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Review

Two-Wheeled Urban Vehicles—A Review of Emissions Test Regulations and Literature

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Abstract: Two-wheeled vehicles, due to their population, constitute a significant share of road vehicles in Europe. Therefore, this article presents an overview and analysis of the applicable legal regulations regarding two-wheeled vehicle engines in terms of toxic exhaust emission tests. For the correct interpretation of emission standards, the authors of this work made the necessary analysis of the categorization of two-wheeled vehicles based on Polish law and the criteria of European regulations. The presented analysis concerns not only the current regulations, but also their development trends over the years. These considerations are supplemented with a literature review, which includes the problems of the ecology, energy consumption and construction of the considered group of vehicles. The work presented in this article also concerns the assessment of the conditions for conducting tests on objects belonging to category L in laboratory conditions on chassis dynamometers. On this basis, considerations were made to evaluate the currently applicable WMTC (World Motorcycle Test Cycle) test by comparing it with the actual operation of two-wheeled vehicles. This resulted in the formulation of conclusions regarding the need to introduce procedures for testing pollutant emissions in road conditions in the approval process.

Keywords: mopeds; exhaust emission; laboratory test; real operating conditions; L-category

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1. Introduction

Air quality, especially in large urban centers, is a matter of serious concern for both the inhabitants of the area and the decision makers responsible for them. Although mobility is a key enabler of economic growth and citizens' well-being, its sustainability aspect has become fundamental. Transport is one of the main sources of environmental pollution on a global scale, which results in global warming caused by greenhouse gases and local smog in urban agglomerations. Most scientists now agree that climate change is due to the Greenhouse Effect (GHE), which is largely caused by CO_2 (Carbon Dioxide) [1–3].

Recent findings also confirm the adverse health effects caused by air pollution (nanoparticles, suspended dust mass, ozone, nitrogen oxides, etc.). Near main roads, the level is significantly higher than that resulting from general pollution in urban areas. Populations living and working close to major transport infrastructure may, therefore, be more exposed to the negative effects of increased levels of air pollution [4–8]. According to the report of the World Health Organization [8], the level of pollution in urban agglomerations is significant in both developed and developing countries. According to data provided by the organization, 90% of the urban population around the world breathes air that significantly exceeds the permissible values of toxic compounds (Figure 1), and the number of deaths caused by air pollution is also excessive [8].

Continuous economic development and the related increase in the wealth of the population of global agglomerations leads to an increasing share of road transport. It is predicted that, by 2050, the number of vehicles in the world will double [9]. This justifies the need for research and development on low-emission drive system solutions, e.g., all-electric drives [10–14]. The increase in the number of vehicles in recent years applies to all categories, including two-wheeled vehicles, which are the subject of the article.

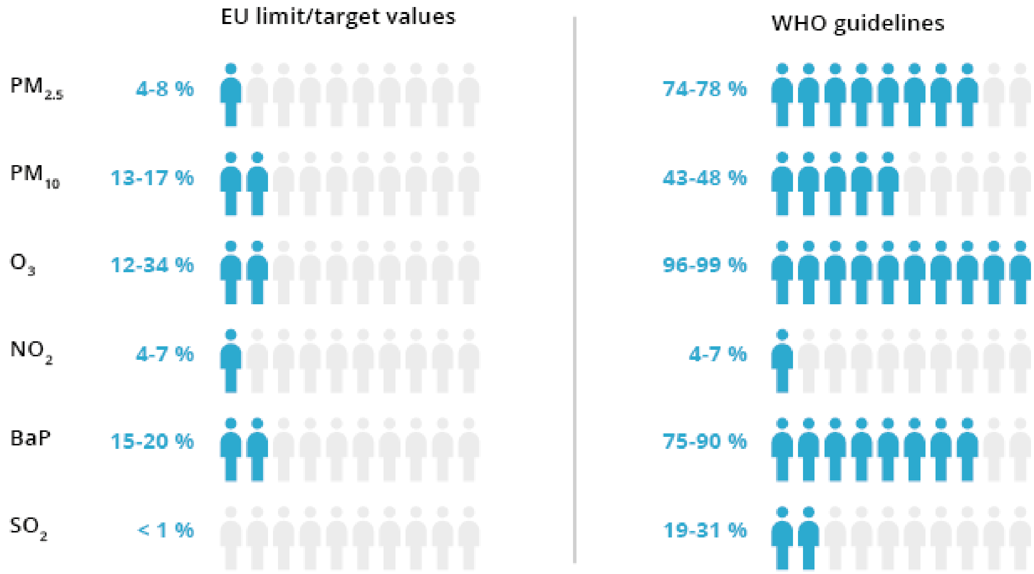

Figure 1. Percentage of the EU's population and urban population exposed to air pollution concentrations exceeding EU and WHO reference values in 2016–2018 [8].

For the transport policy of the European Union, including Poland, the reduction of exhaust gas emissions and road congestion, where one of them is a result of the other, are extremely important issues. The problem has been noticed by international entities such as the European Union, for which the idea of sustainable development is extremely important, as evidenced by the document published in 2011 entitled White Paper "Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system". It constitutes the basis for all member states to implement a sustainable and integrated transport policy, the main goal of which is to reduce emissions by 60% while supporting mobility and the development of the transport sector. This policy should be understood as a socio-economic development strategy that aims at ecological balance. The aim of this strategy is to improve the quality of life of society while maintaining the economic efficiency of the transport sector [15].

The solution, aimed at reducing the level of traffic congestion in cities and non-urban areas, is the use of two-wheelers, which causes a continuous increase in the share of this category of vehicles, mainly in Asian countries, where the problem of urban congestion is particularly visible. Moreover, two-wheeled vehicles compensate for the lack of public transport in remote non-urban areas and they also ensure the effective and sustainable mobility of services and goods as well as special transport, such as emergency medical services and police forces.

The year 2020, in which the whole world struggled with the COVID-19 pandemic (Coronavirus Disease 2019), showed another advantage of using two-wheeled vehicles, namely, a revival on the sales market. This was due to the renewed attractiveness and convenience of two-wheeled motor vehicles for urban and suburban commuting, in a sanitary context where public transport was not considered a safe option for many of its previous users. However, the increasing share of motorcycles and mopeds obviously results in their significant contribution to generating emissions of toxic compounds, especially in urban agglomerations. This is confirmed by numerous works on this problem. Sahu et al., 2014 [16], estimate that in India, 37% of CO (Carbon Oxides) emissions from transport are generated by two-wheelers, while according to Wu et al. 2016 [17] in China, 17.5% of Volatile Organic Compounds (VOCs) come from two-wheeled vehicles. The data cited indicate the scale of the problem of emissions from two-wheeled vehicles, although the scale varies depending on the location.

In recent years, RDE (Real Driving Emission) research has become increasingly important, including fuel consumption and the emissions of harmful exhaust gases. From 1 September 2017, the European Commission introduced such tests into the approval procedures for LDVs (Light-Duty Vehicles). RDE research creates new cognitive and development perspectives for vehicles. Moreover, measurements in real operating conditions enable a full understanding of the relationship between driving parameters and toxic exhaust emissions. This is not possible through tests conducted in laboratory conditions, where it is not possible to faithfully reproduce all operating conditions. By conducting RDE tests, it is possible to determine all cause-and-effect relationships occurring during the operation of vehicles and their engines.

