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International Emission Standards for Mining Machinery and Equipment**Mark L. Khazin**

Ural State Mining University (30 Kuybysheva st., Ekaterinburg, 620144, Russian Federation)

Экологические стандарты стран мира для горных машин и оборудования**М.Л. Хазин**

Уральский государственный горный университет (Россия, 620144, г. Екатеринбург, ул. Куйбышева, 30)

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The paper analyses problems associated with the use of mining machinery equipped with diesel engine releases of exhaust gases that have a harmful impact on human health and the environment.

The mining industry uses a wide range of equipment powered by diesel engines: dump trucks, backhoe loaders, drill jumbos and other mining machinery. Engine exhaust gases contain toxic elements that have a significant impact on human health and the environment. Air pollution from gases leads to standbys of mine sites, while a reduced visibility on a route results in a partial or total equipment shutdown. At present, environmental requirements to vehicle engines are a top concern. The problem of air pollution with harmful substances contained in diesel engine exhausts is becoming a global challenge. Solutions of these issues require joint efforts from many countries. International conventions and adoption of relevant standards serve as a means of rapprochement in this sphere.

Most operations in Europe, Asia and America are guided by similar standards as to the content of harmful substances in exhaust gases, the European Union being an influencer in this regard by frequently introducing updates and stringent regulations. Other countries are following this trend and revising their emission standards too. European states had paid attention to this issue earlier than other countries. Today, environmental requirements to vehicle engines are a top priority. Research in this field is focused on such issues as increasing productivity of mining machinery engines, reducing labour costs of maintenance and repairs, enhancing fuel efficiency and significantly improving environmental performance.

Ключевые слова:

горные машины, экология, открытые горные работы, выбросы, токсичные элементы, дизельное топливо.

Анализируются проблемы, связанные с использованием горных машин, оснащенных дизельными двигателями, выхлопные газы которых оказывают вредное влияние на здоровье человека и окружающую среду.

В горнодобывающей промышленности эксплуатируется огромное количество оборудования с дизельными двигателями: карьерные самосвалы, экскаваторы, буровые станки и другие горные машины. Выхлопные газы двигателей содержат токсичные элементы, оказывающие значительное влияние на здоровье персонала и окружающую среду. Загазованность рабочей атмосферы влечет за собой необходимость остановки карьера, а ухудшение видимости на трассе обуславливает частичную или полную остановку работы оборудования. На сегодняшний день экологические требования к двигателю автомобиля являются приоритетными. Проблема загрязнения атмосферы вредными веществами, содержащимися в выхлопе дизельных двигателей, становится глобальной. Для ее решения требуются совместные усилия многих стран. Инструментом для сближения в данной сфере служат международные конвенции и принятие соответствующих стандартов.

Большинство стран Европы, Азии и Америки ориентируется на сходные нормы по содержанию вредных веществ в выхлопных газах. Евросоюз в этом плане является своеобразным авторитетом: он наиболее часто обновляет данные показатели и внедряет жесткое правовое регулирование. Другие страны следуют такой тенденции и также обновляют нормы выбросов. Европейские страны раньше других обратили внимание на данную проблематику. На сегодняшний день экологические требования к двигателю автомобиля являются приоритетными. Исследования в этой области связаны с такими направлениями, как повышение производительности двигателей горных машин, уменьшение затрат труда на их техническое обслуживание и ремонт, повышение топливной экономичности, значительное улучшение экологических характеристик.

Mark L. Khazin (Author ID in Scopus: 6506526940) – Doctor of Engineering, Professor of the Department of Mining Equipment Operation (tel: +007 3432 83 09 57, e-mail: Khasin@ursmu.ru).

Хазин Марк Леонтьевич – доктор технических наук, профессор кафедры эксплуатации горного оборудования (тел: +007 343 283 0956, e-mail: Khasin@ursmu.ru).

Introduction

The mining industry operates a wide range of equipment mainly powered by internal combustion engines: dump trucks, backhoe loaders, drill jumbos and other mining machinery. Enhancing the mining equipment performance and increasing the depth of openpits entail the necessity to adopt increasingly more powerful engines for service vehicles, mostly represented by dump trucks [1-5].

