

Представлено результати дослідження зміни зведених масових експлуатаційних викидів забруднювальних речовин дорожніми транспортними засобами європейських екологічних класів від «Євро-0» до «Євро-6» всіх основних категорій. Охоплено легкові автомобілі, легкий комерційний транспорт, вантажні автомобілі, автобуси, та транспортні засоби категорії L (мопеди та мотоцикли). Зведені масові викиди забруднювальних речовин визначено в єдиній системі координат як від традиційного транспорту з двигунами внутрішнього згоряння, так і від електромобілів. Враховано викиди в атмосферне повітря продукти зносу пневматичних шин, дорожнього покриття та елементів гальмівних систем. В методиці розрахунку зведених масових експлуатаційних викидів враховано 64 види найбільш вагомих забруднювальних речовин, об'єднані в 8 умовних груп. Охоплено монооксид вуглецю, діоксид вуглецю, оксиди азоту, закис азоту, аміак, легкі вуглеводні, альдегіди, кетони, ароматичні вуглеводні, поліциклічні ароматичні вуглеводні, стійкі органічні забруднювачі, частинки, з'єднання сірки, метали та з'єднання металів. Враховано викиди частинок у складі відпрацьованих газів двигунів, продуктів зношування пневматичних шин, дорожнього покриття і гальм. З викидами частинок враховано як елементарний вуглець, так і окремо адсорбовані і абсорбовані канцерогени в їх складі. Усереднені експлуатаційні масові викиди забруднювальних речовин визначено з використанням методики Європейського агентства навколишнього середовища. Для кожної з 64-х забруднювальних речовин запропоновано коефіцієнт відносної шкідливості (агресивності), визначений на основі наявних даних щодо граничнодопустимих концентрацій речовин в атмосферному повітрі, для використання розрахунків масових викидів, зведених до монооксиду вуглецю. Встановлено, що: зведені викиди легковими автомобілями рівня «Євро-5»–«Євро-6» з бензиновими двигунами лише в 4 рази перевищують зведені викиди електромобілів; зведені викиди легкових автомобілів рівня «Євро-6++» з дизелями в два рази є більшими, ніж від легкових автомобілів рівня «Євро-5»–«Євро-6» з бензиновими двигунами; зведені викиди вантажних автомобілів та міських автобусів рівня «Євро-6» в середньому лише в 5 разів більше зведених викидів електричного транспорту; зведені викиди транспортними засобами категорії L (мопедами та мотоциклами) можуть істотно перевищувати викиди легкових автомобілів та навіть автобусів і вантажівок. Отримані результати можуть бути основою розроблення екологічної класифікації та маркування дорожніх транспортних засобів (ДТЗ). Це надає можливості запровадження фіскальних та інших механізмів стимулювання використання екологічно більш сприятливих видів транспортних засобів відповідно до практики країн-членів ЄС з використанням принципу «забруднювач платить». Запропоновано загальні принципи запровадження універсальної системи маркування рівня екологічної небезпеки ДТЗ. Дискретні базові рівні екологічної небезпеки запропоновано встановлювати з кроком збільшення сумарних зведених викидів в 1,259 рази, що дорівнює збільшенню умовної енергетичної величини в  $10^{0.1}$  разів, тобто на 1 дБ

**Ключові слова:** дорожні транспортні засоби, викиди забруднювальних речовин, маркування рівня екологічної небезпеки

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# RESULTS OF RESEARCH OF THE REDUCED EMISSIONS OF POLLUTANTS BY ROAD VEHICLES OF VARIOUS ENVIRONMENTAL CLASSES "EURO" AS THE BASIS OF ENVIRONMENTAL HAZARD LABELING

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## 1. Introduction

Reducing the negative impact of road transport on the environment is an important issue and requires the development and implementation of more effective technical and fiscal regulation measures.

Different and mainly inconsistent "coordinate systems" of such regulation are used in different regions of the world. For example, in the EU Member States and the US, different lists of standardized pollutants, their

maximum permissible values, and the test procedures to determine them during certification are used. Diesel and gasoline-powered vehicles of the same environmental level "Euro", are not identical in terms of both the pollutant emission limit values (norms) and their average operational values. Also, the authorized bodies are in the constant process of improvement of technical regulation. They are introducing time to time serious changes in the procedures and types of testing and expanding the list of standardized pollutants as well.

However, regulatory measures require certain resources, and, in order to be effective, ideally regulation should be proportional to the magnitude of the aggregate negative impact of the road vehicle on the environment. Integral assessment of this impact can be summarized, using reduced to carbon monoxide emissions of different pollutants, taking into account its relative toxicity.

The study of the reduced emissions of pollutants by vehicles of different environmental classes “Euro”, as well as electric vehicles, in a common “coordinate system”, identified by a broad list of major pollutants, provides the basis for improving technical and fiscal regulation in this field.

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## 2. Literature review and problem statement

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In [1], the analysis of the global experience of technical and fiscal regulation of CO<sub>2</sub> emissions and energy efficiency of road transport is done, and detailed proposals are made for its further dissemination. The need for state regulation in this area is shown. However, insufficient attention has been paid to the aspect of so-called local pollution by toxic substances, which should be an integral part. A systematic review of emission control standards is given, in particular, in [2], which proves the incompatibility of standards and approaches of different regions of the world. But this problem needs to be addressed.

Sources [3–6] provide an analysis of the fiscal arrangements currently in place in this area, showing their wide diversity and practical incompatibility, which is also the barrier to the development of international trade. In more than half of European countries, taxes on the acquisition or ownership of vehicles are directly or indirectly differentiated depending on the environmental class of a vehicle [3]. The EU Member States have used a level of the standard for toxic pollutant emissions, CO<sub>2</sub> emissions, fuel economy indicators, and the age of a vehicle. Also, an engine capacity, power, fuel type, vehicle weight, number of axles and more are used in different combinations. Almost all countries have used an individual system of differentiated taxation and incompatible sets of indicators at its core [3].