The RDE methodology is currently being dynamically developed for other types of vehicles—light and heavy motor vehicles and off-road vehicles [18–22]. The long-term and intensive research phase and pilot work for vehicles from the road vehicle groups [23,24] and HDVs (Heavy-Duty Vehicles) [25–29] resulted in the introduction of appropriate procedures for controlling the emissions of toxic compounds in real operating conditions. However, there are no studies enabling the assessment of the emission of two-wheeled vehicles in real road conditions.

2. Legal Regulations Regarding Testing of Emissions of Toxic Exhaust Gases from Two-Wheeled Vehicle Engines

Guidance on testing exhaust emissions from engines of two-wheeled vehicles is contained in Directive 2002/51/EC [30], relating to the reduction of the emissions of an environmental pollutant from two- and three-wheeled motor vehicles (referred to as L-category vehicles in the later Directives) and amending the earlier Directive 97/24/EC. On its basis, in subsequent years, numerous corrections and additions were introduced, resulting from the standardization of regulations on a global scale. In 2013, Regulation (EU) No. 168/2013 [31] and in 2014, the supplementary Technical Regulation (EU) 134/2014 [32] introduced significant changes:

- Directive 2002/51/EC of the European Parliament and of the Council of 19 July 2002 was completely repealed,
- the number of L-categories was expanded,
- environmental requirements and implementation dates for Euro 4 and 5 standards were defined (whereby the second stage—Euro 5—is mandatory for new types of vehicles from 1 January 2020),
- a previously unregulated limit value for particulate emissions was introduced: for one of the classes of three-wheeled vehicles and heavy road quadricycles—Euro 4; for all L-category vehicles—Euro 5,
- all new types of vehicles for the individual (sub-)categories of motorcycles, tricycles and light and heavy quadricycles, apart from OBD I (On-Board Diagnostic), must be equipped with an OBD II system at the stage of the application of the Euro 5 standard, which monitors and signals the failures and deterioration conditions of the emission control system resulting in the exceedance of emission thresholds,
- guidelines were defined and implemented, partly at the stage of the Euro 4 standard and completely at the stage of the Euro 5 standard, for the laboratory global harmonized test cycle for WMTC emissions, which was specified in the Global Technical Regulations of the United Nations Economic Commission for Europe.

In Asian countries, such as China and Japan, the regulations governing emissions tests of harmful compounds are contained in documents issued by national Ministries of the Environment. The analysis of regulations shows that European and American regulations constitute the basis for their formulation in the rest of the world. Moreover, legislators are slightly more liberal in their efforts to tighten the regulations on exhaust emissions from two-wheeled vehicles compared to the regulations on passenger cars.

The history of regulations for L-category vehicles is relatively short. The first standard (Euro 1) came into force in 2000, while for passenger cars 7 years earlier, the entry into force of the next standard (EURO 2) took place after another six years. In the periods 1990–2000 and 2011–2020, there were as many as two or three standards for passenger cars per one standard for two-wheeled vehicles (Table 1).

Table 1. Years of introduction of EURO standards for PC, HDV and L-category vehicles.

L-Category	PC	HDV	Year of Validity	Years
		EURO I	1992	1990–2000
	Euro 1		1993	
	Euro 2	EURO II	1996	
Euro 1			1999	
	Euro 3	EURO III	2000	
Euro 2			2002	>2000–2010
		EURO IV	2005	
Euro 3	Euro 4		2006	
		EURO V	2008	
	Euro 5a		2009	
	Euro 5b		2011	>2010–2020
		EURO VI	2013	
	Euro 6b		2014	
Euro 4			2016	
	Euro 6d Temp		2017	
Euro 5	Euro 6d		2020	

3. Categorization of Two-Wheeled Vehicles

For the correct interpretation of exhaust emission standards, two-wheeled vehicles should be assigned to the appropriate category in accordance with the classification of vehicles specified in Regulation (EU) No. 168/2013 of the European Parliament and of the Council of 15 January 2013 [31]. Category-L vehicles are two-, three- or four-wheeled vehicles, the detailed division of which is presented in Table 2.

Table 2. General division of L-category vehicles [30].

Category	Sub-Category
L1e (Light two-wheel-powered vehicle)	L1e-A (powered cycles) L1e-B (two-wheel mopeds)
L2e (Three-wheel moped)	L2e-P (three-wheel mopeds for passenger transport) L2e-U (three-wheel mopeds for utility purposes)
L3e (Two-wheel motorcycle, division by motorcycle performance)	L3e-A1 (low-performance motorcycles) L3e-A2 (medium-performance motorcycles) L3e-A2 (high-performance motorcycle)
L3e (Two-wheel motorcycle, division by special use)	L3e-A1E, L3e-A2E lub L3e-A3E (enduro motorcycles) L3e-A1T, L3e-A2T lub L3e-A3T (trials motorcycles)
L4e (Two-wheel motorcycle with side-car)	
L5e (powered tricycle)	L5e-A (tricycles) L5e-B (commercial tricycles)
L6e (light quadricycle)	L6e-A (Light on-road quad) L6e-B (light quadri-mobile) L6eBP (for passenger transport) L6eBU (for utility purposes)
L7e (quadricycle)	L7e-A (heavy on-road quad) L7e-B (heavy all-terrain quad)

The L-category vehicles are further classified on the basis of their type of propulsion:

1. vehicles equipped with an internal combustion engine:
    - with spark ignition,
    - with compression ignition,
2. vehicles equipped with an external combustion engine, a turbine or an engine in which a piston rotates inside a cylinder. For the purposes of compliance with environmental protection and functional safety requirements, a vehicle powered in this way is considered to be the same as a vehicle powered by an internal combustion engine,
3. vehicles equipped with a pre-compressed air engine that does not emit levels of pollutants or inert gases higher than those present in ambient air, provided that, with respect to functional safety and fuel storage and fueling requirements, such vehicles are considered to be gaseous fuel vehicles,
4. electric vehicle,
5. hybrid vehicle.

Table 2 describes the detailed classification of individual categories. Their characteristic criteria are described in detail in the European Commission Regulation (EU) No 168/2013 [31].

4. Emission Standards for Toxic Compounds in the European Union and in the World

The exhaust emission standards that apply in Europe are referred to as Euro standards, translated as a "European exhaust emission standard". They contain the permissible emission values for vehicles used in the European Union. They are developed in a series of European directives, which are characterized by a certain restrictiveness. The beginning of the 1990s was characterized by a 20% share of two-wheeled vehicles in the total emissions of toxic compounds from all road vehicles [33]. Therefore, from June 1999, the Euro 1 standard came into force, intended only for two-wheeled vehicles (motorcycles and mopeds), and their values were determined only by the engine displacement [30]. During the development of subsequent Euro standards, the restructuring process between Euro 1 and Euro 3 led to a significant 80% reduction in carbon monoxide and hydrocarbon emissions and an 83% reduction in nitrogen oxide emissions (Figure 2). The limit values for Euro 2 and 3 standards are regulated by Directive 2002/51/EC [31].