Beside the mining machinery, stationary diesel-electric generator sets notably contribute to environmental pollution from harmful emissions of exhaust gases. Diesel emissions of equipment contain a range of heavy metals (beryllium, cadmium, mercury, etc.) that enter soil, surface and ground waters [6], and have a sizeable effect on the total concentration of black carbon (soot) particles [7, 8].

Exhaust from diesel engines seriously impacts productivity due to increased idle periods resulting from atmospheric gas pollution at openpits, impaired road visibility and deteriorated personnel health [9-12].

Concentrations of harmful gases from mining machinery diesel engines, nonroad and special-service equipment in work areas have become quite threatening due to the specific working conditions involving presence of large numbers of people on a limited site area. At some sites, this leads to a complete stoppage of operations until levels of pollutants in the air and visibility on the roads become normal [4, 9-11]. Additional costs arise for the openpit ventilation [13, 14] and personal protective equipment for drivers and other personnel [15, 16].

Constant exposure to exhaust gases leads to immunodeficiency, bronchitis, damage to brain vessels, nervous system and other body organs [17, 18]. Formaldehyde and other hydrocarbons in diesel exhaust gases may cause cancer if exposed thereto over the course of one year. For example, mining workers who had been exposed to diesel engine exhaust gases for 10-20 years were diagnosed with lung cancer [19-21].

The work is intended to analyse the environmental issues of using mining machinery and equipment powered by diesel engines.

Methods

Service mobile equipment, such as nonroad vehicles and dump trucks, is a main source of air pollution in open pits [4, 3, 9, 11, 22]. The issue of transport ecological compatibility dates back to

the mid-twentieth century, when vehicles became a mass product. European states, located on a relatively small territory, started to introduce various environmental regulations earlier than other countries. Such standards were adopted in individual states and included various requirements to the content of harmful substances in vehicle engine exhaust gases.

As of today, environmental requirements to vehicle engines are a top concern [22-24]. The development of mining machinery engines is focused on increasing their productivity, reducing labour costs of maintenance and repairs, enhancing fuel efficiency and significantly improving environmental performance.

Environmental Standards in the European Union

For nonroad vehicles, tractors and dump trucks, as well as diesel generator sets, a series of the European Stage standards (Directive 97/68/EC) is applicable, which regulate the maximum content of four toxic components in exhaust gases: nitrogen oxide (NO_x), carbon oxide (CO), hydrocarbons (CH) and solid particles or soot (particulate matter, PM) [25, 26].

The first standard Stage 1 was introduced in 1999. The more stringent regulations of Stage 2 were phased-in from 2001 to 2004, subject to net engine power. Since January 2001, they were applied to 18-37 kW engines, and then to 130 to 560 kW diesel engines used in construction and mining machinery weighing from 20 to 100 tons (Table 1).

Reducing sulphur compounds in diesel fuels is a way to improve their environmental performance. Requirements to their content are becoming increasingly restrictive: from 500 million⁻¹ in 1996 to 50 million⁻¹ in 2005. In 2010, in accordance with European Euro 5 regulations, the sulphur content in petrol and diesel fuel shall not exceed 10 million⁻¹ [6].

Stage 3 standards were gradually phased-in between 2006 and 2013, and Stage 4 regulations were introduced in 2014. Further to the engine categories covered by Stage 1 and Stage 2, these standards limit exhaust emissions from railway locomotive and inland watercraft engines. Only new vehicles and equipment fall within the scope of Stage 3-4 regulations (see Table 1), while the use of vehicles already in service may be continued provided the engines comply with Stage 1 and Stage 2.

