Faculty of Engineering

Department of Vehicles and Ground Transport

Measurement of exhaust and noise emissions of an unrestricted enduro motorcycle

Introduction

Mobile sources, including on-road and off-road vehicles and other mobile machinery, are one of the principal sources of air pollution in densely inhabited areas. Exhaust gases emitted by internal combustion engines contain carbonaceous nanoparticles, nitrogen oxides, and other compounds harmful to the environment and especially to human health, and are often emitted in the middle of streets and roads, at the breathing level, in close proximity to urban population[1,2].

While the emissions of larger vehicles, from cars to trucks and buses, have been drastically decreased through efficient exhaust aftertreatment, some categories, especially very small engines, were abated to a considerably lower extent. This is the case with many mopeds, scooters and motorcycles, for which emission limits (per km or mile driven)[3,4,5] have been less stringent than those for light-duty vehicles, and for which any limit for particulate matter is, at present, only considered. As a result, motorcycle emissions (per vehicle and km driven) have been reported in the past to be higher than those of passenger cars[6,7,8,9]. Motorcycle emissions in Europe have been recently examined in Horizon Europe LENS project[10].

[1] Stolcpartova, J., Pechout, M., Dittrich, L., Mazac, M., Fenkl, M., Vrbova, K., ... & Vojtisek-Lom, M. (2015). Internal Combustion Engines as the Main Source of Ultrafine Particles in Residential Neighborhoods: Field Measurements in the Czech Republic. *Atmosphere*, *6*(11), 1714-1735.

[2] Rönkkö, T., Kuuluvainen, H., Karjalainen, P., Keskinen, J., Hillamo, R., Niemi, J. V., ... & Dal Maso, M. (2017). Traffic is a major source of atmospheric nanocluster aerosol. *Proceedings of the National Academy of Sciences*, *114*(29), 7549-7554.

[3] https://www.aecc.eu/legislation/motorcycles-and-mopeds/

[4] https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-emissions-motorcycles-light-duty

[5] https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-86/subpart-E

[6] Vasic, A. M., & Weilenmann, M. (2006). Comparison of real-world emissions from two-wheelers and passenger cars. *Environmental science & technology*, *40*(1), 149-154.

[7] Tsai, J. H., Huang, P. H., & Chiang, H. L. (2017). Air pollutants and toxic emissions of various mileage motorcycles for ECE driving cycles. *Atmospheric Environment*, *153*, 126-134.

[8] Hassani, A., & Hosseini, V. (2016). An assessment of gasoline motorcycle emissions performance and understanding their contribution to Tehran air pollution. *Transportation research part D: Transport and environment*, *47*, 1-12.

[9] Martini, G., Manfredi, U., and De Gennaro, M., "Gaseous Emissions from Euro 3 Motorcycles and Euro 5 Passenger Cars Measured Over Different Driving Cycles," SAE/KSAE 2013 International Powertrains, Fuels & Lubricants Meeting, Seoul, South Korea, October 21, 2013, https://doi.org/10.4271/2013-01-2619.

[10] www.lens-horizoneurope.eu

Additionally, many motorcycles are operated for recreational purposes, and of these, many are modified with claims of improved response, power output, sound performance, or other parameters. A LENS project report found that 12% of motorcycles inspected in Europe were visibly tampered and estimates the real tampering rate to be around 20% or higher[11]. Aside from their intended goal of providing an improved riding experience, such modifications may increase noise and emission levels[12]. For example, excessive noise from loud motorcycles has been found to be a major source of annoyance in Dutch cities[13] as well as rural valleys in Austria[14], and to be, in some cases, a "most annoying environmental noise sources introducing a degradation of the urban environment"[15].

Enduro motorcycles derive their name from demanding long-distance off-road races through a variety of terrain. They are relatively lightweight and simple, yet robust, high powered, but built more for agility and handling terrain than for speed. Some enduro motorcycles meet standards for on-road use and are designed as "road legal", classified by Article 4 of EU 168/2013[16] as special use motorcycles, class L3e-A1E, L3e-A2E, L3e-A3E, and can be registered and operated on public roads. Other enduro motorcycles do not meet noise and/or emission standards and cannot be registered for on-road use. Some motorcycles have alternate settings for on-road and off-road use. Some are manufactured as road-legal, but are modified to obtain better response, higher horsepower, and more pronounced, and often extreme, characteristic sound.

This study examines noise and exhaust emissions from a typical enduro motorcycle, available on the market in two versions: One is a road-legal version, where the 2-stroke, 300 cc engine, rated at less than 10 kW maximum power, is equipped with an exhaust gas oxygen sensor, a catalytic converter, and a resonating muffler, reaching emissions and noise levels compliant with Euro 4 limits for L-category vehicles, referred to as the „restricted" version, for which a Certificate of Conformity (CoC) has been issued, allowing it to be registered as an L-category road vehicle. The other is a „de-restricted", or unrestricted, version allowing for much higher engine output, not intended for use on public roads. The motorcycle was procured from its owner in unrestricted configuration and tested as delivered to preserve its "in-use" condition.

[11] Dittrich, M., Grigoradou, A., Steven, H., Triantafyllopoulos, G. (2025). "Impact of interventions in decreasing LV noise and pollutant emissions". https://lens-horizoneurope.eu/wp-content/uploads/2025/12/LENS_D6.4_Impact-of-interventions-in-decreasing-LV-noise-and-pollutant-emissions.pdf

[12] Zardini, A.A.; Suarez-Bertoa, R.; Dardiotis, C.; Astorga, C. Unregulated Pollutants from Tampered Two-Wheelers. *Transp. Res. Procedia* **2016**, *14*, 3109–3118.

[13] Dittrich, M., & Wessels, P. (2024, October). Noise monitoring of loud vehicles in four Dutch cities. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* (Vol. 270, No. 6, pp. 5840-5851). Institute of Noise Control Engineering.

[14] Lechner, C., Schnaiter, D., Siebert, U., & Böse-O'Reilly, S. (2020). Effects of motorcycle noise on annoyance—a cross-sectional study in the Alps. *International journal of environmental research and public health*, *17*(5), 1580.

[15] Paviotti, M., & Vogiatzis, K. (2012). On the outdoor annoyance from scooter and motorbike noise in the urban environment. *Science of the total environment*, *430*, 223-230.

[16] 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.