A critical analysis of regulatory systems based mainly on CO<sub>2</sub> emissions and fuel efficiency is given in [4], and a brief overview of the standards is given in [5]. Certified indicators of CO<sub>2</sub> emission and fuel economy are increasingly not only not reflecting real CO<sub>2</sub> emission and energy consumption in operation but are also more likely to mislead consumers and public authorities. Relying solely on CO<sub>2</sub> emissions is also ineffective because of electric car technology, where CO<sub>2</sub> emissions during energy generation need to be considered separately and depend on the structure of the country's electricity generation. However, the use of differentiated taxes and discounts is considered an effective tool [6].

In [7] it was proposed to introduce the energy efficiency labeling of road vehicles at the same time, that is, within a single system, with the labeling of the current level of the environmental hazard

Other measures that will stimulate investment in a quality renewal of the fleet and new technologies, and will force usage of vehicles that causes minimal damage to public health in places of high concentration of people, are highlighted in [8–12]. The position of the European Automobile Manufacturers Association (ACEA), formulated in [8], and contains the schemes, principles, approaches, and criteria for

the implementation of low emission zones (“green zones”). At the same time, recommendation [8] to use the environmental level “Euro” directly is contrary to one of the declared basic principles in terms of proportionality of measures, since it does not take into account technology and actual level of pollution.

European cities in 2018 already had a total of 260 “green zones”, a detailed analysis of the implementation experience of which is given in [9]. The access to green zones in many cities is differentiated not only regarding the “Euro” class, but also the type of fuel, technology, the mass of a vehicle, etc. The Brussels experience in this area is given in [10] and the expected results in [11], which fully prove the feasibility of introducing green zones. But in general, different cities use different and incompatible approaches, which is a problem. The problem of regulating the admission of cars with foreign registration is also mentioned.

[12] provides an in-depth analysis of international experience and proposals for the implementation of vehicle environmental class and energy efficiency labeling, including in the context of necessary organizational measures. Noise level and issues of recycling and reuse of structural materials are also taken into account. But the question of regulating vehicles imported from the North American market remains open.

In general, the world experience testifies to the feasibility of introducing so-called green zones in cities. Proposals for the introduction of CO<sub>2</sub> emission regulation and energy consumption of new passenger cars and light commercial transport are given in particular in [13].

The incompatibility of standards and approaches applied by different countries in different regions of the world, where cars, in particular, are manufactured, requires the creation of an appropriate methodological framework to overcome these barriers and introduce more effective regulatory instruments on a single basis.

It seems appropriate to consider the possibility of refraining from current practice (and legal requirements) of setting a minimum obligatory level of environmental standards “Euro” for road vehicles at the time of import and first state registration. It may be more effective to identify and label the vehicle's current environmental hazard level, taking into account age, technical condition, and other factors. At the same time, a fair fiscal policy should be introduced in line with the practice of EU Member States with differentiation depending on the current environmental hazard and energy efficiency levels and other factors by taxing the purchase and ownership of the vehicle.

Differentiated restrictions and preferences on access to infrastructure using the “polluter pays” principle should also be introduced. It means the basic possibility and cost of access to the central parts of cities and green areas defined by local communities, the cost of parking, access to separate lanes of public transport, etc.

An effective system for marking the level of environmental hazard of road vehicles cannot be based directly on the indication of the environmental standards “Euro” to which the vehicle responded at the time of production, because:

1) vehicles within the same level of “Euro” norms that use different types of fuels differ significantly in the level of toxic pollutant emissions;

2) the ordinal figures of the “Euro” norms characterize only the successive stages of implementation of increasingly

stringent environmental requirements, but not the relative change in the emission limit values;

3) emission limit values according to the “Euro” standards, which are confirmed in artificial laboratory conditions, and emissions in actual operation, as a rule, differ substantially in the direction of increasing the latter;

4) the efficiency of engine toxicity reduction systems decreases significantly over time [14, 15], especially if these systems have already spent their resource or are technically defective;

5) the vehicle can be converted into service for use, for example, gaseous fuel, which can alter the combined emissions of pollutants towards a significant increase compared to the base type of vehicle. It is since manufacturers fine-tune the vehicle’s design to meet strict environmental standards for specific fuels. Changing the type of fuel requires additional complex R&D work to ensure compliance with environmental standards. But this requires high-tech and high-cost equipment, which is not available if such conversion is carried out in operation;

6) vehicles are imported into Ukraine from different markets, where virtually incompatible technical regulation systems operate (the most striking example is cars imported from the USA that do not have European type approval);

7) in the case of trucks and buses, gross emissions of pollutants and, consequently, environmental damage are a pronounced function of not only the specific emissions per useful engine work unit (in g/kW×h) but also of transport work (in tkm), and, consequently engine power;

8) Electric vehicles are also a source of pollutant emissions, mainly due to the wear of pneumatic tires, road pavements, and brakes, and it is advisable to treat them with “traditional” vehicles in a common coordinate system.

Therefore, it seems appropriate to design a solution of the above mentioned and highlighted in [1–13] problems on a fundamentally new basis, considering a system of classification and labeling of vehicle’s environmental hazards. It should be based on the aggregate and reduced total emissions of main pollutants per unit of vehicle’s mileage and transport work, taking into account the type of fuel.

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### 3. The aim and objectives of the study

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The purpose of the study is to investigate the aggregate and reduced average operational mass emissions of pollutants by road vehicles of European environmental classes from “Euro-0” to “Euro-6”, and electric vehicles, in a common coordinate system, as a basis for further development of the system of vehicle’s environmental hazard labeling.