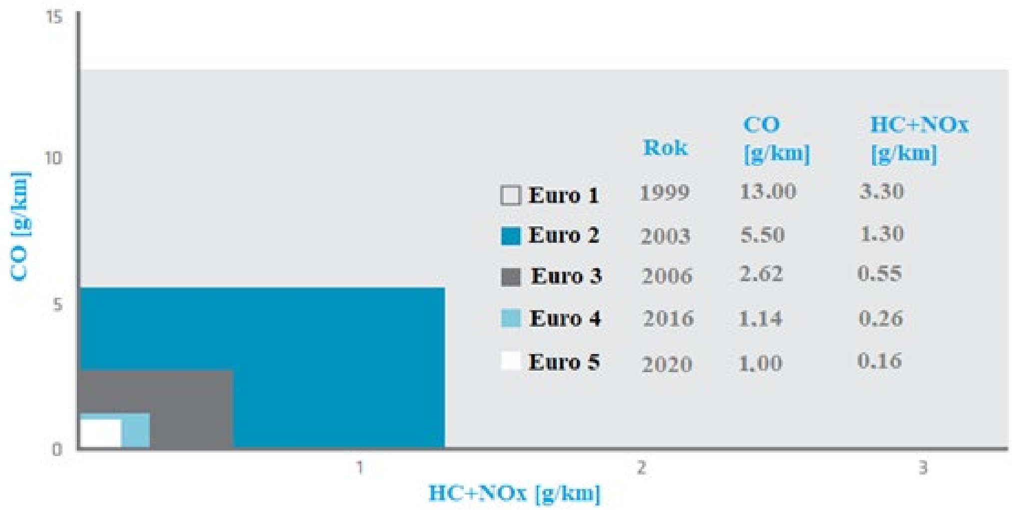

Figure 2. Development of European regulations for two-wheeled vehicles [33].

From 1 January 2016, under Regulation (EU) 168/2013, the next stage came into force for new types of two-wheeled vehicles—Euro 4—and after another four years, the Euro 5 standard. The document expanded the number of L-categories and regulated the emission limit value that had not been standardized until then, as well as the mass of particulate matter, and also included hybrid vehicles in the regulation. The permissible values, divided into individual subcategories for subsequent Euro stages, are presented in Tables 3–6.

Table 3. Limit values for emissions of toxic exhaust gases from engines of two-wheeled vehicles of particular categories in Europe; Euro 1–3 [30,33].

Euro 1							
Category	**Category Name**	**Classification**	**Euro Standard**	**Emission [g/km]**			
				CO	**HC**	**NO_x**	**HC + NO_x**
all vehicles	mopeds motorcycles	<150 cm^3 ≥150 cm^3	1 1	13	3	0.3	-
Euro 2 + 3							
L1e	mopeds	<50 cm^3	2 + 3	1	-	-	1.2
L3e	motorcycles	<150 cm^3	2	5.5	1.2	3	-
		≥150 cm^3	2	5.5	1	3	-
		<150 cm^3	3	2	0.8	1.5	-
		≥150 cm^3	3	2	0.3	1.5	-
		v_{max} < 130 km/h	3	2.62	0.75	1.7	-
		v_{max} ≥ 130 km/h	3	2.62	0.33	2.2	-

Table 4. Limit values for emissions of toxic exhaust gases from engines of two-wheeled vehicles of particular categories in Europe; Euro 2–3 [30].

Euro 2 + 3							
Category	**Category Name**	**Classification**	**Euro Standard**	**Emission [g/km]**			
				CO	**HC**	**NO_x**	**HC + NO_x**
CI							
L2e L5e L6e L7e	Three-wheel moped Tricycle Light quadrimobile Heavy quadrimobile	<50 cm^3 ≥50 cm^3 <50 cm^3 ≥50 cm^3	2 + 3 2 2+3 2	7	1.5	0.4	-
PI							
L2e L5e L6e L7e	Three-wheel moped Tricycle Light quadrimobile Heavy quadrimobile	<50 cm^3 ≥50 cm^3 <50 cm^3 ≥50 cm^3	2 2 2 2	2	1	0.65	-

Table 5. Limit values for emissions of toxic exhaust gases from engines of two-wheeled vehicles of particular categories in Europe; Euro 4 [31].

Euro 4						
Vehicle Category	**Vehicle Category Name**	**Propulsion Class**	**Emission [g/km]**			
			CO	**HC**	**NO_x**	**PM**
L1e-A	Powered cycle	PI/CI/Hybrid	0.56	0.1	0.07	-
L1e-B	Two-wheel moped	PI/CI/Hybrid	1	0.63	0.17	-
L2e	Three-wheel moped	PI/CI/Hybrid	1.9	0.73	0.17	-
L3e L4e	Two-wheel motorcycles with and without side-car	PI/CI/Hybrid v_{max} ≥ 130 km/h	1.14	0.38	0.07	-

Table 5. *Cont.*

Euro 4						
Vehicle Category	Vehicle Category Name	Propulsion Class	Emission [g/km]			
			CO	HC	NO_x	PM
L5e-A L7e-A	Tricycle Heavy on-road quad	PI/CI/Hybrid $v_{max} \leq 130$ km/h	1.14	0.17	0.09	-
		CI/CI Hybrid	1	0.1	0.3	0.08
L5e-B	Commercial tricycle	PI/PI Hybrid	2	0.55	0.25	-
		CI/CI Hybrid	1	0.1	0.55	0.08
L6e-A	Light on-road quad	PI/PI Hybrid	1.9	0.73	0.17	-
L6a-B	Light quadrimobile	CI/CI Hybrid	1	0.1	0.55	0.08
L7e-B	Heavy all-terrain quad	PI/PI Hybrid	2	0.55	0.25	-
L7e-C	Heavy quadrimobile	CI/CI Hybrid	1	0.1	0.55	0.08

Table 6. Limit values for emissions of toxic exhaust gases from engines of two-wheeled vehicles of particular categories in Europe; Euro 5 [31].

Euro 5							
Vehicle Category	Vehicle Category Name	Propulsion Class	Emission [g/km]				
			CO	THC	NHMC	NO_x	PM
L1e-A	Powered cycle	PI/CI/Hybrid	0.5	0.1	0.068	0.06	0.0045
L1e-B-L7e	Other L-category	PI/PI Hybrid CI/CI Hybrid	1 0.5	0.1 0.1	0.068 0.068	0.06 0.06	0.0045 0.0045

In the United States, emission limits for two-wheeled vehicles were regulated by one unchanging set of standards for all model years from 1978 to 2005 (Table 7).

Table 7. Limit values for toxic exhaust emissions from two-wheeled vehicle engines in the United States; model years 1978–2005 [34].

1978–2005				
Class	Classification	Emission [g/km]		
		HC	CO	NO_x
I	50–169 cm^3	5	12	-
II	170–279 cm^3	5	12	-
III	>279 cm^3	5	12	-

Since 15 January 2004, pursuant to document 69 FR 2398 signed by the EPA (Environmental Protection Agency), federal Tier regulations have been established. The Tier 1 standard came into force in 2006 with a new definition of classes (Table 8).

Previously unregulated vehicles with an engine capacity of less than 50 cm^3 are class I-A, and the previously existing class I has been replaced by class I-B. The standard has also been optionally extended to include a limit value for nitrogen oxide emissions, which is presented as the sum of emissions with hydrocarbons. In 2010, the standards for Class III motorcycles were updated to the Tier 2 standard.