Methodology

Vehicle

A popular enduro motorcycle, KTM EXC 300 TPI, variant COP3, with a 2-stroke, single cylinder, fuel-injected KTM 557 petrol engine, with a displacement of 293 cm^3, a 6-speed manual gearbox and chain drive, has been procured used from its first owner. This model of motorcycle is available in both restricted, road-legal version, with rated engine power 9.8 kW at 4500 rpm, and in unrestricted off-road version (one dealer website does not state engine power[17], an unofficial website claims rated power of about 38 kW[18]). According to the dashboard display, the motorcycle has logged 177.6 hours of operation and 3816 km at the beginning of the testing. The motorcycle was in unrestricted configuration, with engine control unit settings and intake and exhaust system different from the version type-approved for on-road use. The technology for the unrestricted version – primarily different intake and exhaust system and engine control unit (ECU) software – has been found to correspond to that available through the dealer for the unrestricted version. Original parts for the restricted configuration, including intake, exhaust and a catalytic converter, as well as a Certificate of Conformity, were provided with the motorcycle. No information was given as to who performed the conversion, other than that the conversion took place when the motorcycle was new.

Table 1: Motorcycle parameters

Class	L3e-A2E: “enduro” use medium-performance two-wheel motorcycle, with max net power of 35 kW; max power-to-weight ratio of 0.2 kW/kg (restricted)
Motorcycle model	KTM 300 EXC TPI
Engine	KTM 557, 2-stroke, fuel injected, single cylinder
Displacement	293 cm^3
Engine power	9.8 kW @ 4500 rpm per CoC (restricted version)
Mass in running order	115 kg
Maximum permissible mass (gross weight rating)	335 kg
Mileage at the beginning of the tests	177.6 hours (3816 km)

The motorcycle has been transported to a closed test track, where coastdown tests were performed to determine its rolling resistance. The motorcycle was then transported to an accredited vehicle emissions testing laboratory, where it was mounted to a chassis dynamometer, and subjected to emissions tests. Finally, stationary and in-motion noise tests, and exhaust emissions tests during accelerations from standstill to 50 and 80 kph were performed at the test track.

[17] https://www.ktm-shop24.de/KTM-300-EXC-2023
[18] https://www.motorcyclespecs.com/ktm-300-exc-tpi/

Coastdown tests

The purpose of the coastdown test was to determine the rolling resistance of the motorcycle for further chassis dynamometer testing. The inputs are the mass and the measured deceleration. The deceleration F is linearized by a polynomial F = f2 * v2 + f1 * v + f0, where v is the vehicle speed and f2, f1 and f0 are constants. The quadratic term represents aerodynamic drag which is proportional to the square of the velocity, while the constant term represents tyre rolling resistance and drivetrain losses, which are independent of vehicle speed. During the coastdown test, the motorcycle has been driven with original all terrain, knobby tyres, on a level test track, at tire pressures recommended by the manufacturer, 2.0 bar for on-road and 1.0 bar for off-road use. The motorcycle was accelerated, the gear selector was placed in neutral, and the decay in road speed was measured by a GPS. From the decay in road speed, the coefficients were determined by least-square regression, with the f1 coefficient set to zero.

Chassis dynamometer tests

In a chassis dynamometer test, the motorcycle rear wheel is mounted on a dynamometer roll, while the front wheel is held steady. The dynamometer roll exerts a resistance corresponding to the sum of vehicle inertia and the road resistance. The test rider operates the motorcycle according to a pre-defined speed trace, called a driving cycle, simulating loads comparable to those experienced during driving in the same pattern on the road. The chassis dynamometer tests consisted of two dynamic cycles and one set of steady-state points. E10 reference gasoline (41.66 MJ/kg, 83% carbon by mass, 744.4 kg/m3) used for Euro 6 light-duty vehicle testing was used. The dynamic tests were a type I exhaust emissions test, consisting of preconditioning, an overnight soak at 23 °C, and one run of the World Harmonized Motorcycle Test Cycle (WMTC)[19], starting with a cold engine (cold start) at 23.2 °C cell temperature. Since the road load coefficients were not found in the Certificate of Conformity (CoC), default values prescribed by the legislation for the vehicle were used. (The default values represent an average motorcycle of a given weight range. In this case, they represent a conservative estimate, as the actual resistance with off-road tyres is higher.) The CoC states rated engine power of 9.8 kW at 4500 rpm and a maximum speed of 100 km/h. It should be noted that the rated engine rpm is reached at approximately 50 km/h in fifth gear and at approximately 58 km/h in the sixth (highest) gear. The CoC lists the vehicle emissions category as Euro 5 but refers to compliance with the Euro 4 limits set out in Regulation (EU) No 168/2013[20]. This is because the Euro 5 standards, which entered into force in 2020, postpone the applicable date for enduro motorcycles to January 1, 2024[21]. The WMTC test followed the same procedure as the one prescribed for the type approval. Additionally, the motorcycle has been subjected to one run of the Real Driving Cycle (RDC), starting with the engine at

[19] Worldwide harmonized Motorcycle emissions Certification/Test procedure (WMTC) informal group: Informal group on the development of a Worldwide Harmonized Motorcycle Emissions Certification/Test Procedure (WMTC) http://www.unece.org/trans/main/wp29/wp29wgs/wp29grpe/wmtc.html

[20] 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.

[21] https://www.aecc.eu/applications/two-and-three-wheelers/

operating temperature (hot start). This cycle was developed within the Horizon Europe LENS project. The steady-state points were intended for calibration of the fuel flow calculation used to determine the exhaust flow during the field emissions tests.

Exhaust was directed into a full-flow dilution tunnel, set to operate at 16.5 m^3/min, the highest flow that was technically possible due to observed high emission levels during a preliminary run. Diluted exhaust from the tunnel and dilution air were sampled into bags. In each bag, concentrations of total hydrocarbons (HC) and methane (CH4) were measured with a heated flame ionization detector, carbon monoxide (CO) and carbon dioxide (CO2) with a non-dispersive infrared analyser, and nitrogen oxides (NOx) with a chemiluminescence detector. Total emissions for each phase of each cycle were calculated from the total tunnel flow during the phase and from the difference of concentrations in diluted exhaust and dilution air bags. In addition to the measurements prescribed for the type I type approval test[22,23,24], concentrations of HC, CH_4, CO, CO_2 and NOx in the dilution tunnel were measured online throughout the test.

On-board instrumentation

For the field tests, the motorcycle was equipped with on-board analysers, GPS receiver, and an on-board diagnostics (OBD) data interface, set to report engine rpm, fuel injector pulse width, intake air pressure and temperature, and coolant temperature (all are basic parameters in EOBD and OBD-II protocols).