To achieve this goal, the following tasks were set:

- to determine the coefficients of relative toxicity for the most significant and currently investigated pollutants emitted by road transport, for calculation of aggregate mass emissions reduced to carbon monoxide;

- to determine in the unified (common) system of coordinates the aggregate and reduced average operational mass emissions of pollutants both from traditional transport with internal combustion engines and from electric vehicles;

- to analyze the nature of the evolution of the reduced emissions of vehicles of different technological levels, including their comparison and taking into account the type of fuel (energy);

- to develop the general principles for the introduction of the universal system of road vehicle’s environmental hazard labeling.

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### 4. Method of calculation of the combined emissions of pollutants

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The cumulative combined emissions of  $\Sigma\text{CO}_{\text{add}}$  (g/km) of major pollutants are calculated based on their relative hazard ( $R_i$ ) relative to carbon monoxide according to the approach outlined in [16], which has become widely used:

$$\Sigma\text{CO}_{\text{add}} = \sum_{i=1}^n m(i) \times R_i(i), \quad (1)$$

where:

$\Sigma\text{CO}_{\text{add}}$  is the total reduced emissions of the main pollutants (in conventional grams of carbon monoxide (CO), the toxicity (aggressiveness) of which is taken per unit, g/km;

$m(i)$  is the mass emissions of the  $i$ -th pollutant, g/km;

$R_i(i)$  is the coefficient of the relative toxicity of the  $i$ -th pollutant (relative to carbon monoxide (CO));

$n$  is the total number of pollutant species taken into account.

It is advisable to calculate mass emissions per unit of the mileage of a wide range of pollutants that are close to actual operational emissions, as opposed to the emission limit values under the “Euro” standards. Such emissions can be calculated on the basis of, for example, the methodology of the European Environment Agency [17, 18], which is used in many EU countries for the inventory of pollutants by road transport.

Appropriate methodologies can also be used to calculate vehicle emissions from the North American market and other non-European approved markets. This study presents the results of calculations using the formula (1) of the reduced emissions using the emissions of individual pollutants set in [17, 18] and the coefficients of relative toxicity set out in Section 5 below.

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### 5. Establishment of relative toxicity coefficients of main known pollutants

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In this work, from the list of contaminants taken into account in [17, 18], 64 pollutants are used, which are the most influential in terms of determining the total toxicity of emissions.

The coefficients of the relative toxicity of pollutants are established on the basis of the analysis of available data [19–25] regarding the maximum permissible concentrations of pollutants in the atmospheric air of settlements and in the air of the work area, as well as data [16].

Accepted by the ratio of the maximum permissible concentration of carbon monoxide to the permissible concentrations of the 64 major pollutants, the values of the coefficients of relative toxicity ( $R_i$ ) are given in Table 1. For ease of use, they are divided into eight groups.

Table 1

Coefficients of relative to carbon monoxide toxicity ( $R_t$ ) of 64 major known pollutants

