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Use of toxicity indicators related to CO_2 emissions in the ecological assessment of an two-wheel vehicle

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The subject of the article is proposed proprietary M toxicity indicator, which is based on the assumption that CO_2 emissions are a measure of the correctness of the combustion process. For this purpose, gaseous exhaust compounds such as hydrocarbons, nitrogen oxides, carbon monoxide and carbon dioxide were measured and analyzed. The test object was a motorcycle, equipped with an gasoline engine with a displacement of 0.7 dm^3 and a maximum power of 55 kW. The tests were carried out using the PEMS (Portable Emissions Measurement System) AxionR/S+. The exhaust emissions measurement was done in line with the WMTC (World Motorcycles Test Cycle) certification test, dedicated to vehicles in this category. The test consists of three parts, each of them lasts 600 s and has a different maximum speed value. The test was performed on a single-roller chassis dynamometer, designed for testing two-wheeled vehicles. The toxicity indicators and rotation speed results were presented as a function of time.

Key words: *motorcycles, toxicity indicator, laboratory conditions, WMTC test, PEMS*

1. Introduction

For several years, the leading direction of vehicle type-approval tests has been testing them in real operating conditions, i.e. when using the vehicle on public roads. Many scientific papers [2, 3, 5, 8, 11, 12] have shown that adopted type approval tests, such as WMTC do not fully reproduce the real operating conditions of two-wheeled vehicles, and thus also their emissions. This solution enables finding the real energy consumption and exhaust emission of the tested vehicle. In 1992, the Earth Summit was held in Brazil in Rio De Janeiro, during which 172 participating countries have agreed on their commitment, among other things, to reducing CO_2 emissions by 50 percent by 2050, compared to 1987 [13]. The largest reduction was to apply to highly developed and highly industrialized countries – including Poland. The automotive industry is one of the main sources of carbon dioxide formation. For this reason, alternative drive solutions for automotive vehicles are being developed. China, for example, has completely barred its drivers from driving taxis and buses with internal combustion engines in the centers of some cities, replacing them with those equipped with electric motors [4].

Another of the ideas to reduce emissivity is the use of an electric engine and an internal combustion engine cooperating with each other in larger vehicles. Such a hybrid system is currently widely promoted by most of the major automotive OEMs. Many manufacturers also see a niche in the European automotive market, which is two-wheeled vehicles.

Legislation in Poland allows driving two-wheeled vehicles with a category B driving license up to vehicles with an engine displacement of 125 cm^3, which also facilitates exposure of more people to ecological two-wheeled vehicles. Two-wheeled vehicles help to avoid urban congestion, consume less fuel, save time spent commuting to and from work. In addition, many cities offer free parking spaces for two-wheelers and enable bus lanes [1].

From 2017, with the entry into force of the Euro 4 limits, all newly-manufactured two-wheeled vehicles must be additionally equipped with several safety enhancing elements (braking system equipped with ABS) and a signaling device on economic driving clocks. For people requiring low fuel consumption from two-wheelers, while maintaining very good movement dynamics and having a category A driving license, motorcycles of medium engine displacement, small dimensions and compact design are provided.

2. Methodology

2.1. Test vehicle

The tests during vehicle operation were performed on a motorcycle of one of the leading Japanese manufacturers. The technical data provided in Table 1 accurately describe its specification. From the data presented in the table 1, it can be concluded that the tested vehicle has a naturally aspirated engine. The compression ratio of 11.5:1 is indeed high in relation to the classification of gasoline internal combustion engines in passenger cars, but motorcycles often have a compression ratios of even 13:1 and higher. The engine of the tested vehicle is supplied by injectors located indirectly in the inlet (one for each cylinder).