Two analytical setups were used. One was with a Fourier-Transform Infrared (FTIR) spectrometer, highly miniaturized and packaged into a 70 x 35 x 35 cm, 40 kg enclosure with heated sampling system, and placed in a wearable enclosure worn by the rider (Fig. 1), adjusted so that the bulk of its mass rests on the passenger seat. (For dynamometer tests, the prescribed test weight was 190 kg, 115 kg empty weight plus 75 kg weight of the rider. Here, with instrumentation, batteries, protective equipment, etc., the total motorcycle weight was about 250 kg, lower than the 335 kg gross vehicle weight rating. On a road motorcycle, with a passenger seat, the on-board instrument package corresponds to a lighter passenger.) The FTIR spectrometer was equipped with a mercury cadmium telluride detector cooled by liquid nitrogen and a heated multi-pass White cell with optical path length of 5 m, and provided mid infrared spectra, 4000-700 cm^{-1}, at 0.5 cm^{-1} optical resolution and 5 Hz scanning frequency. The spectra were later interpreted for concentrations of various gaseous compounds. The second setup included a 9 kg, 40x20x20 cm miniaturized portable on-board emissions monitoring system (Mini-PEMS, Fig. 2), using non-dispersive infra-red spectrometer with an optical path length of 0.1 m to analyze the

[22] 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

[23] Commission Delegated 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

[24] Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008

concentrations of HC, CO and CO_2, and fast-response electrochemical cells to measure concentrations of NO, NO_2 and O_2, validated for motorcycle use in (Vojtisek-Lom et al., 2020)[25]. The second setup also included a non-volatile particle number (nvPN) measurement system (Nanomet3, Matter Engineering), consisting of a heated sampling line, a heated rotating disc diluter, an evaporator tube, a secondary diluter, and a two-stage diffusion charger.

Fig. 1: Mobile FTIR (left) mounted in an external frame backpack worn by the rider (right).

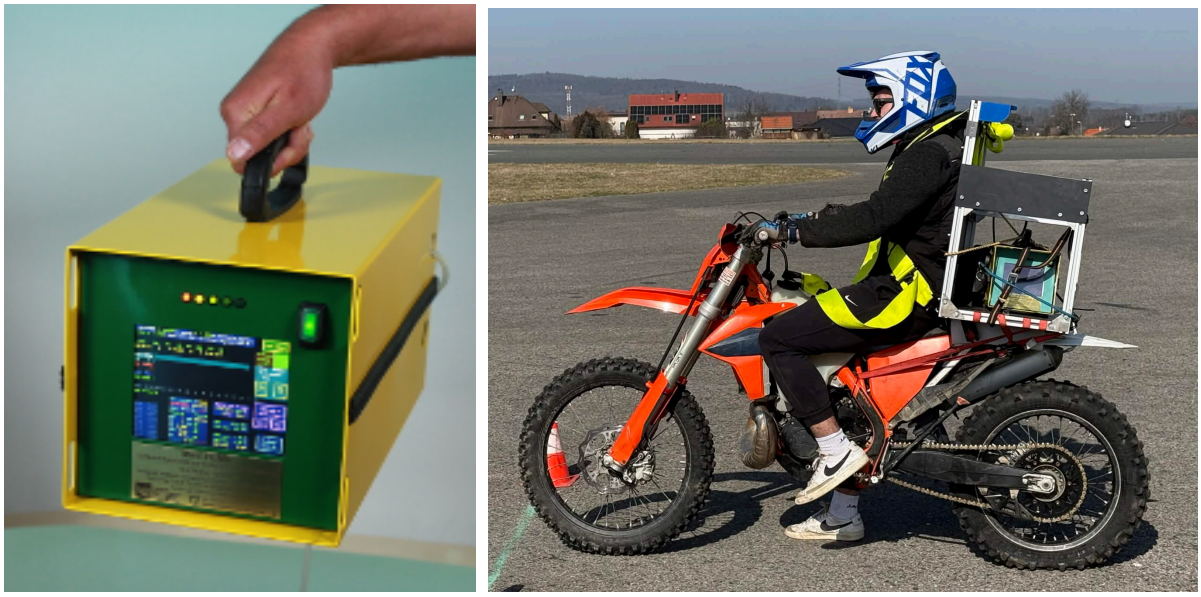

Fig. 2: Mini-PEMS (left) mounted in an external frame backpack worn by the rider (right).

[25] Vojtisek-Lom, M., Zardini, A. A., Pechout, M., Dittrich, L., Forni, F., Montigny, F. Carriero, M., Giechaskiel, B., Martini, G. (2020). A miniature Portable Emissions Measurement System (PEMS) for real-driving monitoring of motorcycles. *Atmospheric Measurement Techniques*, *13*(11), 5827-5843.

Exhaust flow determination during field tests

As the two-stroke engine, especially in its performance version, is highly sensitive to the intake and exhaust flow profiles, exhaust gas flow was not measured directly, but computed from exhaust carbon content inferred from measured pollutant concentrations and the fuel flow computed from OBD data. This approach has an added advantage of being relatively insensitive to the dilution of exhaust gases by outside air during flow pulsations, with rapidly alternating forward and reverse flows in the exhaust system.

To do this, exhaust concentration data and OBD data are synchronized in time to adjust for measurement delays, including the time needed for the exhaust sample to travel to the analysers. The exhaust flow is then computed by multiplying the fuel flow by carbon content of the fuel and divided by the total carbon concentration in the exhaust. To compute the fuel flow from the fuel injector pulse width, the relationship between the fuel injector pulse width and the quantity of the fuel injected needs to be determined experimentally. In this study, this relationship has been established during steady-state operating points by comparing mass emissions data from the on-board system with those obtained from the laboratory.

Calibration of fuel flow computation and validation of on-board instrumentation

To establish the relationship between the actual fuel flow and the fuel flow inferred from OBD parameters, fuel injector characteristics, specific for each model, and sometimes for individual injectors, need to be known or determined, and corrected for fuel pressure, density, viscosity and composition. The calculation can be simplified by running calibration tests on the very same vehicle, injectors and fuel, under operating conditions reasonably covering those anticipated or experienced during the field test.

During the laboratory tests, all instruments intended to be used for field testing were operational, with analysers sampling raw exhaust and on-board diagnostic (OBD) data interface connected. This was done to calibrate the fuel flow computation and to validate the overall setup.

Noise tests

Noise tests were carried out on a closed test track away from interfering noise sources. Two noise meters, Peak Tech 8005 and CESNA SC310, were used. During stationary tests, the microphone was placed 0.5 m from the end of the tailpipe, at the height of the tailpipe, pointing at the end of the tailpipe at an angle of 45°. The motorcycle was placed in neutral, and the engine speed was maintained a) at 3300-3400 rpm (3375 rpm, listed in the CoC, is 75% of the rated engine speed, as prescribed in EU 134/2014[26], and b) at 9000 rpm (not a test condition prescribed by the legislation). Additionally, a free acceleration burst was performed.

During in-motion tests, the microphones were placed 15 m away from each other, and the motorcycle was cruising at, or accelerating from, 50 km/h, in the direction perpendicular to the line defined by the two

[26] Commission Delegated 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

microphones, approximately midway between the microphones (at its closest point, at 7.5 m from each microphone). The tests were performed in second and third gears. Acceleration tests were performed under similar conditions, except that the motorcycle was operated at full throttle.