Group	Chemical formula or denotation	Pollutant title	Rt
1	2	3	4
Group I (the bulk of the exhaust emissions)	CO	carbon monoxide	1
	CO <sub>2</sub>	carbon dioxide	0.0022
	NO <sub>x</sub>	oxides of nitrogen	75
	N <sub>2</sub> O	nitrous oxide	188
	NH <sub>3</sub>	ammonia	75
	"LHC"	"light hydrocarbons"	3.16
Group II (aldehydes)	CH <sub>2</sub> O/H <sub>2</sub> CO	formaldehyde	1,000
	C <sub>2</sub> H <sub>4</sub> O/CH <sub>3</sub> CHO	acetaldehyde	300
	C <sub>3</sub> H <sub>4</sub> O/CH <sub>2</sub> =CHCHO	acrolein	100
	C <sub>7</sub> H <sub>6</sub> O/C <sub>6</sub> H <sub>5</sub> CHO	benzaldehyde	50
	C <sub>4</sub> H <sub>6</sub> O/CH <sub>3</sub> CH=CHCHO	crotonaldehyde	5
	C <sub>4</sub> H <sub>6</sub> O/CH <sub>2</sub> =C(CH <sub>3</sub> )	methacrolein	5
	C <sub>4</sub> H <sub>8</sub> O/CH <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CHO	butyraldehyde	5
	C <sub>4</sub> H <sub>8</sub> O/(CH <sub>3</sub> ) <sub>2</sub> CHCHO	isobutanaldehyde	5
	C <sub>3</sub> H <sub>6</sub> O/CH <sub>3</sub> CH <sub>2</sub> CHO	propionaldehyde	5
	C <sub>6</sub> H <sub>12</sub> O/CH <sub>3</sub> (CH <sub>2</sub> ) <sub>4</sub> CHO	hexanal	5
	C <sub>5</sub> H <sub>10</sub> O/CH <sub>3</sub> (CH <sub>2</sub> )	i-valeraldehyde	5
	C <sub>5</sub> H <sub>10</sub> O/CH <sub>3</sub> (CH <sub>2</sub> )	valeraldehyde	5
	C <sub>8</sub> H <sub>8</sub> O/CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> CHO	o-tolualdehyde	5
	C <sub>8</sub> H <sub>8</sub> O/CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> CHO	m-tolualdehyde	5
C <sub>8</sub> H <sub>8</sub> O/CH <sub>3</sub> C <sub>6</sub> H <sub>4</sub> CHO	p-tolualdehyde	5	
Group III (ketones)	C <sub>3</sub> H <sub>6</sub> O/CH <sub>3</sub> -CO-CH <sub>3</sub>	acetone	8.57
	C <sub>4</sub> H <sub>8</sub> O/CH <sub>3</sub> -C-CH <sub>2</sub> -CH <sub>3</sub>	methylethylketone	5
Group IV (aromatics)	C <sub>7</sub> H <sub>8</sub> /C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub>	toluene	5
	C <sub>8</sub> H <sub>10</sub> /C <sub>6</sub> H <sub>5</sub> C <sub>2</sub> H <sub>5</sub>	ethylbenzene	150
	C <sub>8</sub> H <sub>10</sub> /C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub>	m, p-xylene	15
	C <sub>8</sub> H <sub>10</sub> /C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub>	o-xylene	15
	C <sub>9</sub> H <sub>12</sub> /C <sub>6</sub> H <sub>3</sub> (CH <sub>3</sub> ) <sub>3</sub>	1,2,3 trimethylbenzene	100
	C <sub>9</sub> H <sub>12</sub> /C <sub>6</sub> H <sub>3</sub> (CH <sub>3</sub> ) <sub>3</sub> (asym.)	1,2,4 trimethylbenzene	200
	C <sub>9</sub> H <sub>12</sub> /C <sub>6</sub> H <sub>3</sub> (CH <sub>3</sub> ) <sub>3</sub> (sym.)	1,3,5 trimethylbenzene	300
	C <sub>8</sub> H <sub>8</sub> /C <sub>6</sub> H <sub>5</sub> CH=CH <sub>2</sub>	styrene	1,500
	C <sub>6</sub> H <sub>6</sub>	benzene	30
	C <sub>9</sub>	C9	5
	C <sub>10</sub>	C10	10
C>13	C>13	20	
Group V (PAHs & POPs)	C <sub>22</sub> H <sub>12</sub> /C <sub>22</sub> H <sub>10</sub> O <sub>2</sub> /ID(1,2,3,cd)P	indeno(1,2,3-cd)pyrene	1,500,000
	C <sub>20</sub> H <sub>12</sub> /C <sub>20</sub> H <sub>10</sub> O <sub>2</sub> /B(k)F	benzo(k)fluoranthene	3,000,000
	C <sub>20</sub> H <sub>12</sub> /B(b)F	benzo(b)fluoranthene	3,000,000
	C <sub>20</sub> H <sub>12</sub> /B(a)P	benzo(a)pyrene	3,000,000
Group VI (particulate matter (PM))	"BC"	black carbon	41.5
	PM <sub>2.5</sub> petrol	PM (<2.5 μm) originated from petrol engines exhaust gases	300
	PM <sub>2.5</sub> diesel	PM (<2.5 μm) originated from diesel engines exhaust gases	200
	PM <sub>2.5</sub> tire	PM (<2.5 μm) originated from pneumatic tire wear products	100
	PM <sub>2.5</sub> brake	PM (<2.5 μm) originated from brake wear products	150
	PM <sub>2.5</sub> road	PM (<2.5 μm) originated from road surface wear products	50
Group VI (sulfur compounds)	SO <sub>4</sub> <sup>--</sup>	sulfates	30
	SO <sub>2</sub>	sulfur dioxide	22

1	2	3	4
Group VIII (metals and its compounds (MS))	Cd	cadmium	2,000
	Cu	copper	40
	Cr	chromium	1,000
	Ni	nickel	4,000
	Se	selenium	200
	Zn	zinc	40
	Hg	mercury	4,000
	As	arsenic	2,000
	Fe	iron	75
	Mg <sup>2+</sup>	magnesium ion	60
	Mo	molybdenum	150
	Sb	antimony	150
	Si	silicon	60
	Sn	tin	150
	Ti	titanium	20
	Pb	lead	400
C <sub>8</sub> H <sub>20</sub> Pb	tetraethyllead	224,000	

The main part of the gross mass emissions from the exhaust gases of internal combustion engines is in the group I of gaseous components, which also includes CO<sub>2</sub>. Despite the very low (0.0022) relative toxicity factor of CO<sub>2</sub> (which is 454.5 times less than CO), its high gross emissions, which are the lion's share of fuel combustion products, lead to a significant toxic effect in large cities. The CO<sub>2</sub> contribution to the reduced emissions (that is, calculated from formula (1)) is 0.2–0.9 % for diesel and 0.8–2.3 % for gasoline engines (higher values naturally correspond to a higher environmental class of vehicle).

Nitrogen oxides (NO<sub>x</sub>) provide a significant contribution to the combined toxicity, which has decreased from 35 % to 24 % for gasoline engines and from 48 % to 30 % for diesel cars by changing environmental standards from “Euro-2” to “Euro-6”. The NO<sub>x</sub> “contribution” to reduced emissions of diesel-powered city buses has decreased accordingly from 79 % to 31 %.

The emissions of aldehydes and ketones together with the emissions of aromatic hydrocarbons (respectively, Groups II, III, and IV) make a significant (2.9–4.8 % for diesel and 19–26 % for gasoline engines) contribution to the total toxicity.

Particularly dangerous are the emissions of polycyclic aromatic hydrocarbons and persistent organic pollutants (Group V). Their “contribution” for gasoline engines increases from 6 % for “Euro-2” to 18 % for “Euro-6”, and for diesel engines from 4–16 % for “Euro-2” to 27–42 % for “Euro-6”. Smaller values correspond here to passenger cars engines.

Particulate matter emissions (Group VI) from various sources, especially from diesel (up to 10 % for “Euro-2”, for example), also contribute significantly to the total toxicity.

Emissions of sulfur compounds (Group VII) and metals (Group VIII) do not have a decisive effect (up to 0.1 % of the contribution) but are essential methodologically and takes into account acid precipitation.

In addition, the pollutant emissions of Group VI, VII, VIII, and V with pneumatic tire, road pavement and brake wear products make an essential contribution to the overall toxicity of high environmental classes (“Euro-5” and “Euro-6”) vehicles (up to 16–25 %). It also takes into consideration emissions from electric vehicles that are actually not zero-emission vehicles, as previously thought.