Table 8. Limit values for toxic exhaust emissions from two-wheeled vehicle engines in the United States; Tier 1–2 [35].

Tier 1				
Class	Classification	Emission [g/km]		
		HC	HC + NO_x *	CO
I–A	<50 cm^3	-	-	-
I–B	50–169 cm^3	1	1.4	-
II	170–279 cm^3	1	1.4	-
III	>279 cm^3	-	1.4	
Tier 2				
III	>279 cm^3	-	0.8	12

* This is an optional standard that allows manufacturers to average their emissions or transfer emissions values between classes.

Currently, in India, the share of two-wheeler vehicles is over 80% of all road vehicles. The history of regulations regulating the emissions of toxic compounds from two- and three-wheeled vehicles in this country begins in 1991 with the restriction of carbon monoxide and hydrocarbons. Since then, other toxic compounds have been covered by regulations and emission restrictions have been significantly tightened (Table 9).

Table 9. Limit values for toxic exhaust emissions from two-wheeled vehicle engines in India; Bharat Stage I–III [34].

BS I–III				
Year of Implementation	Standard	Emission [g/km]		
		HC	CO	HC + NO_x
1991	-	8–12	12–30	-
1996	-	-	4.5	3.6
2000	Bharat I	-	2	2
2005	Bharat II	-	1.5	1.5
2010	Bharat III	-	1	1

On 4 July 2014 and 12 June 2015, India introduced the next, fourth stage of exhaust emission standards for two- and three-wheeled vehicles, called Bharat Stage IV. The regulation has reduced the HC + NO_x limits by an average of 42% (depending on the vehicle class), compared to the previously applicable BS III norm. This forced the manufacturers of two-wheeled vehicles to use three-function reactors and an eclectic fuel injection. The classification of vehicles in terms of specific permissible values of toxic compounds refers to the engine displacement and maximum vehicle speed (Table 10). The Ministry of Road Transport and Highways, on 18 February 2016, issued a notification about the next phase of the India-wide Bharat Stage VI norms for light and heavy vehicles, including two- and three-wheelers. The emission limits for toxic compounds in this standard have been harmonized with the values of the European Euro 5 standard, and their levels depend on the type of engine power supply.

Table 10. Limit values for toxic exhaust emissions from two-wheeler engines in India; Bharat Stage IV–VI [34].

BS IV						
Category	**Year of Implementation**	**Classification**	**Emission [g/km]**			
			CO	**HC**	**NO_x**	**PM**
2 Wheels	2016	Class 1 Sub-class 1–2	1.403	-	0.39	
		Sub-class 2–1	1.97	-	0.34	
		Sub-class 3–1, 3–2	1.97	-	0.2	
BS VI						
2 Wheels	2020	PI engine	1			

Chinese regulations regarding two-wheeled vehicles distinguish two groups: two-wheeled and three-wheeled. The permissible level of exhaust emissions depends on the engine displacement and the maximum speed of the vehicle, and in the case of three-wheeled vehicles, the type of engine power supply is also important. The introduction of exhaust emission standards, similarly to Europe, the United States and India, took place in stages spread over time.

The current standard in China for two-wheeled vehicles is Stage IV (Table 11). The much larger share of this group of vehicles in Asian countries has not translated into legislators' expenditure in terms of tightening the permissible values of toxic compounds that would be equal to the values applicable in the EU. Nevertheless, a clear tendency is to systematically reduce the permissible emission values of toxic exhaust gases and standardize them around the world.

Table 11. Limit values for emissions of toxic exhaust gases from two-wheeled vehicle engines in China; Stage IV [34].

Stage IV								
Vehicle Type	**Vehicle Class**	**Engine Size [cm^3]**	**Vehicle Speed [km/h]**	**Emission [g/km]**				
2 Wheels	mopeds	≤ 50	$v_{max} \leq 50$	HC	NO_x	CO	HC + NO_x	PM
	I	$50 < V < 150$	$v_{max} \leq 50$	0.63	0.17	1	-	-
		$V < 150$	$50 < v_{max} < 100$				-	-
	II	$V < 150$	$100 < v_{max} < 115$	0.38	0.07	1.14	-	-
		$V \geq 150$	$v_{max} < 115$				-	-
		$V \leq 1500$	$115 < v_{max} < 130$				-	-
	III	$V \leq 1500$	$130 < v_{max} < 140$	0.17	0.09	1.14	-	-
		$V > 1500$ lub $v_{max} \geq 140$					-	-
3 Wheels	mopeds	$V \leq 50$	$v_{max} \leq 50$	0.73	1.9	1.9	-	-
	PI engine	$V > 50$ lub $v_{max} > 50$		0.55	2	2	-	-
	CI engine	$V > 50$ lub $v_{max} > 50$		-	0.74	740	0.46	0.06

5. Legislative Guidelines for Research

The obligations of L-category vehicle manufacturers regarding environmental performance tests (including approval tests) for the Euro 4 and 5 standards, the specific requirements of which are described in Articles 6–13, are set out in Chapter II of the EU Commission Regulation of 16 December 2013. Individual articles deal with (Table 12):

- *Article 6*—Type I test requirements: exhaust emissions after starting a cold engine;
- *Article 7*—Type II test requirements: an exhaust emissions test (at an elevated engine speed) at idle and under free acceleration;
- *Article 8*—Type III test requirements: crankcase emissions;
- *Article 9*—Type IV test requirements: vapor emissions;

- *Article 10*—Type V test requirements: durability of pollution control devices;
- *Article 11*—Type VII test requirements: CO_2 emissions, fuel consumption, electricity consumption or electric range;
- *Article 12*—environmental requirements for the on-board diagnostic system;
- *Article 13*—Type IX test requirements: noise level.

Table 12. Obligations of L-category vehicle manufacturers regarding environmental performance tests (including approval test procedures) for the Euro 4 and 5 standards [32].

Test Type	Description	Requirements	
		Euro 4	Euro 5
I	Tailpipe emissions after cold start	Annex VI (A1)	Annex VI (A2)
II	Exhaust emissions test (at elevated revs) at idle and under free acceleration	Directive 2009/40/EC	
III	Emissions of crankcase gases	Zero emission, closed crankcase. Crankcase emissions shall not be discharged directly into the ambient atmosphere from any vehicle throughout its useful life	
IV	Evaporative emissions	Annex VI (C1)	Annex VI (C2)
V	Durability of pollution control devices	Annex VI (A), VII (A), VII (B) Euro IV restrictions and test procedures	Annex VI (A), VII (A), VII (B) Euro V restrictions and test procedures
VI	A test-type VI has not been attributed	Not applicable	
VII	CO_2 emissions, fuel and/or electric energy consumption and electric range	Measurement and reporting, no limit value for type approval purposes	
VIII	OBD environmental tests	OBD stage I, annex VI (B1)	OBD stage II, annex VI (B2)
IX	Sound level	Annex VI (D), Euro IV restrictions and test procedures	Annex VI (D), Euro V restrictions and test procedures

The type I test takes place in the WMTC driving cycle on a single-roller chassis dynamometer, where the movement resistance and reference mass of the vehicle are simulated, which is understood as the mass of the vehicle with all fluids, increased by 75 kg (Figure 3). The fuel tank is filled to half its capacity. The ambient temperature at which the measurement is carried out must be in the range of 20–30 °C. The vehicle is conditioned for 6–36 h before starting the measurement or until the coolant temperature, oil temperature or spark plug socket temperature is close to the ambient temperature. It differs from tests for light vehicles by constant acceleration and gear changes carried out in accordance with the manufacturer's recommendations.