Fig. 3: Stationary (left) and in-motion (right) noise test setup

Limited possibility of restricted configuration

The motorcycle was type-approved, according to the CoC, for on-road use in its restricted version, with exhaust gas oxygen sensor and with catalytic converter. The unrestricted configuration features a different intake system, a different exhaust system, and a different engine control unit (ECU) mapping. Both restricted and unrestricted configurations, and parts for conversion from restricted to unrestricted version, are available on the market. According to a local dealer, on this model, the user is not freely able to revert the ECU to the restricted version. Once converted to the unrestricted version, reverting the ECU back to the restricted version would require a special service intervention from the manufacturer with a delivery time of about two months. Therefore, as of the time of writing this report, the motorcycle was not tested in the restricted configuration.

Results

Coastdown tests

The results of the coastdown tests are presented, for both tyre pressure specified for on-road and off-road use, in Table 2. The substantially higher constant drag is attributed to the higher rolling resistance of knobby all-terrain tires. The higher second term, representing aerodynamic drag, corresponds to the relatively basic, bare-frame design of the motorcycle, without aerodynamic cladding.

The relative contribution of the knobby tyres to the overall mechanical work strongly depends on driving conditions, which affect the relative contribution of overcoming inertia during accelerations, aerodynamic drag, rolling resistance, and drivetrain internal losses. For example, over the 13 km WMTC cycle, the positive mechanical work at the dynamometer roll was 0.37 kWh when default coefficients were applied. The additional 59 N and 71 N, respectively, for off-road tyre pressure, correspond to 0.76 MJ (0.21 kWh) and 0.93 MJ (0.26 kWh), increasing the road losses by 57% and 70%, respectively, over the WMTC cycle (since the aerodynamic resistance did not change considerably, the effect is dependent on motorcycle speed).

Table 2: Road resistance coefficients

	f2 N/km2*h2	f1 N/km*h	f0 N
Measured at high (on-road) tyre pressure	0.0304	0	75.53
Measured at low (off-road) pressure	0.0310	0	88.24
Default table values from legislation used for chassis dynamometer tests	0.0229	0	16.70

Chassis dynamometer tests

The bag measurement results are shown in Table 3. For WMTC, the result is a weighed sum of stage 1 (with a weight factor of 0.3) and stage 2 (weight factor 0.7). The measurement ranges for both HC and CO analysers have been exceeded; therefore, HC and CO emissions were higher than those listed. The fuel consumption is not measured directly, but is calculated from HC, CO (low-range) and CO_2 readings, and from measured fuel density (744 kg/m^3) and carbon mass fraction (83 %).

It should be noted that the measured HC and CO emissions, observed in the unrestricted configuration, are substantially higher than the type approval limits set by EU 168/2013, applicable to the WMTC cycle and to the restricted configuration type-approved for on-road use. For enduro motorcycles, the WMTC emissions are a weighted average of first (30% weight, 4 km) and second (70% weight, 7 km) stage results, and HC and NOx emissions (HC+NOx) are evaluated as the sum of HC and NOx (the limit applies only to the sum of HC+NOx). The motorcycle is listed as Euro 5, but due to a later effective date for enduro motorcycles, Euro 4 limits apply[27].

[27] Euro 4 limits, applicable to the WMTC cycle, are 1.14 g/km CO, 0.38 g/km HC, 0.07 g/km NOx, no limit on PM (there is a limit for diesel engines), no limit on PN. Euro 5 limits, applicable to the WMTC cycle, are 1.0 g/km CO, 0.1 g/km HC, 0.068 g/km NMHC, 0.06 g/km NOx, no limit on PM or PN (there is a PM limit for diesel engines). There is no limit applicable to the RDC cycle or to any other operating conditions.

Table 3: Bag data results from dynamometer testing, unrestricted configuration

	HC + NOx	HC	CO	CO_2	NOx	NMHC	CH_4	Fuel	Fuel
	mg/km	mg/km	mg/km	g/km	mg/km	mg/km	mg/km	l/100km	mpg
WMTC	1625.44	1616*	2928*	36.85	9.79	1244.03	391.17	2.01†	116.96†
RDC	1472.29	1461*	2589*	38.23	10.86	1027.35	456.90	2.03†	116.04†
CoC	309	300	42	66	9			2.9	
EU limit‡	450	(380)	1140		(70)				

* analyser at upper measurement limit, actual value is higher
† fuel consumption is calculated from HC, CO and CO2 emissions, actual value is higher due to actual HC and CO being higher than measured
‡ Euro 4 limit, applicable to WMTC cycle, applies as per a temporary derogation for enduro vehicles within the Euro 5 regulation

Modal data, the sum of second-by-second emissions calculated from measured concentrations and tunnel flow, are listed in Table 4 and shown on graphs in Fig. 4. Laboratory data are based on diluted exhaust measurement. For CO, the high-range CO analyser has been used (note: the measured values exceeded the measurement range of the low-range CO analyser). Mini-PEMS and FTIR data are based on measured concentrations in raw exhaust gas, on fuel consumption calculated from OBD data, and exhaust flow calculated from fuel consumption and carbon content of exhaust, calculated from concentration data. The volumetric fuel consumption is calculated as the sum of carbon emitted as HC, CO and CO_2, divided by fuel carbon content and fuel density. Miles per gallon refer to U.S. statutory mile (1609 m) and gallon (3.78 dm^3).

The measured values are subject to several sources of uncertainty: measurement range exceedance on laboratory HC analyser resulting in HC being underestimated, probable contamination of Mini-PEMS analyser optics with liquid hydrocarbons resulting in HC being overestimated, and total attenuation of several spectral regions, making determination of some organic compounds not possible, probably leading to HC being underestimated. Since the fuel consumption is calculated as the sum of carbon emitted as HC, CO and CO_2, divided by the carbon content in the fuel, this error then propagates to fuel consumption estimates. Underestimation of HC by laboratory and by the FTIR results in underestimation of the fuel consumption. HC emissions and fuel consumption are therefore likely to be higher than those measured by modal instruments and by the FTIR, and lower than those measured by Mini-PEMS.