Thus, the proposed list of major pollutants makes it possible to objectively compare the total toxicity of vehicles of different technological levels using various energy sources.

## 6. Results of the calculation of reduced emissions of pollutants by vehicles of different environmental classes “Euro” and electric vehicles

The results of the calculations according to formula (1) and based on the accepted values of relative toxicity coefficients of main known pollutants are presented in Fig. 1–6.

The following abbreviations for types of vehicles and fuels are used in the graphic materials:

- “E0”, “E1” and beyond are respectively the environmental levels of “Euro-0”, “Euro-1” and further for passenger cars and light commercial transport (for simplicity, only Arabic numerals are used to indicate the environmental level of all type of vehicles);
- “PC” is passenger cars);
- “EV” is electric vehicles;
- “EV(R)” is electric vehicles with clean recuperation (that is, electric vehicles of next-generation with close to 100 % utilization of the energy recovery system during braking;
- “LDV” is light-duty vehicles (light lorry and commercial vehicles);
- “HDV” is heavy-duty vehicles;
- “UB” is urban buses (city buses of large capacity);
- “L” is vehicles of category L (mopeds and motorcycles);
- “P” is petrol (gasoline);
- “D” is diesel oil.

Fig. 1, 2 summarizes the reduced emissions of pollutants  $\Sigma CO_{add}$  (in g/km) of relatively new (within the first 30–60 thousand km) by passenger cars, depending on the environmental class “Euro” and of electric vehicles as well.

Fig. 3–6 summarizes the reduced emissions of pollutants correspondingly of new light commercial vehicles, L-category vehicles, trucks, and buses (in g/km), as well as per unit of full mass (in g/tkm).



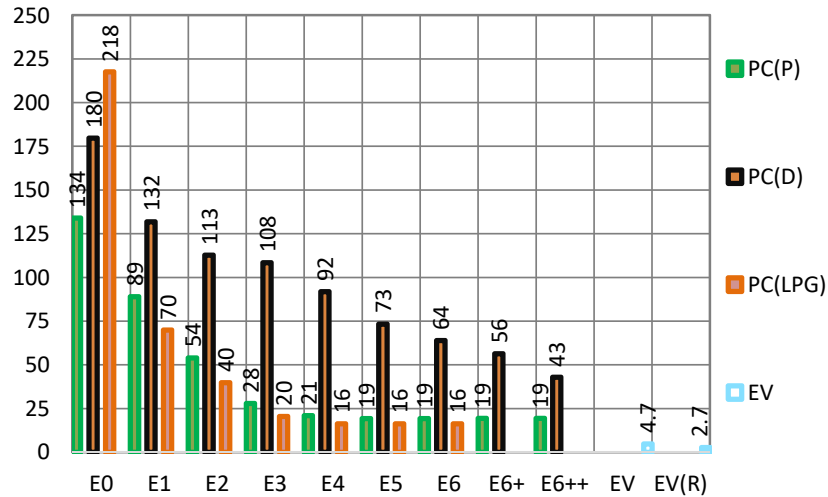


Fig. 1. Total average emissions reduced to CO (g/km) by “Euro-0”–“Euro-6” petrol-powered (PC(P)), diesel-powered (PC(D)), and LPG-powered (PC(LPG)) passenger cars, as well as modern (EV) and future EV(R) electrical vehicles

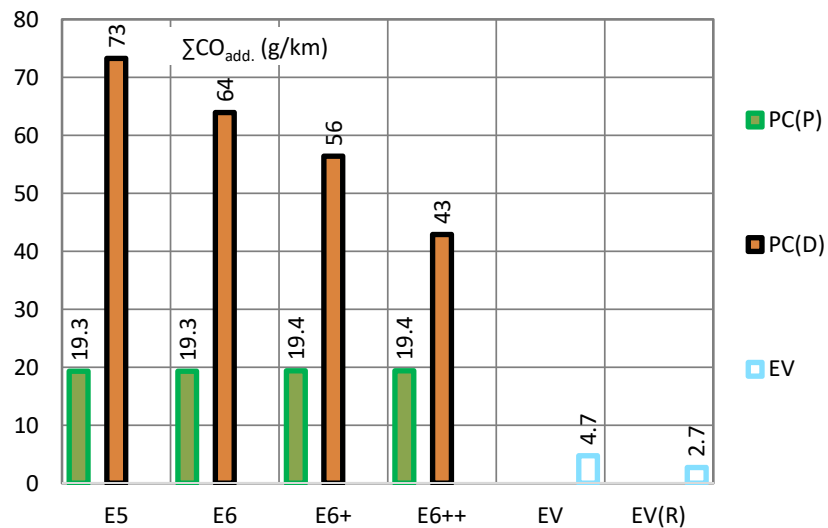


Fig. 2. Total average emissions reduced to CO (g/km) by passenger cars of “Euro-5” and “Euro-6” levels (and “Euro-6+”, “Euro-6++” equipped with diesel engines) in comparison with electric vehicles (EV)