Three measurements are taken. In one of them, emissions may exceed the permissible values by a maximum of 10%, but the arithmetic mean of all measurements must remain within the set limits. The exception to this rule is a situation where, for all pollutants, the emission does not exceed 70% of the permissible value. Then the tests can be completed with one measurement. At least two measurements are performed when three conditions are met for all pollutants: the emission in the first measurement does not exceed 85% of the permissible value, the total emission in both measurements does not exceed 170% of the permissible value of a single measurement and the emission in the second measurement does not exceed the permissible value.

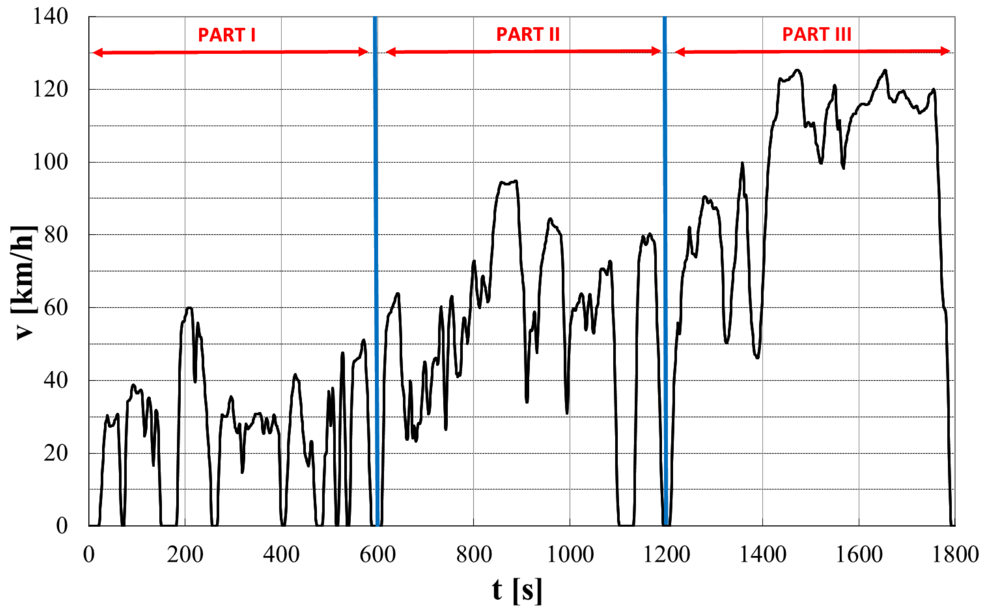

Figure 3. WMTC test [32].

The currently valid worldwide approval test for L-category vehicles is the WMTC test cycle, consisting of three parts. Each of them lasts 600 s and has a different maximum vehicle speed. The first part has a maximum speed of 60 km/h and the vehicle covers a distance of 4.1 km. In the second part, the maximum and average vehicle speeds are 95 km/h and 54.7 km/h, respectively, over a distance of 9.1 km. The third part reflects highway driving conditions with a maximum speed of 125.3 km/h.

The test is part of the Global Technical Regulations established by the United Nations as part of the World Forum for the Harmonization of Vehicle Regulations. The history of the test's use begins with the entry into force of the Euro 4 standard, and its validity was limited to the categories L3e, L4e, L5e-A and L7e-A. From 2020, and the introduction of the Euro 5 standard, European manufacturers of all L-category vehicles have been obliged to use and meet approvals based on the "Revised WMTC" driving test, also known as "WMTC stage 3". For vehicles of the categories L3e, L4e, L5e-A, L7e-A, L7e-B and L7e-C, the described test procedure applies.

The WMTC stage 3 test, to be used on a chassis dynamometer for vehicles of the subcategories L1e-A, L1e-B, L2e, L6e-A and L6e-B, shall follow the course shown in Figure 4. The vehicle speed curve cut-off, limited to 25 km/h, applies to L1e-A and L1e-B vehicles, with a maximum design speed limited to 25 km/h. This test lasts 1200 s and consists of two equivalent parts that should be performed without interruption. The purpose of the WMTC test is to determine the emissions of carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons and, where appropriate, the mass of dust, as well as fuel consumption and range when powered by electricity. The tests are performed on a chassis dynamometer, the specification requirements and the necessary preparatory work of which are specified in the EU Commission Regulation of 16 December 2013.

The ECE (Economic Commission for Europe) R47 research test, valid for subcategories L1e, L2e and L6 for standards preceding the Euro 5 standard, lasts 896 s and consists of eight basic cycles (Figure 5). They must be carried out without interruption, and the measurement is made throughout the entire driving cycle, from the moment the starter is turned on. Each cycle consists of seven phases. For two-wheeled vehicles of categories L1e-A and L1e-B with a maximum design speed of 25 km/h, the cut-off speed curve applies.

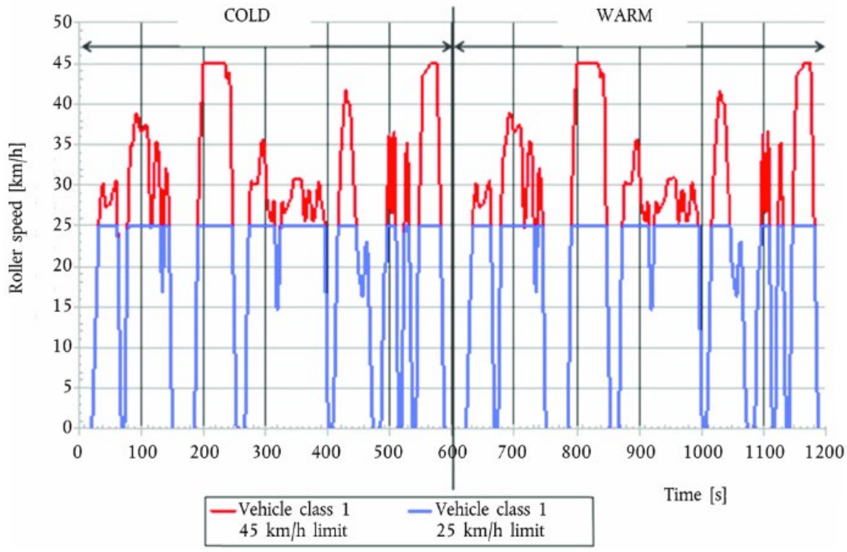

Figure 4. Shortened WMTC test [32].