Table 1. Test motorcycle operating parameters

Engine type	2 cylinders, liquid-cooled 4-stroke, DOHC, 4-valve
Displacement	0.7 dm^3
Minimum power	55 kW/9000 rpm
Maximum torque	68 Nm/6500 rpm
Cylinder diameter/piston stroke	80.0 mm × 68.6 mm
Compression ratio	11.5:1
Lubrication system	wet oil sump

DENSO 32-bit controller communicating with other vehicle controllers (ABS module, clock display) via CAN bus was responsible for controlling the proper fuel dosage and combustion process. It had at its disposal a number of sensors monitoring the external conditions in which the vehicle is moving (external temperature, atmospheric pressure) as well as those reading the parameters of the engine itself. The engine unit, after warming up to its operating temperature, works in a closed loop using a narrowband lambda probe, correcting the fuel dose with its readings and ignition maps saved in the controller so as to keep the mixture close to stoichiometric. Only when switching to maximum throttle opening the controller enters the open loop and uses rigid saved maps without the need for corrections with data from the probe. This is a solution often used in road-class vehicles. Figure 1 shows the test object at the chassis dynamometer.

Fig. 1. Picture of the tested motorcycle along with the measuring apparatus on the designated dynamometer

The design of the entire engine is among the simpler designs – it has no variable timing phases, four valves per cylinder in the head are controlled by two camshafts driven by a chain directly from the crankshaft. The power supply system is also one of the less complex of those found on the motorcycle market. There are no dynamically changed lengths of the intake system, no valves or flaps in the exhaust system, one 4-hole injector per cylinder. The only important element that distinguishes this engine from the competition is the crankpins rearrangement by 270 degrees, unlike the classic 360 degrees. Despite its simplicity, the vehicle met the applicable emission standards and was approved for the European market.

2.2. Measuring equipment

In order to perform the intended tests, the device of the American company Global MRV – AxionR/S+ was used to analyze the exhaust gases. The device allows to measure emissions of harmful and toxic compounds, both gaseous: hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (NO) as well as solid particles. NO_x emission was estimated on the basis of the producer's assumption and own experience that NO constitutes 95% share in the total NO_x emission. Technical data of the apparatus is presented in Table 2, while the test object with the measuring setup on the dynamometer stand is shown in Fig. 2. Electrochemical analyzers are used to determine NO and O_2. The concentration of the first three of these compounds is measured by an NDIR (Nondispersive Infrared Sensor) analyzer. The PM measurement method uses a Laser Scatter based method [14].

In addition, the manufacturer equipped the device with a meteorological station, a GPS and a module enabling registration of data from the on-board vehicle diagnostic system (OBD). Measurement and data acquisition was done at a frequency of 1 Hz. Corrections are made to the obtained results from the recorded data, and then the road/unit emissions of the tested exhaust gases are calculated. Moreover the AxionR/S+ allows measurement and recording of vehicle and engine data: vehicle speed, acceleration, engine speed, intake air temperature, manifold air pressure.

Fig. 2. The view of AxionR/S+

Table 2. AxionR/S+ device technical data [14]

Gas	Measurement range	Accuracy	Resolution	Type of measurement
HC	0–4000 ppm	±8 ppm abs. or ±3% rel.	1 ppm	NDIR
CO	0–10%	±0.02% abs. or ±3% rel.	0.001 vol. %	NDIR
CO_2	0–16%	±0.3% abs. or ±4% rel.	0.01 vol. %	NDIR
NO	0–4000 ppm	±25 ppm abs. or ±3% rel.	1 ppm	E-chem
O_2	0–25%	±0.1% ppm abs. or ±3% rel.	0.01 vol. %	E-chem
PM	0 mg/m^3 to 300 mg/m^3	±2%	0.01 mg/m^3	Laser Scatter

2.3. Chassis dynamometer

The test was carried out on a motorcycle chassis dynamometer, INERTIAL 70, manufactured by SOFT-ENGINE. It made it possible to read the instantaneous power and torque on the wheel of the vehicle, as well as acceleration, speed and distance traveled. When preparing the test stand, data on temperature and ambient pressure, humidity as well as correction factor were input into the software. The final parameter is individual for a given motorcycle model. A large number of introduced environmental parameters has a positive effect on the measurement accuracy. The dynamometer technical data were presented in Table 3.