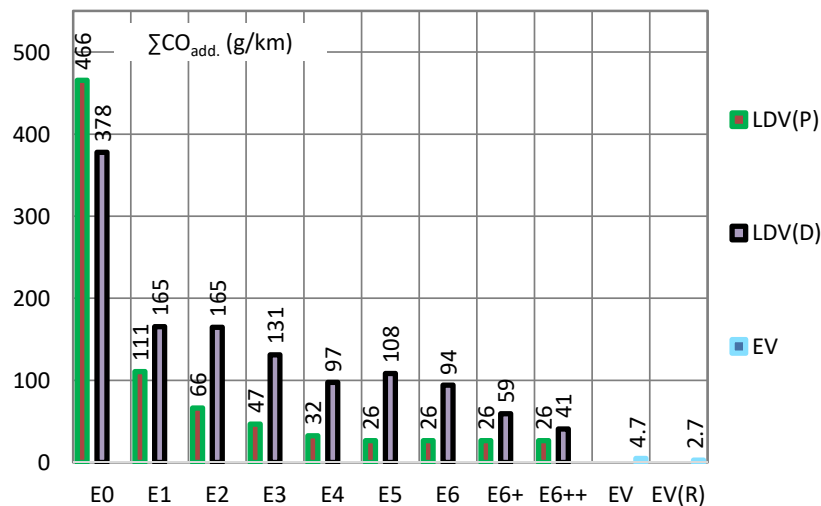


Fig. 3. Total average emissions reduced to CO (g/km) by “Euro-0”–“Euro-6” petrol-powered (LDV(P)) and diesel-powered (LDV (D)) light-duty vehicles as well as electric vehicles (EV)

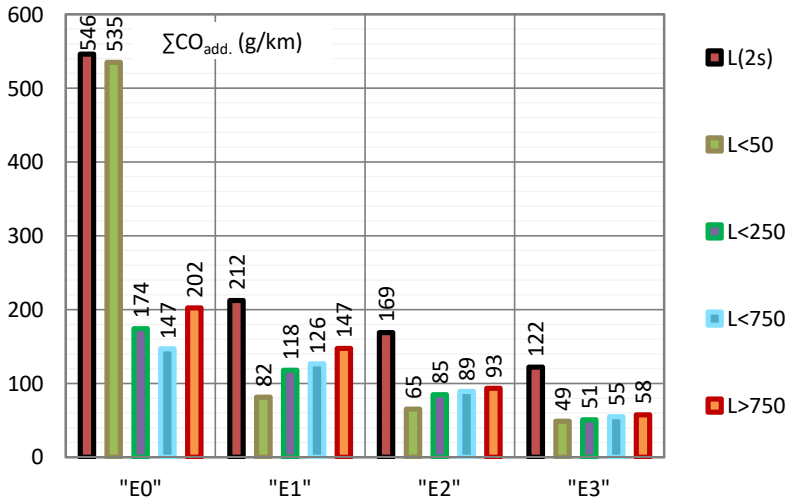


Fig. 4. Total average emissions reduced to CO (g/km) by petrol-powered mopeds and motorcycles of different range of four-stroke engine volume (cub/cm) and two-stroke L(2s) engines

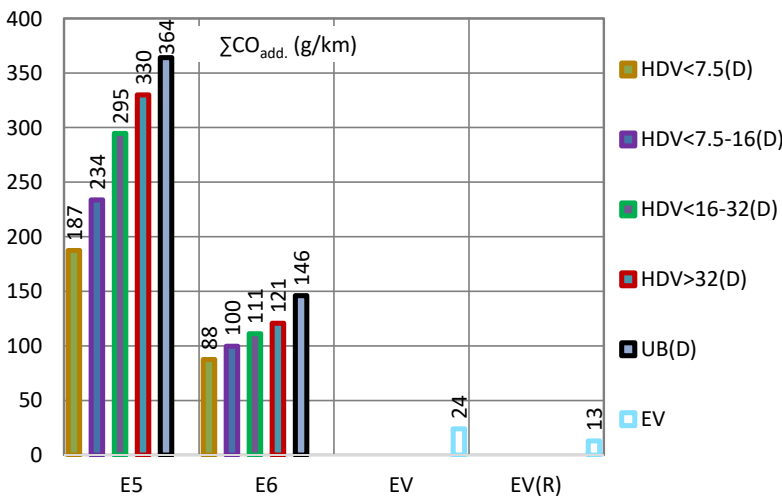


Fig. 5. Total average emissions reduced to CO (g/km) by "Euro-5" and "Euro-6" diesel-powered heavy-duty vehicles (HDV) of different full mass range and urban buses (UB) in comparison with electric vehicles (EV)

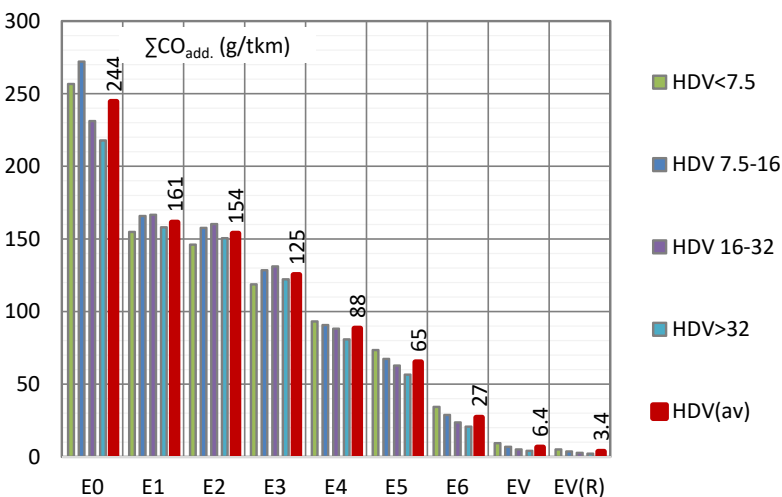


Fig. 6. Total average emissions reduced to CO (g/tkm) by "Euro-0"-"Euro-6" diesel-powered heavy-duty vehicles (HDV) and electrical vehicles (EV) of different full weight as well as average values (HDV(av))

Gross pollutant emissions by commercial transport are also largely a function of mass (Fig. 5), respectively, of transport work, which should be taken into account in the same coordinate system. The reduction of specific emissions neither to the unit of transport work nor to the full mass of the vehicle makes it possible to do so in a practical way. The reduction of the specific emissions, calculated based on the methodology of the European Environment Agency [17] (many countries in the world recognize that), to the square root of the full mass of the vehicle gives quite satisfactory results (Fig. 6).