Table 4: Modal data, results from dynamometer testing, unrestricted configuration

Modal data		HC	CO	CO_2	NOx	CH_4	Fuel	Fuel
		g/km	g/km	g/km	mg/km	mg/km	l/100km	Mpg
Laboratory	WMTC Bag 1	2.54*	26.96	37.68	8.38	425.54	3.76*	62.40
	WMTC Bag 2	1.17*	28.76	36.63	12.14	336.53	3.66*	64.26
	WMTC sum	1.60*	28.20	36.95	10.97	364.36	3.69*	63.66
	WMTC wt.sum	1.58*	28.22	36.94	11.01	363.23	3.69*	63.69
	RDC	1.15*	31.05	37.81	12.62	405.38	3.86	60.89
Mini-PEMS	WMTC Bag 1	15.81†	26.60	38.50	14.39		5.56†	42.25
	WMTC Bag 2	11.98†	28.22	36.34	15.97		5.06†	46.43
	WMTC sum	13.18†	27.71	37.02	15.48		5.22†	45.04
	WMTC wt.sum	13.13†	27.73	36.99	15.50		5.21†	45.09
	RDC	13.64	32.25	40.43	23.51		5.73†	41.01
FTIR	WMTC Bag 1	3.75‡	24.85	40.22	4.08	420.67	3.89‡	60.32
	WMTC Bag 2	3.01‡	27.65	36.90	6.74	338.96	3.84‡	61.17
	WMTC sum	3.24‡	26.77	37.94	5.91	364.51	3.86‡	60.90
	WMTC wt.sum	3.23‡	26.81	37.90	5.94	363.47	3.86‡	60.91
	RDC	3.77‡	30.34	41.15	8.44	448.97	4.31‡	54.55

* HC analyser at upper measurement limit, actual HC emissions and actual fuel consumption are higher
† reading affected by deposition of hydrocarbons on analyser optics, actual value is lower; this also affects fuel consumption calculation
‡ sum of analyzed hydrocarbons; measurement affected by total attenuation of some spectral regions, actual value is probably higher; this also affects fuel consumption calculation

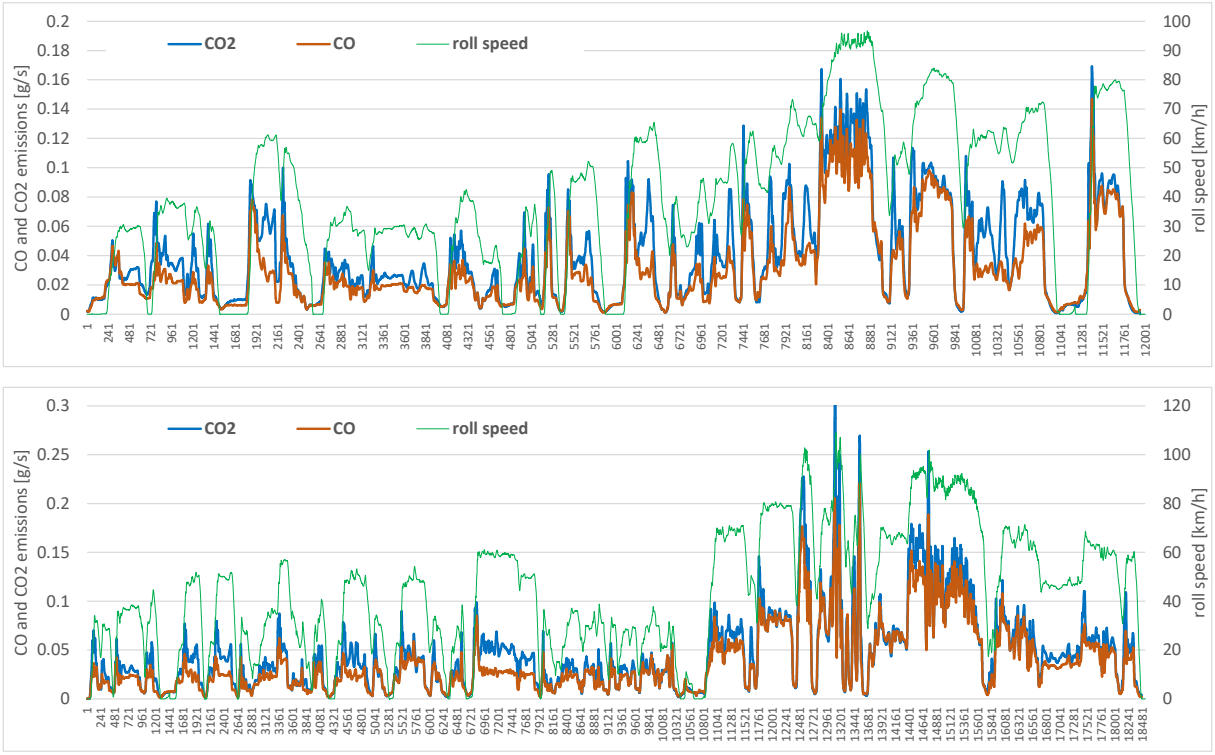

Fig. 4: Dynamometer roll speed and modal CO and CO_2 emissions over WMTC (top) and RDC (bottom) cycles.

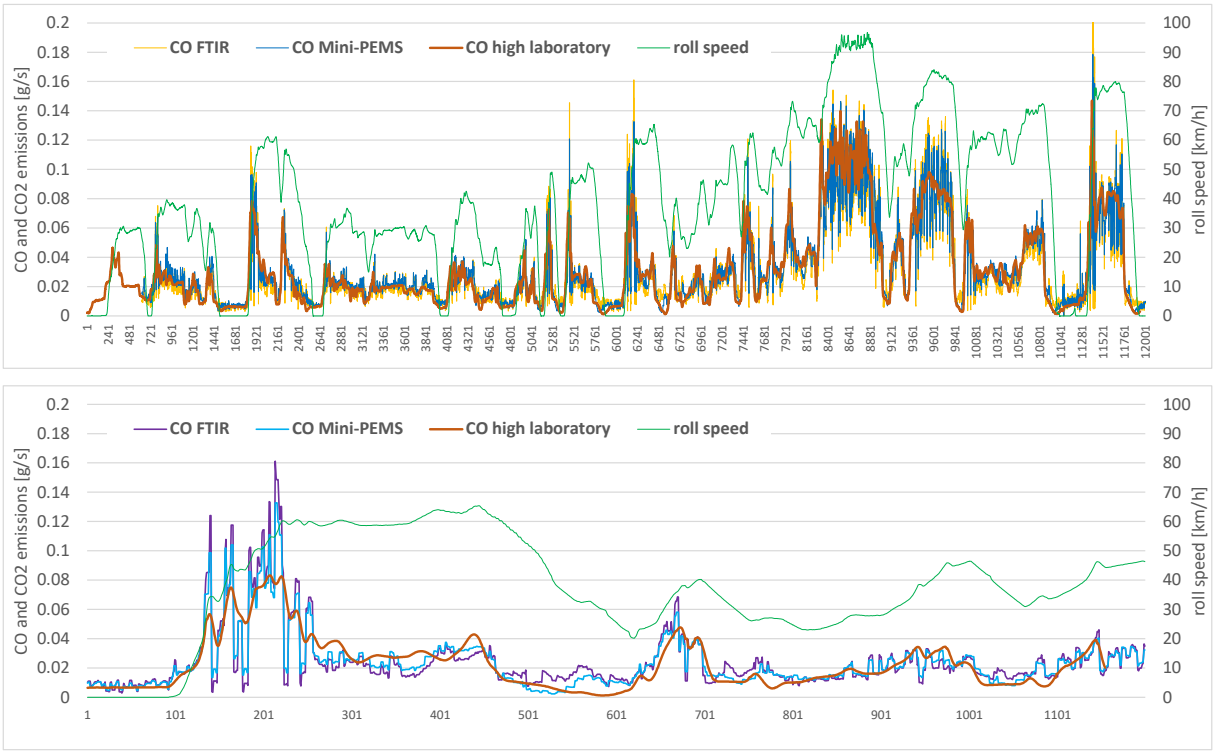

Fig. 5: Comparison of CO emissions measured by laboratory (CO high), mobile FTIR and Mini-PEMS over WMTC cycle (top) and first two minutes of Phase 2 of the WMTC cycle (bottom) (data at 10 Hz resolution).