Table 3. Technical specifications of the dynamometer station [15]

Dynamometer	Inertial
Maximum received power	59 kW (80 HP)
Maximum received velocity	180 km/h
Dimensions: length/width/height	1900/800/4200 mm
Own weight	450 kg
Software	INERTIAL 3.0

2.4. WMTC test

The World Motorcycle Test Cycle (WMTC) is a driving cycles used to measure fuel consumption and emissions in motorcycles. The methods of WMTC cycle are set up as part of the Global Technical Regulation established under the United Nations' World Forum for Harmonization of Vehicle Regulations. The speed curve was a reflection of the speed characteristic of the harmonized WMTC type approval test, consisting of three phases (Fig. 3). Each of them lasted 600 seconds and was characterized by a different maximum value of the speed.

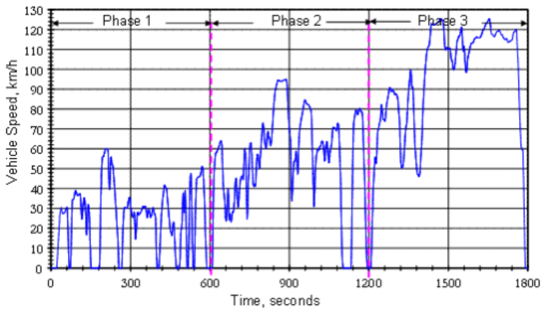

Fig. 3. WMTC test [10]

2.4. Phases of the test

After setting up the test vehicle on the stand, a number of sensors and probes had to be mounted on the vehicle. To the stub pipe, before the throttle, a cable was routed that passed information about the engine vacuum to the vacuum transducer. The transducer converts the pressure values into the corresponding DC voltage in the range from 0.5–5.5 V (Fig. 4). Next, a temperature probe was placed in the intake system) connected to the measuring device.

To read the rotational speed of the crankshaft, it was necessary to use a sensor fastened with a high-voltage cable behind the ignition coil attached by the PEMS manufacturer to the measuring equipment kit. Figure 5 shows the speed sensor after mounting it on an adapted high voltage cable.

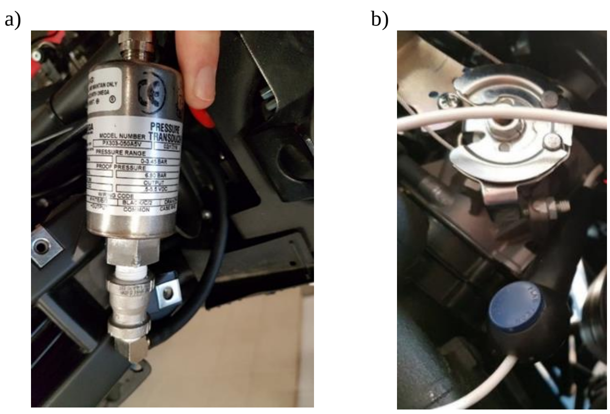

Fig. 4. Tooling for the intake manifold: a) vacuum transducer, b) temperature probe

Fig. 5. Speed sensor mounted on the high voltage cable

After preparation of the vehicle, it was necessary to calibrate the AxionR/S+ measuring device using technical gases in gas bottles located at the test stand. After a successful calibration process, the probe was mounted on the end of the motorcycle exhaust system introduced to a depth of about 20 cm. With the coordinated cooperation of the recording equipment operator and the motorcycle operator, the measurement process was started so that the values of speed, duration it is maintained, distance traveled and accelerations corresponded as closely as possible to the WMTC test procedure.