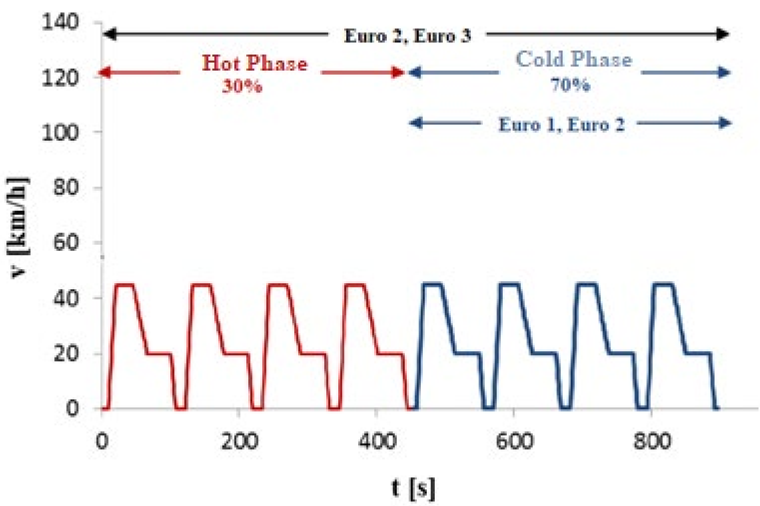

Figure 5. ECE R47 test [32].

The ECE R40 test lasts 1170 s and consists of six basic urban cycles, each of which must be performed without interruption (Figure 6). One basic cycle consists of fifteen phases that reflect driving conditions:

- at constant speed (3 phases),
- idle operation (6 phases),
- acceleration (2 phases),
- speed reduction (4 phases).

The cold phase of the test takes place for the first 195 s (one basic cycle), counted from the cold start of the engine. The warm engine phase covers the last 975 s (five basic urban cycles), during which the engine continues to warm up and finally reaches the operating temperature. The test was valid for the subcategories L5e-B, L7e-B and L7e-C in the case of the Euro 4 standard, and for L1e, L2e and L6e for the Euro 2 + 3 standard, in force since 2003. In summary, type I tests depending on the vehicle (sub)category and exhaust emission standard should be carried out for the specific test cycles described above (Table 13).

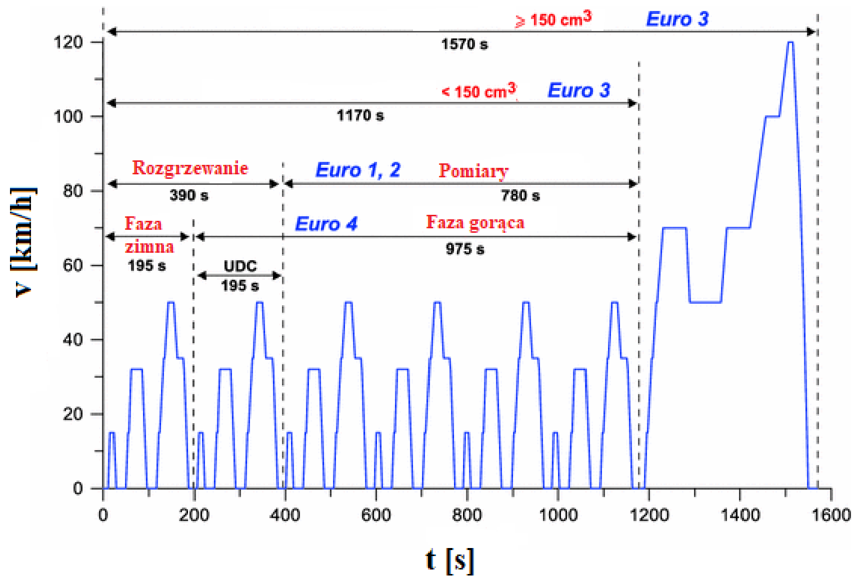

Figure 6. ECE R40 test [32].

Table 13. Test cycles used in the type I test depending on the subcategory of the two-wheeled vehicle [32].

	Euro 4		
Vehicle Category	**Test**	**t [s]**	**s [m]**
L1e, L2e, L6e	ECE R47	897	4433/6529
L3e, L4e, L5e-A, L7e-A	WMTC, stage 2	1800	28,912
L5e-B, L7e-B, L7e-C	ECE R40	1170	5971
	Euro 5		
L1e, L2e, L6e-A, L6e-B	WMTC, stage 3	1200	11,541
L3e, L4e, L5e-A L7e-A, L7e-A, L7-C	WMTC, stage 3	1800	28,912

A proportionate portion of the diluted exhaust emissions is continuously collected for subsequent analysis using a continuous volume (variable dilution) CVS bag sampling system. The analysis shall start as soon as possible and, in any case, no later than 20 min after the end of the test cycle.

6. Literature Review in the Aspect of Testing the Emission of Toxic Exhaust Compounds from Two-Wheeled Vehicle Engines

In preparation for the implementation of the topic of the article, a literature analysis was performed. Studies in this area included issues related to ecology, energy consumption, the construction of modern motor vehicles, including those belonging to the L-category, as well as tests carried out in laboratory conditions on single-roller chassis dynamometers and in real operating conditions.

The review showed that, in recent years, RDE tests of fuel consumption and emissions of harmful exhaust gases have become increasingly important, and from 1 September 2017, the European Commission introduced such tests into the approval procedures of LDV vehicles. RDE research creates new cognitive and development perspectives for vehicles. By conducting research in real conditions, it is possible to determine all cause-and-effect relationships occurring during the operation of objects and their engines.

In the scientific literature, many researchers describe various aspects of RDE research. Due to the introduction of such tests into approval procedures, numerous items concern the development of the test methodology and comparison with laboratory tests. In works published on this topic, attention was turned to the non-representativeness of laboratory tests [18,36–40]. At the same time, the results of these studies draw attention to the multitude of factors influencing the level of emissions and the fuel consumption of vehicles depending on the conditions of actual operation, such as road congestion, the road profile and ambient conditions.

Traditionally, for many years, emissions and fuel consumption tests for two-wheeled vehicles have been conducted in laboratory conditions, mainly using chassis dynamometers. These tests are conducted within the framework of developed standardized driving cycles, but their representativeness is questionable. This was the starting point for the development of research in real operating conditions. This type of research already covers motor vehicles and trucks [41] and should be extended to other categories of engines because tests in laboratory conditions do not fully reflect the real operation, which is confirmed by numerous publications [42–44]. A group of vehicles that are not yet subject to road tests are two-wheeled vehicles. The stage preceding legislative steps is usually a long-term research phase.

A literature review from the last twenty years has shown a large disproportion between the number of published studies on the emission of two-wheeled vehicles and vehicles from the LDV+PC and HDV categories. In the online database of technical and scientific journals—the phrases "emissions from vehicles [. . .]" were first entered for LDV+PC, HDV and motorcycles. It was reported that between 2002 and 2021, the total number of publications for two-wheeled vehicles was only 644, representing a small share of published works for light vehicles and passenger cars, for which 5123 search results were obtained. For heavy vehicles, there were 1669 publications on this issue (Figure 7).