The emissions computed from raw exhaust gas composition measured by Mini-PEMS and FTIR and from exhaust flow computed from OBD data and exhaust composition are compared to laboratory measurements in Fig. 5, with the upper graph showing the entire WMTC cycle and the lower graph showing first two minutes of the Phase 2 of the cycle. The data were normalized to the 10 Hz used by the laboratory, however, FTIR data is at 2.5 Hz, OBD data at 4 Hz, and Mini-PEMS data at 1 Hz. The time response (t90), net of constant delay accounting for travel of sample through the sampling line, of both Mini-PEMS and FTIR is about 2 seconds. The laboratory delay time varies due to transfer line between the motorcycle and the dilution tunnel.

The concentrations of hydrocarbons measured by the Mini-PEMS over the WMTC cycle, shown in Fig. 6, do not drop to zero during decelerations, as do CO_2 emissions, but are highest during deceleration, suggesting either unburned fuel entering the exhaust or release of previously accumulated oil and fuel. Relatively slow decays in measured concentrations suggest accumulation of hydrocarbons in the sampling system and/or on analyser optics, as the concentrations of hydrocarbons measured by FTIR drop more rapidly. Low concentrations measured by FTIR correspond to deceleration, while zero concentrations correspond to the value not calculated due to total attenuation of spectral regions (suggesting very high concentrations of compounds absorbing in a given region, which, however, cannot be resolved for individual compounds).

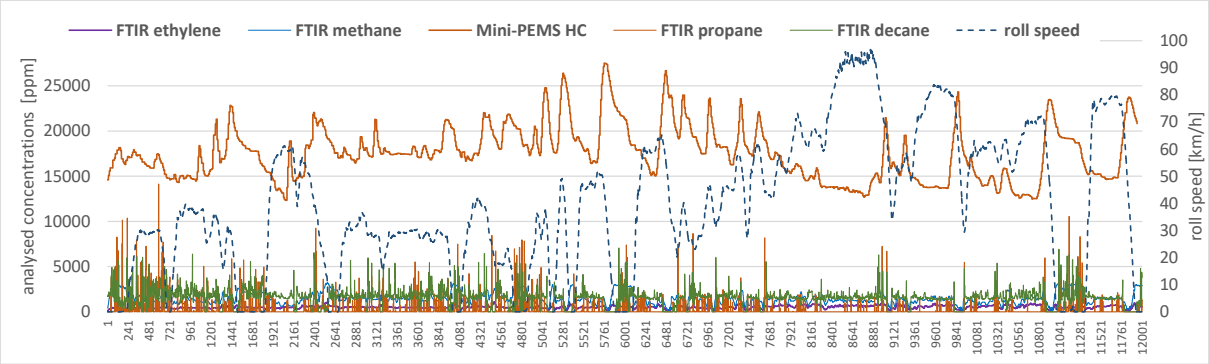

Fig. 6: Hydrocarbon concentrations measured by Mini-PEMS and selected hydrocarbons measured by FTIR over the WMTC cycle.

The emissions of NO_2 were, in all combinations of test cycle and instrumentation, negligible. This is typical for engines operated with low excess air ratio. The NH_3 (ammonia) emissions measured by the FTIR were generally low, well below 1 mg/km, with concentrations of units to low tens of ppm. While NH_3 forms in a three-way catalyst during fuel-rich operation, the measurements did not indicate the presence of a functional catalytic converter in the unrestricted version. The emissions of N_2O were negligible.

In terms of greenhouse gas emissions, methane emissions were on the order of 1 % of CO_2 emissions. Considering that global warming potential of methane is, compared to CO_2, 28 times higher over a 100 year horizon and 84 times higher over a 20 year horizon[28], methane CO_2 equivalent is about 25-90 % of direct CO_2 emissions, depending on horizon length and cycle.

Particle number (PN) emissions

Quantitative particle number data are not reported as the measurement range of the nvPN analyser has been exceeded throughout the entire test run, with the exception of the first few seconds after the engine start. (The nvPN concentrations were within the normal range before and after the tests.) If the measured nvPN concentrations, mostly $7.57 \cdot 10^8$ particles per cm^3 (#/cm^3), measured over 10-700 nm particle diameter range, clearly representing the upper analyser limit, are substituted by the upper measurement range of $3 \cdot 10^8$ #/cm^3, the nvPN values are $1.2 \cdot 10^{14}$ #/km over the WMTC cycle, therefore at least 200 times higher than the $6 \cdot 10^{11}$ #/km limit applicable to Euro 7 light-duty vehicles (not to L-category vehicles including motorcycles). It should be noted that since the particles are believed to be mostly volatile, composed of lubricating oil and fuel, which are not measured here, the total particle number emissions accounting for both volatiles and non-volatiles are likely at least on the order of 10^{15} #/km. At such levels, particle number as a metric is no longer meaningful, due to the very high coagulation rate causing the number concentrations to be underestimated, and making the measurement irreproducible.

It should be noted that there is no PN limit for L-category vehicles, nor there is currently any particle limit for indirect injection spark ignition engines. Euro 4 particle mass limit applied only to compression ignition engines, and Euro 5 limit applies to direct injection spark ignition engines and to compression ignition engines. The closest limit is the light-duty vehicle PN limit of $6 \cdot 10^{11}$ #/km (direct injection positive ignition and all compression ignition engines, at 23 nm threshold, under Euro 6, all engines, at 10 nm threshold, under Euro 7).

Idle HC and CO concentrations

Idle HC and CO concentrations, analogous to those measured during a periodic technical inspection, measured by Mini-PEMS (same NDIR method as used during PTI), were evaluated from steady-state data, shown in Fig. 7. During four idle periods, clearly identifiable by engine rpm being in the 1000-2000 rpm range, CO concentrations were 4-5 % (40 000 to 50 000 ppm), and HC concentrations were approximately 14 000 to 16 000 ppm. This is about three orders of magnitude above 17 ppm and 16 ppm HC listed in the CoC for low and high idle, and 0 % CO listed in the CoC for both low and high idle.