2.5. Definition of motorcycle toxicity indicators in relation to CO_2

Based on the basic combustion equations, a new toxicity factor M was proposed, which is the ratio of CO_2 to other toxic exhaust gas compounds. It was assumed that the toxicity index plays the role of a measure of the correctness of the combustion process. The values to be substituted for the formula structure formulated by the authors must be expressed in the same units, which will allow for its dimensionlessness, as a result of which a comparative analysis of vehicles of different categories and intended use is possible. The toxicity index thus defined makes it possible to efficiently compare different heat engines with each other with exhaust aftertreatment systems. The dimensionless quantitative toxicity index M is defined by the quotient:

$$M_j = b \cdot \frac{e_{real,j}}{e_{CO_2}} \quad (1)$$

where: M – dimensionless toxicity indicator [–]; j – toxic exhaust component for which the emission indicator was determined; b – universal constant (for CO, THC and NO_x = 10^3, for PM = 10^5); $e_{real,\,j}$ – specific emission, road emission or mass of toxic compound j determined during the measurements in the emission test [g/(kW·h); g/(km); g]; e_{CO2} – specific emission, road emission or mass of CO_2 determined during the measurements in the emission test (having the same unit as $e_{real,\,j}$) [g/(kW·h); g/(km); g].

The presence of the constant b allows to increase the readability of the results, because the number of decimal places is limited. This has been confirmed on other vehicles that meet various emission standards [6, 7, 9]. Therefore, it is possible to ecologically assess the L-category vehicles and vehicles of other categories based on the proposed M factor in terms of emission tests obtained both in laboratory tests and in real operating conditions.

3. Results

On the basis of the measurement data recorded during the tests, the second emission of individual toxic compounds (HC, CO, NO_x) was determined, which was then compared to the second emission value of CO_2. When analyzing the results obtained during the test, some dependencies of CO_2 emissions and toxicity indicators on the instantaneous test conditions can be observed.

Due to the direct relationship of the amount of CO_2 with the amount of fuel consumed, it was found that when the demand for fuel is high (driving at higher speed, sudden accelerations) the amount of carbon dioxide increases in direct proportion (Fig. 6). The average rate of CO_2 emissions in the test was 1.69 g/s.

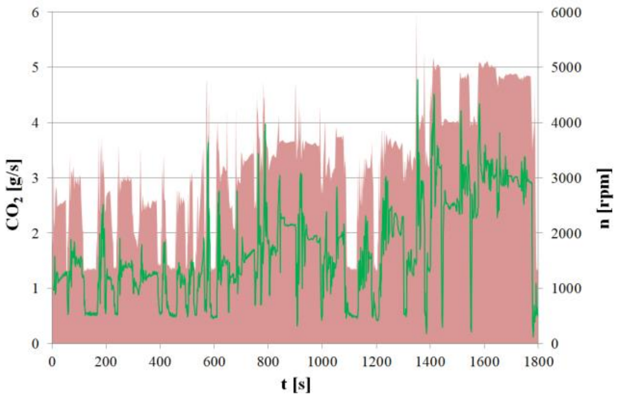

Fig. 6. The course of the engine torque and the CO_2 emission intensity recorded during the tests in the WMTC test

The observed relationship is the significantly increasing value of carbon monoxide toxicity during engine braking, where the local maximum M_CO of the engine operation near idling and CO_2 emission close to zero at these points was recorded (Fig. 7). This is, among others, due to insufficient heating of the combustion chamber and low temperature of the exhaust system (idling). This enriched the mixture to the lambda < 1 range, which is one of the main causes of carbon monoxide formation.

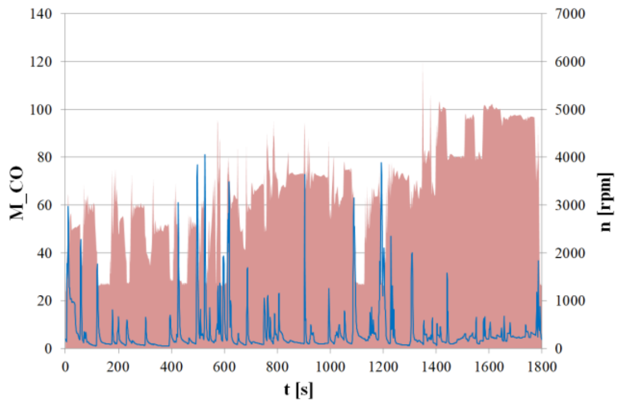

Fig. 7. The course of the engine torque and the M index for CO recorded during the tests in the WMTC test

In addition to the negative phenomena in the engine cylinders, a significant impact on the significant value of the dimensionless M index is also caused by the incorrect operation of the exhaust gas treatment system – a three-way catalytic converter. Significant values of M_CO (~ 60) were obtained in the first minute of the research test, i.e. for idling, where the aftertreatment systems had not yet worked, and the combustion temperature was low.