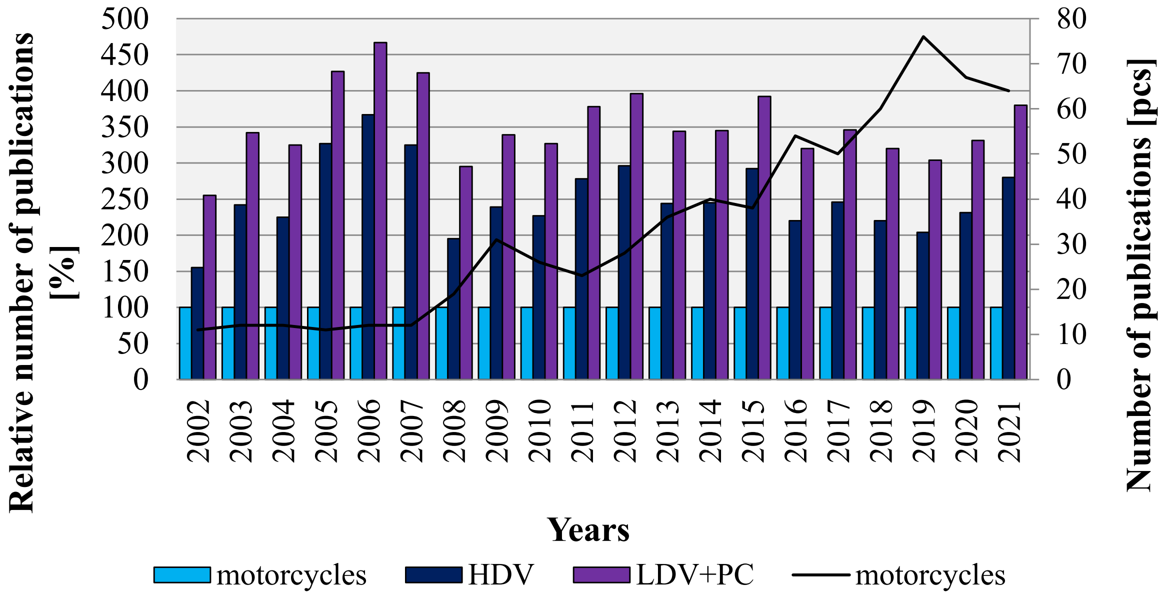

Figure 7. Relative number of publications on toxic emissions from various vehicle categories.

Another analysis was performed for a more precise phrase, i.e., "emissions in real road conditions [. . .]", for the same groups of vehicles. In the last twenty years, only 66 studies have been published for two-wheeled vehicles, while in 2002 alone, there were 58 studies for vehicles from the LDV+PC category, and this number only increased to reach a maximum in 2017 of 397 publications (Figure 8). The most frequently cited works relating to the emission of two-wheeled vehicles, along with studies on the issue of emission tests in real operating conditions, include [39,45–48].

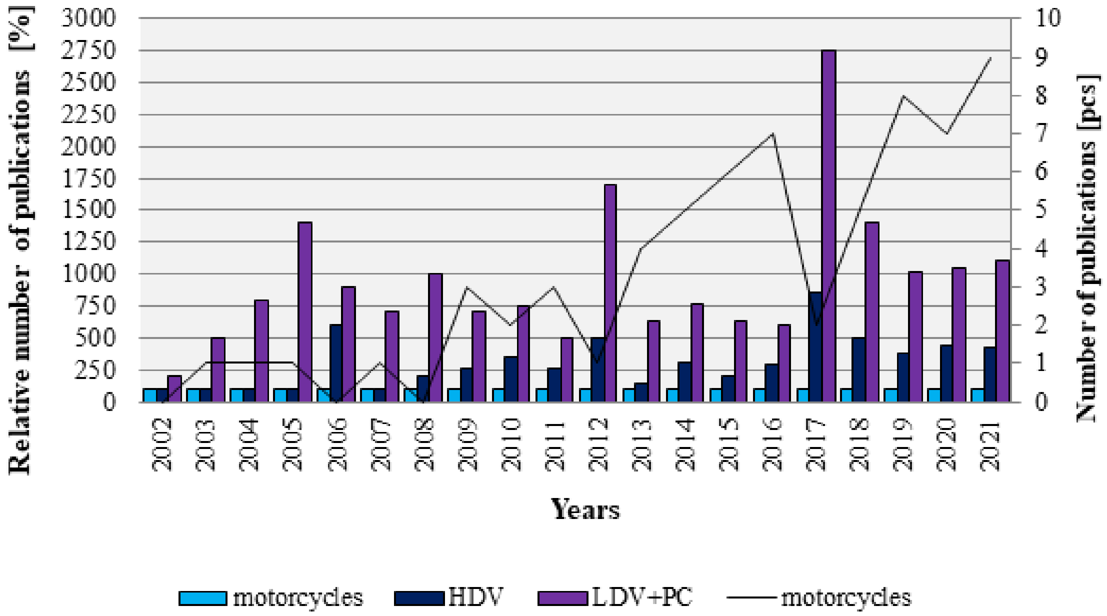

Figure 8. Relative number of publications on emissions of toxic compounds from various categories of vehicles in road conditions.

The long-term and intensive research phase and pilot work for vehicles from the LDV+PC and HDV groups resulted in the introduction of appropriate procedures for controlling the emissions of toxic compounds in real operating conditions. In 2013, detailed requirements for determining the in-service compliance of used engines or vehicles were presented for the Euro VI standard under EU Regulation 582/2011 [49].

The document concerns the obligation to measure specific emissions of pollutants in real road conditions, using PEMS equipment. In the case of LDV and PC vehicles, the European Commission introduced this type of testing in September 2017 along with the EURO 5 standard. Guidelines for the RDE procedure for this group of vehicles were included in Commission Regulation (EU) 2017/1154 of 7 June 2017 [50]. The subsequent stages of introducing tests in real operating conditions for individual vehicle groups in Europe are schematically presented in Figure 9.

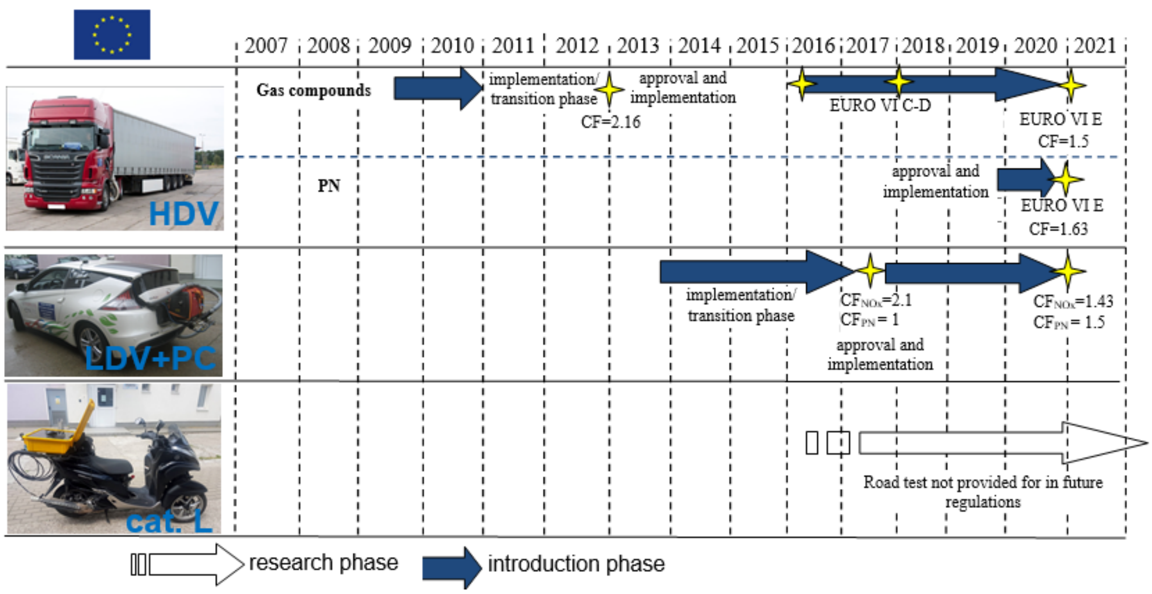

Figure 9. Introducing tests in real operating conditions for individual vehicle groups in Europe.

