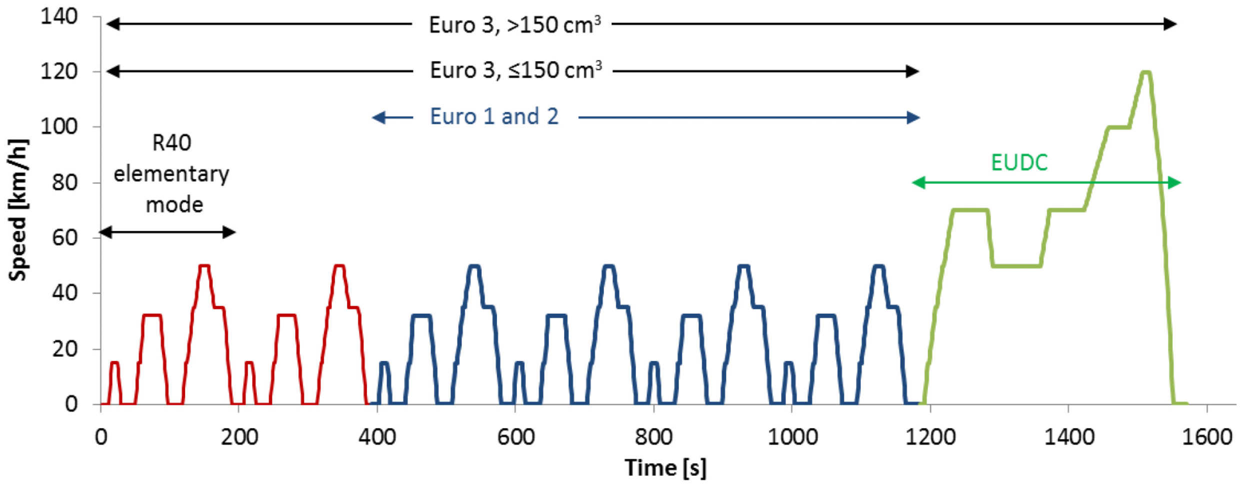

Figure A2. Driving cycles for motorcycles (Euro 1 to 3), or L5e, L7e-B, and L7e-C categories (Euro 4) based on the R40 and the EUDC. Pollutant sampling is conducted depending on the Euro level during the periods shown in the Figure. Euro 4 is like Euro 3 with sampling one R40 elementary mode as cold phase.

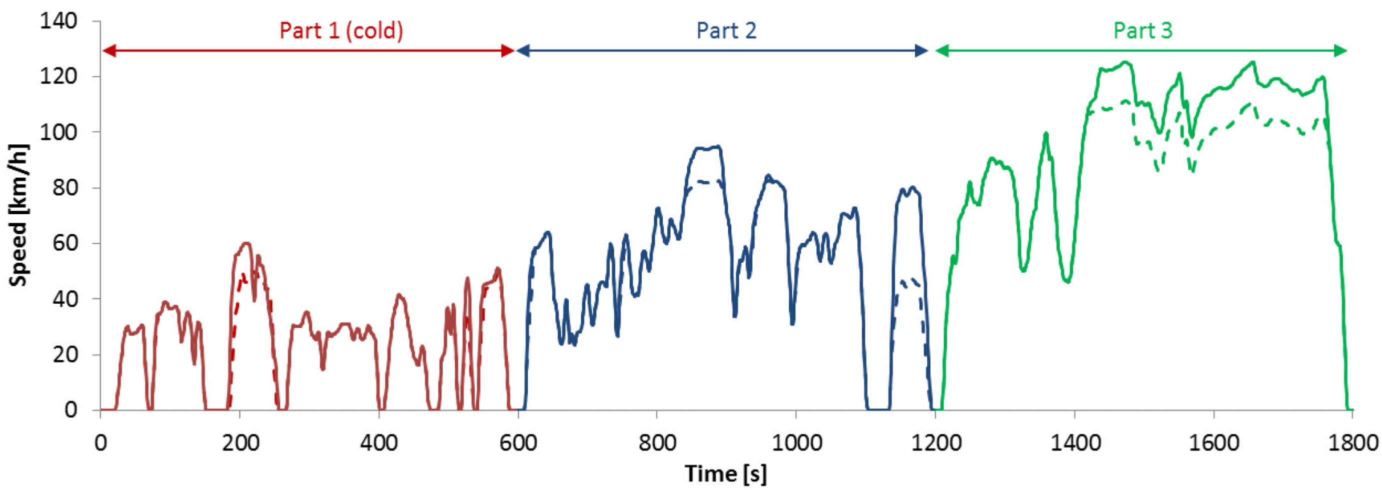

Figure A3. WMTC (stage 2) speed profile (reduced speed also shown with dashed lines).

Table A4. Classification of vehicles examined in this study. All are gasoline unless otherwise specified.