Most of the factors contributing to the formation of an excessive amount of carbon monoxide in the exhaust gas (flame extinction, incomplete combustion) also cause an excessive content of hydrocarbons, hence the highest toxicity values of both compounds were recorded at the same points of the test (engine braking), where CO_2 emission was close to zero (Fig. 8). The local maximum (55) was recorded in the third phase of the test during sudden braking. The mean value of the toxicity index for the entire trip was 2.7.

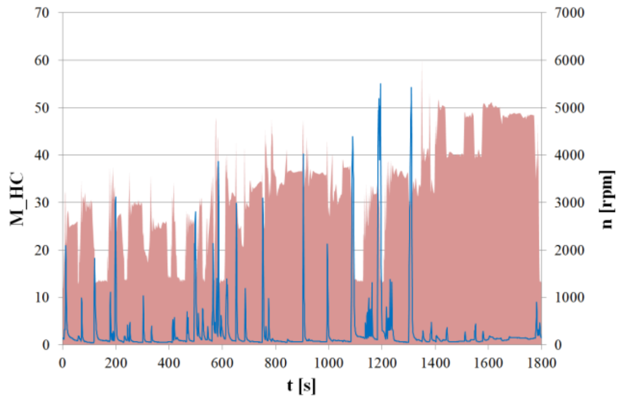

Fig. 8. The course of the engine torque and the M index for HC recorded during the tests in the WMTC test

The analyzed index M in the cases considered so far is characterized by a strong dependence in the points of the engine operation where the reduction of the engine torque occurs. Otherwise, it is the opposite in relation to NO_x (Fig. 9).

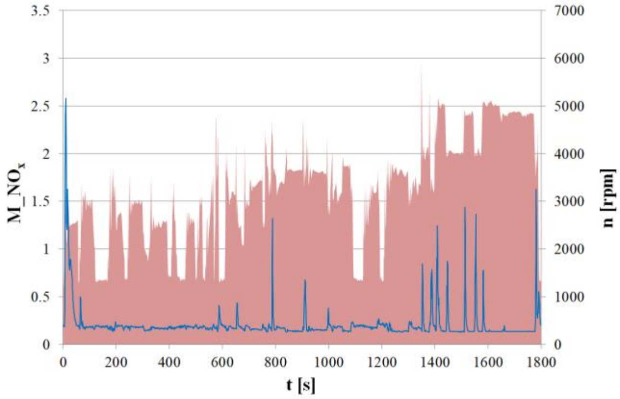

Fig. 9. The course of the engine torque and the M index for NO_x recorded during the tests in the WMTC test

The maxima of the considered parameter occur during the rapid increase of the rotational speed. When accelerating the vehicle, when the power train requires a lot of energy, more fuel is transferred to the cylinders. This has a direct impact on obtaining significant temperatures (over 2300 K) in the front of the flame during combustion. According to Zeldowicz's theorem, these are very favorable conditions for NO_x formation. The sudden and strong emission intensity of the compound under consideration is so significant in comparison to CO_2 that it causes the extremes (above 1) in the analyzed test.