For motorcycles and mopeds, due to the small number of studies and, consequently, the lack of a defined problem related to the emission of toxic compounds, road tests are not even provided for regulations in the future. Nevertheless, there is an upward trend in the appearance of studies on this issue. Based on the history of work for other vehicle categories, it is possible that this will contribute to pilot studies and subsequent legislation.

It should be noted that two-wheeled vehicles constitute a large group, especially in Asia and South America. Tests of this type for two-wheeled vehicles are performed very rarely. In fact, the problem of RDE testing two-wheeled vehicles is presented only in a few publications. This is primarily due to the limited space available for installing the PEMS equipment and its weight. Nevertheless, attempts to test in real operating conditions for L-category vehicles have been and are still being made. Due to problems with adapting PEMS equipment for RDE tests of two-wheeled vehicles, numerous researchers have focused on conducting research in real operating conditions and creating representative tests on their basis, which were then reproduced in laboratory stations [37,46,51–58].

As a result of these studies, research cycles have been developed which are more representative than standardized cycles, but usually reflect the operating conditions for selected cities and agglomerations [37,39,46,48,54,56]. When analyzing the mentioned cycles, it should be noted that they differ significantly, which proves that building a representative global test is difficult. Most often, local tests were used to determine emission and fuel consumption indicators [59–61]. The analysis of the research methods and results of these works reveals very large differences in terms of cycles, e.g., research routes, equipment used and results obtained (Figure 10).

References	Test/Region	s [km]	t [s]	t_{bj} [%]	$v_{śr}$ [km/h]	$a_{śr}$ [m/s^2]
Chen et al. 2003	URB (Taiwan)	4.232	877	28	23.95	0.66
Tasi et al. 2005	KHM (Taiwan)	4.35	753	28	28.3	0.61
Tung et al. 2011	CECDC (Vietnam)	11.51	2061	8	21.7	0.46
Adak et al. 2016	Dhanbad (Indie)	12.998	1683	2.91	28.65	0.81
Seedam et al. 2017	Khon Kean (Tailand)	7.14	1279	20	no data	0.62
Mahesh et al. 2005	Chennai (India)	14	2296	26	no data	no data
Murena et al. 2019	Neapol (Italy)	18.9	2742	14.6	no data	no data
Koossalepeerom et al. 2019	Chennai (India)	4.887	775	26.73	30.76	0.65

Figure 10. Analysis of methods and research results included in the mentioned research works [46,51,52,54,55,57–59].

However, one of the few literature items describing emission tests in real operating conditions was based on measurements made using equipment (AVL M.O.V.E.) dedicated to passenger cars, the dimensions and weight of which make it impossible to test them on a smaller two-wheeled vehicle. The research was performed by scientists from the University of Graz [62,63] on a motorcycle with a displacement of 800 cm^3. The results obtained in real operating conditions differed significantly from those obtained in the WMTC homologation test.

The presented research in real operating conditions by scientists most often covers the analysis of one run. This is due to the individual nature of the RDE tests (congestion, changes in traffic lights, road incidents, etc.). The test results on the same route but at different times are averaged, then the average speeds and average accelerations are determined.

By summarizing the considerations related to current technical regulations, as well as the research achievements of other authors, it can be concluded that there is a need for the further development of research methods for the considered group of vehicles. The components of the causes and effects are shown in Figure 11. The authors are working intensively on developing a universal method for testing two-wheeled vehicles in a real environment, taking into account the latest achievements in PEMS equipment.

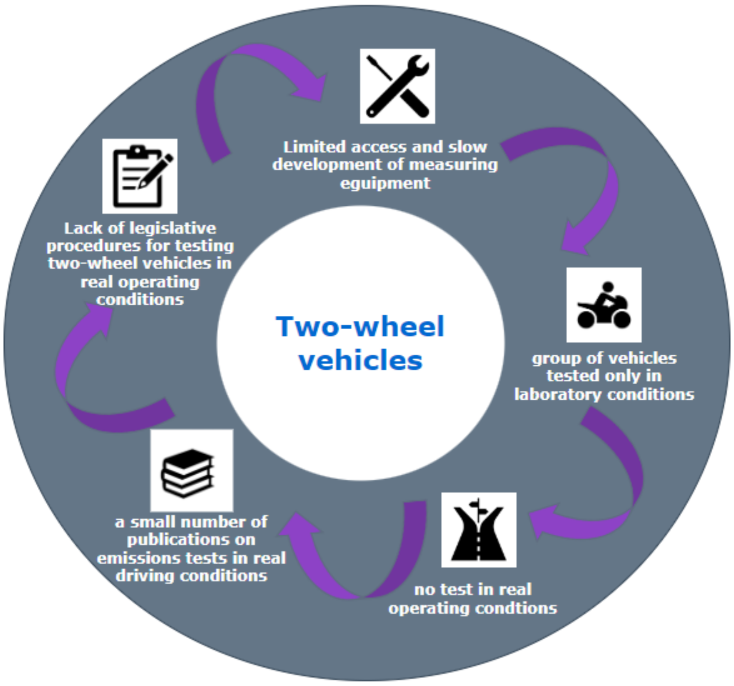

Figure 11. Article summary and cause-and-effect diagram of homologation regulations for urban two-wheeled vehicles.

7. Conclusions

- An extensive literature study and the cited examples of research on two-wheeled vehicles in real operating conditions allow us to formulate the statement that the works undertaken by the authors of this paper are few and are currently still in the initial stage of development.
- The initial stage of the development of scientific research is related to the lack of equipment on the market intended for testing two-wheeled vehicles. This is also related to limitations in the quantity and quality of regulations requiring such research and they are not provided for in future regulations.
- Progressive technological development and the miniaturization of measurement equipment now make it possible to perform RDE tests for two-wheeled vehicles. Undoubtedly, such research is fully justified in the context of gaining experience for future solutions for measuring emissions from two-wheeled vehicles.
- There are many literature items presenting specific solutions aimed at reducing emissions, often of a comparative nature (the use of different fuels or non-engine exhaust gas treatment systems). These publications include such solutions as: the development of an electronic fuel injection system [64], the modification of the catalytic coating of a three-function catalytic reactor [65] and the comparative analysis of the use of fuel with different sulfur contents [66]. Moreover, items such as [67–70] describe the research and analysis of particulate emissions unregulated until 2020 and the introduction of the Euro 5 standard. These measurements were performed in laboratory conditions on various motorcycles and mopeds, using various research methods.
- Based on the literature analysis, it should be noted that there are no existing studies and publications containing a comprehensive description of the problem of toxic exhaust emissions from engines of urban two-wheeled vehicles in real operating conditions.

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