### 7. Analysis of the reduced emissions of vehicles of different technological level

Total reduced emissions of modern "Euro-5" and "Euro-6" passenger cars with gasoline engines are only four times greater than the combined emissions of current electric vehicles (it is assumed that the latter consist of tires, road pavements and brakes wearing products). The combined emissions of "Euro-6++" cars with diesel engines are twice as high as those of "Euro-5" and "Euro-6" cars with gasoline engines (Fig. 2).

The most significant progress in recent years in reducing toxic emissions is demonstrated by heavy commercial transport. Modern "Euro-6" trucks and city buses emit, on average, only five times more combined emissions than electric transport (Fig. 5). Electric vehicle emissions are presented in a somewhat simplified form according to the data [18] (they must also be further differentiated by vehicle weight and wheel formula).

In this case, the emissions of vehicles of category L (Fig. 3) can significantly exceed the emissions of cars and even buses and trucks.

### 8. Proposals for general principles for the introduction of the universal system of vehicle's environmental hazard labeling

The results obtained allow us to propose a comprehensive, convenient, and efficient system of classification of baseline environmental hazard levels (EHL) and appropriate labeling of vehicles of different categories.

Fiscal and other regulatory measures should be tied to the amount of damage caused by air pollution by the vehicle. From the point of view of practical implementation, including management, of these measures, it seems appropriate to use discrete baseline levels of environmental hazard with an incremental aggregate emission increase by 1.259 times.

Such a step in 1.259 times has discovered as optimal and best among all other options

in terms of coverage in the same system of both electric vehicles and obsolete vehicles. This, from one point of view, also provides the minimum possible total number of steps for its practical establishment. From another point of view, this allows the vehicles of different technological levels to be sufficiently differentiated for practice, including by providing reserve levels for differentiating and stimulating the introduction of subsequent generations of vehicles.

Vehicles with new promising internal combustion engines, hybrids, hydrogen technologies, and others, as they will be approximated by the total reduced emissions to electric vehicles, are considered. It is indicative that the optimal step is 1.259 times equal to an increase in the specific energy value of  $10^{0.1}$  times, that is, 1 dB. Thus, the proposed universal classification of environmental hazard is a geometric progression with a denominator of 1 dB, which has become widely used in various fields of science and technology (Bell expresses the ratio of two values of energy by the decimal logarithm of this ratio).

At the same time, precisely the value of reduced specific emissions in g/km or g/tkm can also be used to indicate the degree of environmental hazard, in addition to calculations with the fiscal measures of state regulation in proportion to the environmental damage.

For the calculation of gross reduced emissions in g/km based on the value in g/tkm for heavy-duty vehicles, the full design weight of the vehicle shall be used. The specific value of the reduced emissions in g/tkm is multiplied by the total design weight of the vehicle in tons, thus obtaining the conditional gross emissions in g/km, which can be accepted for calculation of the environmental damage.

The proposed baseline environmental hazard levels also seem appropriate to merge into several (optimally up to six) groups (or zones on other words) by geometric progression with a denominator equal to 2. Thus, each such group (zone) contains three environmental hazards. The combined emissions for each level in the adjacent groups differ by two times ( $1,259 \times 1,259 \times 1,259 \approx 2$ ). It seems to be the most convenient for their further practical use for the introduction of differentiated ecological (or "green") zones with the appropriate color marking by local communities.

Local communities thus receive the possibility of differentiated implementation in the central and other urban areas of the above environmental zones in a unified manner. The proposed system, depending on the environmental situation in a particular area of the city, provides the possibility of introducing different zones of restricted or paid access to vehicles that do not meet the established requirements.

Therefore, each vehicle must be assigned a current level of environmental hazard and a corresponding color-coded group. The order number and the corresponding color define the area to which (and, accordingly, more "dirty" areas) vehicles are granted unlimited access.

The proposed here system of environmental hazard levels (EHL) combines in common (unified) coordinates of vehicles from different markets with practically incompatible environmental standards such as "Euro" standards and North American market requirements (but this is a subject of separate publication).

Another advantage is the ability to account for the increase in emissions with the mileage and lifetime of vehicles. There is also the possibility of stimulating to equip vehicles (including those that have been in operation for a long time) with additional emission control means (so-called

retrofitting). For example, diesel engines can be equipped with particulate filters. Or, it can be stimulation of periodic scheduled replacement of the replacement elements of the exhaust gas neutralization systems (catalytic converters, first of all), etc.

## 9. Discussion of results of studying the reduced emissions of vehicles of different technological levels

The coefficients of relative to carbon monoxide toxicity (Table 1), established for an extensive list of the most essential and investigated pollutants to date, allow an objective assessment of the total toxicity of vehicles of different technological levels.

Despite the very low (0.0022) coefficient of the relative toxicity of CO<sub>2</sub> (which is 454.5 times less than for CO), its high gross emissions lead to a significant toxic effect in large cities. The CO<sub>2</sub> contribution to the reduced emissions is 0.2–0.9 % for diesel and 0.8–2.3 % for gasoline engines respectively.

The contribution to the combined toxicity of nitrogen oxides (NO<sub>x</sub>) has decreased substantially with the introduction of more stringent "Euro" environmental standards but is still a significant component. For "Euro-6" cars, NO<sub>x</sub> contribution is 24 % for gasoline-powered vehicles and about 30 % for diesel-powered vehicles.

Emissions of aldehydes and ketones, together with emissions of aromatic hydrocarbons, make a significant contribution (2.9–4.8 % for diesel and 19–26 % for gasoline engines) to the total toxicity.