[28] Balcombe, P., Speirs, J. F., Brandon, N. P., & Hawkes, A. D. (2018). Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts*, 20(10), 1323-1339.

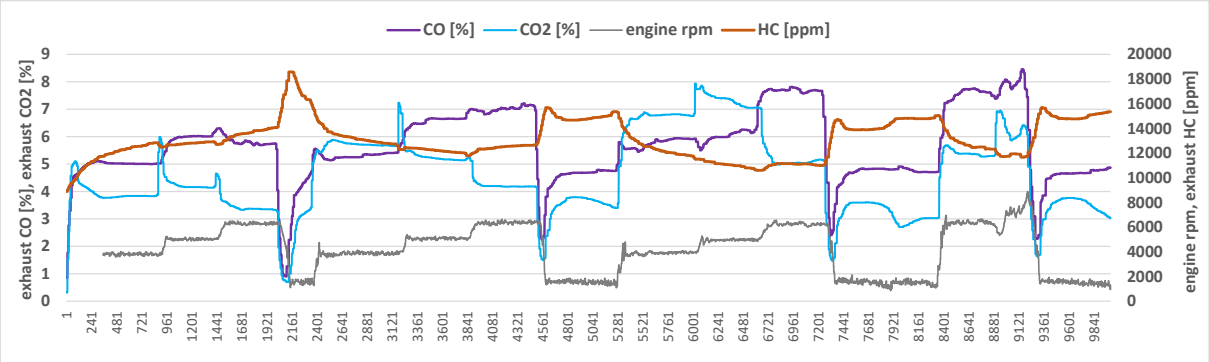

Fig. 7: Exhaust HC and CO concentrations at steady-state points

Field emissions tests

The results of field emissions tests are given in Table 5. It should be noted that despite the motorcycle weight rating corresponding to two riders (335 kg maximum mass, 115 kg unladen mass), there was no practical passenger seat, and when the rider was wearing the FTIR assembly (the FTIR system, including the sampling system, weighed approximately 35 kg, nearly 50 kg including frame and batteries, with most of the weight resting on the passenger seat), the tire knobs came, when passing over uneven terrain, in contact with the mudguard. Therefore, rides with the FTIR were performed in a relatively conservative manner, resulting in lower CO to CO_2 ratio and lower fuel consumption. As in laboratory tests, the FTIR data contain gaps where concentrations of some compounds could not be analysed due to total attenuation of some spectral regions, and the actual emissions were higher than reported, while the Mini-PEMS HC concentrations were affected by accumulation of hydrocarbons within the sampling system and on the analyser optics, and the actual emissions were lower than reported.

No emission limit applies to the unrestricted off-road configuration or to the field operation evaluated here. Nonetheless, for comparison, both the sum of HC+NOx, 6.6-17.5 g/km, and CO, 25-36 g/km, were more than one order of magnitude (more than ten times) higher than the limits applicable to the restricted version and the WMTC cycle.

Table 5: Field emission test summary results

Field test	distance	HC	CO	CO_2	NOx	CH_4	Fuel	Fuel
(test track)	km	g/km	g/km	g/km	g/km	g/km	l/100km	mpg
Mini-PEMS	13.41	17.46†	35.83	46.49	0.055		6.74†	34.84
FTIR	7.84	6.56‡	25.01	42.43	0.012	0.43	4.38‡	53.68
Euro 4 limit (restricted)		0.45	1.14	0.45 g/km HC+NOx, 1.14 g/km CO (WMTC cycle)				

† reading affected by deposition of hydrocarbons on analyser optics, actual value is lower; this also affects fuel consumption calculation

‡ sum of analyzed hydrocarbons; measurement affected by total attenuation of some spectral regions, actual value is probably higher; this also affect fuel consumption calculation

Field noise tests

The results of the stationary noise tests are listed in Table 6 and the results of the in-motion noise tests are listed in Table 7. The values are given in dB(A), a unit that is proportional to a decadic logarithm of the sound intensity level in W/m^2. A sound that is higher by 10 dB has ten times higher sound intensity level in W/m^2, and is perceived as twice as loud. A sound higher by 20 dB has 100 times higher sound intensity level and is perceived as four times as loud. The sound energy is acoustically weighted to represent different sensitivity of human ear to different sound frequencies.

Table 6: Stationary noise tests

Test	Static 3300-3400 rpm	Static 9000 rpm	Free acceleration burst
Microphone	Peak Tech 8005	Peak Tech 8005	Peak Tech 8005
Reading 1 dB(A)	95.4	110.9	118.6
Reading 2 dB(A)	93.6	111.8	115.0
Reading 3 dB(A)	94.5	112.2	107.0
Mean dB(A) value	94.5	111.6	113.5
Average sound pressure dB(A)	94.6	111.7	115.6
Maximum dB(A)	95.4	112.2	118.6
CoC value dB(A)	85	---	---

Note: Stable value not obtained during free acceleration bursts due to irregular behaviour of the engine

The stationary tests have resulted in a value over 9 dB(A) higher than the value listed in the CoC for the restricted version. These tests, however, were run at speed based on the rated engine speed listed in the CoC, while in reality, the engine is capable of running at least nearly twice the rated speed (to reach the 100 km/h maximum speed stated in the CoC), and at even higher speeds during unrestricted settings. Tests at 9000 rpm resulted in 111.6 dB(A) (26.6 dB(A) over the CoC value applicable to 3325 rpm and to the restricted version).

The cruising tests resulted in average sound level, on the side with the higher sound level, of 90.8 dB(A) for the second gear and 84.7 dB(A) for the third gear. The acceleration tests resulted in average sound level, on the side with higher sound level, of 100.0 dB(A) for the second gear and 99.2 dB(A) for the third gear.

The noise limit value of 77 dB(A) is applicable for urban acceleration. Urban acceleration noise is not measured directly, but is calculated as a weighted average of sound levels under constant speed driving and full throttle acceleration. At 38 kW and 190 kg test weight, the power to mass (PMR) ratio as defined in the legislation (EN 134/2014) is 200, and the weights of constant speed and full throttle acceleration values are comparable. In such case, the urban acceleration noise levels, calculated from average sound levels at cruise and acceleration, are 95 dB(A) for the second gear and 92 dB(A) for the third gear.

These values are 18 and 15 dB(A) higher than the 77 dB(A) type approval limit applicable to on-road vehicles (to the restricted version) and more than 16 dB(A) higher than the value listed in CoC for the restricted version. It should be noted that the comparison to legislative limits is only approximate, since the specifications for the unrestricted version, such as the rated engine power and the rated engine speed, used in the calculations, are not precisely known.