The tests were carried out with the utmost care to reproduce the conditions of actual type approval tests as accurately as possible. The test was carried out on a chassis dynamometer, in a ventilated room, but with an ambient temperature lower than recommended in the legislation. In addition, to avoid the stage of heating the vehicle to operating temperature during the test, the vehicle has previously been warmed up. This in turn caused that during the final stages of measurements, the cooling that was to be provided by the electric fan ceased to be sufficient and the temperature of the coolant began to rise above normal operating conditions (78–95°C – operating temperature) and reached 110°C. This temperature was still below the maximum allowable temperature (this was set by the manufacturer at 115°C). Based on the determined masses of individual gaseous compounds, a comparison of their M toxicity indices was made (Fig. 10). Due to the dimensionlessness of the M index, it is possible to compare not only terms of the same category, but also objects belonging to different groups. Therefore, the obtained results from the motorcycle were compared to the results of a vehicle of another category. In the work of the authors [7], considerations were made in the aspect of the use of the toxicity index for conventional, hybrid and alternative fuel city buses. The measurements were made in accordance with the SORT 2 drive test procedure and on the test route in the Poznań agglomeration. The comparison of the results of both studies shows that the two-wheel vehicle achieves the most similar values of the M index for each of the considered toxic compounds with the values recorded for a bus powered by compressed natural gas (M_CO = 6.5; M_HC = 1.65; M_NO_x = 0.51).

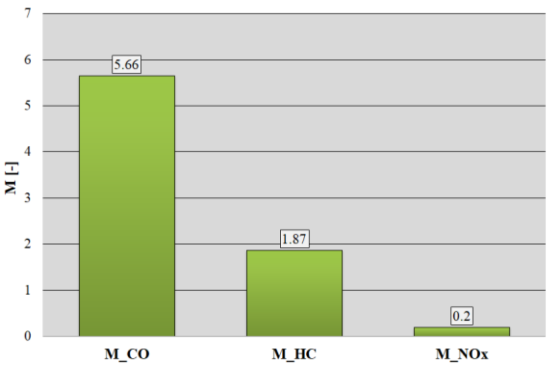

Fig. 10. Summary of M toxicity indicators for CO, HC, and NO_x when tested in the WMTC test

4. Conclusions

At present, concepts such as ecology, environmental protection and global climate change are not just points of discourse but a real challenge for vehicle manufacturers. Therefore, actions are taken that have a direct impact on the development of modern drive systems. Referring to the European policy of Sustainable Development, it can be said that the direction in which the further development of technology will be directed will have a key impact on the future, which will be experienced not only by us, but above all by future generations. Until 1997, two-wheelers were not subject to any Euro emission limits. Only from this moment manufacturers began to use three-way catalytic converters. Considering the progress in reducing emissions of passenger cars and trucks, it is clear that the two-wheeler market is still just waiting for the challenges posed by Euro norms.

The paper presents exhaust emission tests of a vehicle meeting the Euro 4 norm, in which tests were carried out on a chassis dynamometer in accordance with the currently applicable type approval regulations. The test vehicle has been prepared and instrumented in such a way that it was possible to determine its ecological indicators. A new proprietary M toxicity index has been proposed, which is based on the use of carbon dioxide measurements (e.g. the emission intensity of this compound). The values substituted into its structure must be expressed in the same units, which will allow for its dimensionlessness and comparative analysis of vehicles of different categories.

In order to meet the requirements of the Euro 4 norm in motorcycles, there was no need to seek advanced control of the fuel supply system, or relying on direct injection. It was also not necessary to use electronically controlled throttles. From January 1, 2020, a new emission norm – Euro 5 for newly manufactured motorcycles will come into force. Given its guide-lines, it is expected that manufacturers in the near future will be forced to apply the solutions currently commonly used by car manufacturers. Probably the future will mostly rely on turbocharged engines, with direct injection and variable valve timing. Taking into account the construction of the test vehicle and the results of the research, it can be stated that:

- Using an electronically controlled throttle would be beneficial. This would reduce HC emissions primarily by compensating for rapid throttle openings.
- Striving for the fastest and most frequent engine operation in steady state mode would contribute to reducing CO and NO_x emissions. One way to achieve this could be to use a coolant pump that is disconnected during cold start. To do this simply, the pump should be electrically driven and controlled by a separate program in the engine control unit. This would in-crease the speed of warming up the engine to its operating temperature, which would reduce the time operating on rigid maps and allow faster work in closed loop mode.

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