Particularly dangerous are the emissions of polycyclic aromatic hydrocarbons and persistent organic pollutants. On the contrary, their "contribution" increases with the introduction of more stringent environmental standards "Euro" and is up to 18 % for vehicles of the "Euro-6" level with gasoline engines and up to 42 % for vehicles with diesel engines.

According to the results of the study, pollutant emissions from the tire, road, and brake wearing products make an essential contribution (up to 16–25 %) to the overall toxicity of vehicles of high environmental classes ("Euro-5" and "Euro-6"). It also takes into account emissions from electric vehicles that actually are not zero-emission vehicles, as previously thought.

Reduced mass emissions of pollutants of road vehicles of all major categories both with internal combustion engines of different technological levels and electric vehicles are defined in a common coordinate system.

The analysis of obtained in this study values of the reduced emissions of vehicles of different technological levels (Fig. 1–6) gives a comprehensive representation. It is crucial that defined as the lower limit of theoretically possible reduction of reduced emission, as the estimation of the upper limit of vehicles of outdated technological levels (Fig. 1–6).

At the same time, the results correspond to the values of emissions [17, 18] obtained for relatively new vehicles, that is, within the initial range of 30–60 thousand kilometers. According to the results of a large-scale study [14, 15], the emissions of vehicles that have been in operation for a considerable time can significantly exceed these values.

As the age of the vehicle grows, and the emission control system resource is exhausted (depleted), its reduced emissions will increase. It should be a subject of additional research and the main direction of development of the meth-



odology of calculation of reduced emissions of pollutants of vehicles in operation.

The system of vehicle's environmental hazard level (EHL) labeling is proposed to be arranged proportionally to the level of ecological damage caused by vehicles through ingredient pollution in places of mass concentration of people. This damage is estimated on the basis of the reduced mass operational emissions of pollutants by vehicles of different technological levels.

It is proposed to set discrete baseline levels of environmental hazard with the step of increasing total reduced emissions by 1.259 times, which is equal to an increase of  $10^{0.1}$  times the specific energy value, that is, by 1 dB. It is a universal approach that has become widely used in various fields of science and technology. It is proposed to integrate baseline environmental hazards into several (optimally – up to six) groups (zones) by geometrical progression with a denominator of 2. It seems to be the most convenient for their future practical use for introducing differentiated ecological zones with appropriate color-coding by local communities.

It provides the basis for the introduction of fiscal and other mechanisms to encourage the use of more environmentally friendly vehicles, in line with the practice of EU Member States, using the polluter pays principle.

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## 10. Conclusions

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1. The coefficients of relative toxicity for the 64 types of the most significant and investigated pollutants, sources of emissions of which are road transport, have been established. The list of contaminants taken into account allows for an objective assessment of the total toxicity of vehicles of different technological levels, including comparing vehicles with internal combustion engines using different types of fuel and electric vehicles.

2. Reduced mass emissions of pollutants, both from traditional vehicles with internal combustion engines and from electric vehicles, including products of wearing of a pneumatic tire, road pavement and brakes are defined in a common coordinate system. Reduced emissions reflect the average aggregate degree of damage that a vehicle causes to the environment through ingredient contamination in places of mass concentration of people.

The expediency of taking into account CO<sub>2</sub> not only as a greenhouse gas but also as a toxic pollutant has been established. The "contribution" of CO<sub>2</sub> to the reduced emissions

is 0.2–0.9 % for diesel and 0.8–2.3 % for gasoline engines. Nitrogen oxides (NO<sub>x</sub>) provide a significant contribution to the combined toxicity, which has decreased from 35 % to 24 % for gasoline engines and from 48 % to 30 % for diesel cars by changing environmental standards from "Euro-2" to "Euro-6". The average NO<sub>x</sub> "contribution" for diesel-powered city buses has decreased accordingly from 79 % to 31 %.

The emissions of aldehydes and ketones, together with emissions of aromatic hydrocarbons, make a significant (2.9–4.8 % for diesel and 19–26 % for gasoline engines) contribution to the total toxicity. The "contribution" of polycyclic aromatic hydrocarbons and persistent organic pollutants for gasoline engines increases from 6 % for "Euro-2" to 18 % for "Euro-6" and for diesel engines increases from 4–16 % for "Euro-2" to 27–42 % of "Euro-6" (lower values correspond to passenger car's engines). It demonstrates the need for tight controls on the quality of motor fuels.

Emissions of pollutants from a pneumatic tire, road pavement, and brake wearing products have been found as an essential contributor to the overall toxicity of vehicles of high ("Euro-5" and "Euro-6") environmental class (up to 16–25 %). Once again, it has been proven that electric cars are not zero-emission vehicles, as previously thought.

The emissions of the above-mentioned wearing products thus determine the lower limit (or theoretical potential) for further reduction of the reduced toxicity of internal combustion engines, that is, about 3–5 g/km sum of pollutants for passenger cars reduced to CO.

3. The analysis of reduced mass average operational emissions of pollutants by road vehicles of different technological levels is performed. It has discovered that:

- the reduced total mass emissions of passenger cars of level "Euro-5" and "Euro-6" with gasoline engines are only four times higher than the total emissions of electric cars;
- the reduced total mass emissions of "Euro-6++" passenger cars with diesel engines are twice as high as those of "Euro-5" and "Euro-6" cars with gasoline engines;
- the reduced total mass emissions of trucks and city buses of the "Euro-6" level are on average only five times more than the reduced emissions of electric transport;
- the reduced total mass emissions by vehicles of category L (mopeds and motorcycles) can significantly exceed the emissions of passenger cars and even buses and trucks.

4. A new coordinate system has been obtained that can offer general principles for the development and subsequent implementation of a universal approach to road vehicle's environmental hazard labeling.

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