Table 7: Cruising and acceleration noise tests

	Constant 50 km/h 2nd gear		Constant 50 km/h 3rd gear	
Microphone	Peak Tech 8005	CESNA SC310	Peak Tech 8005	CESNA SC310
Reading 1 dB(A)	91.1	92.0	87.4	85.8
Reading 2 dB(A)	89.8	91.3	83.7	83.6
Reading 3 dB(A)	93.1	92.1	86.1	84.5
Average dB(A) value	90.3	**90.8**	**84.7**	83.6
Average sound pressure dB(A)	90.5	90.8	85.0	83.7
	Acceleration 2nd gear		Acceleration 3rd gear	
Microphone	Peak Tech 8005	CESNA SC310	Peak Tech 8005	CESNA SC310
Reading 1 dB(A)	102.1	100.9	98.4	100.5
Reading 2 dB(A)	99.7	101.1	97.4	100.3
Reading 3 dB(A)	99.1	101.0	99.9	99.9
Average dB(A) value	99.3	**100.0**	97.6	**99.2**
Average sound pressure dB(A)	99.5	100.0	97.7	99.2
Average of acceleration and constant speed dB(A) values	2nd gear	95.4	3rd gear	92.0
CoC		76 dB(A) (restricted version)		
Limit		77 dB(A) (restricted version)		

Notes: Note: 1 dB(A) subtracted from all measured values before averaging. Average dB(A) value is arithmetic mean of dB(A) values. Average sound pressure is arithmetic mean of sound pressures, which is a logarithmic mean of dB(A) values. The higher of the average values for each side is used for subsequent calculation.

Discussion

Overall, exhaust emission levels were broadly comparable across the WMTC cycle, the RDC cycle, and field operation. Since the NOx emissions were very low, and HC emissions more than two orders of magnitude higher than NOx emissions, the sum of HC+NOx is, for practical purposes, equivalent to HC emissions. The HC and CO emission levels in the unrestricted configuration were substantially higher than the type-approval values obtained with the restricted version, and also than the limits applicable to the restricted version over the WMTC cycle. HC and CO emissions were substantially higher than values typically reported for contemporary on-road vehicles; for example, CO emissions are comparable, on a per-km basis, to older 60-130 ton diesel passenger train units[29]. At the same time, considering that the engine produced on the order of 1 kWh output over the WMTC cycle (the positive power absorbed by the dynamometer was 0.37 kWh over the WMTC cycle, however, the engine needed to overcome drivetrain losses; the 1 kWh is a rough estimate based on the fuel consumption over WMTC of approximately 0.5 kg), the observed levels, per kWh output produced by the engine, are higher, but on the same order of magnitude as, the current EU standards for snowmobile engines[30] (75 g/kWh HC, 225 g/kWh CO, no limit on other compounds). Considering that snowmobiles have a higher fuel consumption per km driven than the tested motorcycle, the measured values are not overly different, on a per km basis, than a recent snowmobile compliant with the current EU legislation (Table 8).

Table 8: Comparison of measured values with EU snowmobile limits

	HC	CO
Measured emissions in this study, in gram per km, all instruments, all cycles	3-18	25-36
Measured emissions in this study, WMTC cycle estimate in gram per kWh engine output	42-173	353-372
EU snowmobile emission limits, in gram per kWh	75	225

Engine optimization for power (approximately 38 kW in unrestricted version vs. 9.8 kW in restricted version) and performance is the likely reason for the observed emission levels. In on-road restricted configuration, the engine is likely to run with some excess fuel to limit NOx emissions, with additional air introduced into the catalytic converter to oxidize HC and CO, leading to very low levels of HC, CO and NOx. In the unrestricted configuration, up to approximately three to four times more power is available. Achieving such power level requires maximizing the air flow through the engine and for the removal of unnecessary restrictions of intake and exhaust flow to attain such high power levels, and fuel-rich operation to: (a) to avoid abnormal combustion (knocking, misfire)

[29] Vojtisek-Lom, M., Jirků, J., & Pechout, M. (2020). Real-world exhaust emissions of diesel locomotives and motorized railcars during scheduled passenger train runs on Czech railroads. *Atmosphere*, *11*(6), 582.

[30] Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC

during rapid transitions of engine load, (b) avoid engine knocking at high load, and (c) protect the engine by reducing exhaust temperature at high loads. The use of catalyst may still be, with proper thermal management, considered, however, additional excess fuel and higher exhaust flows may both greatly reduce its conversion efficiency, and sustained excessively fuel-rich operation might reduce its durability. Therefore, it is reasonable to expect that switching between “on-road” and high-performance off-road configuration is not a matter of simply switching the power mode in the ECU, but would require, at minimum, changes to the intake and exhaust systems, and installation of the catalytic converter for the on-road setting, in order to retain compliant performance in urban settings.

Engine noise results primarily from combustion noise and from exhaust noise, with noise caused by rapid pulsations of exhaust gases, characteristic for small engines, being the dominant contributor. On the one hand, pulsations in the intake and exhaust systems allow for higher air flow through the engine, achieving higher than ambient pressure in the intake, at a design resonant rpm range. Reducing such pulsations with a muffler or a restrictor would likely reduce this benefit of improved cylinder filling as well as restrict the flow through the engine. On the other hand, relatively high power to mass ratio has been successfully achieved, at acceptable noise levels, on many performance on-road engines. Whether the engineering limits for noise abatement have been reached here, or simply not explored to their fullest extent, or left purposely unexplored as the high level of characteristic noise is a treasured and highly sought-after part of rider experience, is a question beyond the scope of this study.

Overall, the results indicate that both emissions and noise produced in the unrestricted setting, intended for off-road use, by far exceed limits applicable to the restricted setting type-approved for on-road use.

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Credits:

Testing was carried out by the Department of Vehicles and Ground Transport at the School of Engineering at the Czech University of Life Sciences in Prague with instrumentation and methodology developed within the Horizon Europe LENS project (www.lens-horizoneurope.eu).

Martin Kotek, Associate Professor – Engine diagnostics

Martin Pechout, Associate Professor – on-board instrumentation, FTIR spectroscopy

Vojtěch Vobr, Test Engineer – test execution and management

Michal Vojtíšek, Professor of Mechanical Engineering – test design, FTIR spectroscopy, data analysis, report writing

Lukáš Volejník, Test Engineer, Test Rider – test execution and management

Laboratory testing was subcontracted to TÜV SÜD Czech, Roztoky, Czech Republic

Mini-PEMS was originally built by M.V., M.P. and Lubos Dittrich while at the Technical University of Liberec

Mobile FTIR was built on Bruker Matrix platform, based on a working concept by M.P. and M.V., by Luboš Dittrich and František Mejdr (Createch, Pardubice, Czech Republic).

The external-frame backpack was engineered and built in-house by Vojtěch Liška.

Exhaust flow computation from fuel consumption was developed in-house by M.P.

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