Code	Displ. [cm^3]	Speed [km/h]	Engine cycle	Power [kW]	Mileage [km]	Technology	Euro	Type Approval cycle	Type Approval. WMTC (for Euro 4+)	Class WMTC
L1e-B (2s) #1	49	45	2-stroke	4.8	5000	carburetor	Euro 2	R47	P1 (max 45km/h) + P1 (hot)	Class 1
L1e-B (2s) #2	49	45	2-stroke	3.2	2500	carburetor, oxi cat.	Euro 2	R47	P1 (max 45km/h) + P1 (hot)	Class 1
L1e-B (4s) #3	49	45	4-stroke	2.6	2000	carburetor, oxi cat.	Euro 2	R47	P1 (max 45km/h) + P1 (hot)	Class 1
L1e-B (4s) #4	49	25	4-stroke	3.2	2500	carburetor, oxi cat.	Euro 2	R47	P1 (max 25km/h) + P1 (hot)	Class 1
L1e-B (4s) #5	49	25	4-stroke	3.0	2000	carburetor, oxi cat.	Euro 2	R47	P1 (max 25km/h) + P1 (hot)	Class 1
L3e-A1 #1	124	<100	4-stroke	7.9	1000	electr. inj., oxi cat	Euro 3	cold R40	P1+P1(hot)*	Class 1
L3e-A2 #2	149	<100	4-stroke	9.0	3000	carburetor	Euro 1	R40 (because Euro 1)	P1+P1(hot)*	Class 1
L3e-A2 #3	280	<115	4-stroke	16.4	2000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2(reduced)	Class 2-1
L3e-A2 #4	280	<130	4-stroke	16.4	1000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2	Class 2-2
L3e-A2 #5	385	>140	4-stroke	23.5	27000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2+P3	Class 3-2
L3e-A2 #6	700	>140	4-stroke	60.0	26000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2+P3	Class 3-2
L3e-A3 #7	900	>140	4-stroke	101	15000	electr. inj., oxi cat	Euro 2	R40 (because Euro 2)**	P1+P2+P3	Class 3-2
L3e-A3 #8	1100	>140	4-stroke	116	6000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2+P3	Class 3-2
L3e-A3 #9	1200	>140	4-stroke	110	8000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2+P3	Class 3-2
L5e-B (diesel)	420	65	4-stroke	9.0	5000	none	Euro 2	R40	P1+P1(hot)	Class 2-1
L5e-A (3-wh.)	245	<130	4-stroke	16.5	3000	electr. inj., oxi cat	Euro 3	cold R40+EUDC	P1+P2	Class 2-2
L7e-A1 (quad)	500	<90	4-stroke	14.5	500	electr. inj., oxi cat	Euro 3	R40 (because Euro 2)	P1+P2(reduced)	Class 2-1

* For the hot part also P2 was tested but not presented, ** EUDC also tested but not presented

Directives / Regulations

Directive 97/24/EC of the European Parliament and of the Council of 17 June 1997 on certain components and characteristics of two or three-wheel motor vehicles

Directive 2002/24/EC of the European Parliament and of the Council of 18 March 2002 relating to the type-approval of two or three-wheel motor vehicles and repealing Council Directive 92/61/EEC

Directive 2002/51/EC of the European Parliament and of the Council of 19 July 2002 on the reduction of the level of pollutant emissions from two- and three-wheel motor vehicles and amending Directive 97/24/EC

Directive 2003/77/EC of 11 August 2003 amending Directives 97/24/EC and 2002/24/EC of the European Parliament and of the Council relating to the type-approval of two- or three-wheel motor vehicles

Directive 2013/60/EU of 27 November 2013 amending for the purposes of adapting to technical progress, Directive 97/24/EC of the European Parliament and of the Council on certain components and characteristics of two or three-wheel motor vehicles, Directive 2002/24/EC of the European Parliament and of the Council relating to the type-approval of two or three-wheel motor vehicles and Directive 2009/67/EC of the European Parliament and of the Council on the installation of lighting and light-signaling devices on two- or three-wheel motor vehicles

Regulation (EU) No 168/2013 of the European Parliament and of the Council of 15 January 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles

Regulation (EU) No 134/2014 of 16 December 2013 supplementing Regulation (EU) No 168/2013 of the European Parliament and of the Council with regard to environmental and propulsion unit performance requirements and amending Annex V thereof

UN-ECE Regulation No. 40 Uniform Provisions Concerning the Approval of Motor Cycles Equipped with a Positive-Ignition Engine with Regard to the Emission of Gaseous Pollutants by the Engine

UN-ECE Regulation No. 47 Uniform Provisions Concerning the Approval of Mopeds Equipped with a Positive-Ignition Engine with Regard to the Emission of Gaseous Pollutants by the Engine