Table 1

EU Stage emission standards for nonroad diesel engines

Standard	Net engine power, kW	Category	Year	Content of toxic substances in exhaust gas, g/(kWh)			
				CO	CH	NO _x	Particulate matter
Stage 1	75...130	–	1999	5.0	1.3	9.2	0.70
	130...560	–		5.0	1.3	9.2	0.54
Stage 2	75...130	–	2003	5.0	1.0	6.0	0.3
	130...560	–	2002	3.5	1.0	6.0	0.2
Stage 3A	75...130	<i>I</i>	2007	5.0	4.0	–	0.3
	130...560	<i>H</i>	2006	3.5	4.0	–	0.2
Stage 3B	75...130	<i>M</i>	2012	5.0	0.19	3.3	0.025
	130...560	<i>L</i>	2011	3.5	0.19	2.0	0.025
Stage 4	56...130	<i>R</i>	2014	5.0	0.19	0.4	0.025
	130 ... 560	<i>Q</i>	2014	3.5	0.19	0.4	0.025

Note: * – Stage 2 also applies to constant-speed engines effective on 31 December 2006.

Stage 4 limits the maximum content of soot (particulate matter) to the range between 0.020 and 0.025 g/kWh. To comply with these regulations (implying approximately 90 % reduction in toxic contents compared to Stage 2), engine exhaust systems shall be equipped with particulate filters, as it appears. For some engines, exhaust gas aftertreatment may also be required by installation of special systems in the exhaust system, such as selective catalytic reduction (SCR) using ammonia as the reducing agent, to comply with a very stringent NO_x limit of 0.4 g/kWh introduced by Stage 4.

Based on EU directives, national standards are being developed in the member states. Following the European Union, other countries have also introduced equivalent environmental regulations.

Environmental Standards in the USA

The engines of all vehicles (cars, heavy-duty and nonroad vehicles) in the USA are subject to Tier standards [25, 26]. The comprehensive character of Tier regulations is reflected even in the adopted engine power classification: 0-18; 19-55; 56-129; 130-560 and over 560 kW, while the European standards cover only diesel engines of 56-129 and 130-560 kW. Each group has its own pollutant emission limits.

The federal Tier 1 regulations for nonroad diesel engines over 37 kW (50 hp) were adopted in 1994 and phased-in from 1996 to 2000.

In 1996, a Statement of Principles (SOP) regulating the emission standards for nonroad diesel engines was signed between the U.S. Environmental Protection Agency (EPA), the

California Air Resources Board (ARB) and engine manufacturing companies (including Caterpillar, Cummins, John Deere, Detroit Diesel, Deutz, Isuzu, Komatsu, Kubota, Mitsubishi, Navistar, New Holland, Wis-Con, and Yanmar). In 1998, Tier 1 regulations were adopted for equipment under 37 kW (50 HP) with stricter Tier 2 and Tier 3 regulations (Table 2) for all equipment. The Tier 2 and Tier 3 standards were phased-in from 2000 to 2008.

Engines of all sizes must also comply with smoke standards: 20 % opacity during acceleration, 15 % at lugging, and 50 % in peak mode. The standards provide for several other provisions, such as: averaging, banking and trading of emission credits, as well as maximum limits for emission averaging. ‘Family emission limits’ (FEL) serve as an average entire engine family’s emission standard.

Tier 4 standards (see Table 2) phased-in from 2008 to 2015 provide for a significant reduction in NO_x and particulate matter, as well as stricter restrictions on CH content. The standards for CO content remained the same as in Tier 2 and Tier 3.

Tier 4 regulations set ‘not-to-exceed’ (NTE) limits. In most engines, the NTE limits are set at 1.25 times the regular standard for each pollutant. NTE standards apply to engines at the time of certification and throughout the useful life of an engine.

By the specified quantity limits, the latest versions of the US standards correspond to the European regulations (see Tables 1 and 2). As to the limit of sulphur content in diesel fuel, this value was first regulated in Euro 3 and Tier 3 standards.

Table 2

US Tier emission standards for nonroad diesel engines

Standard	Engine power, kW (HP)	Year	Content of toxic substances in exhaust gas, g/(kWh) (g/hph)				
			CO	CH	NMHC + NO _x	NO _x	Particulate matter
Tier 1		1997	-	-	-	9.2 (6.9)	-
Tier 2	75...130 (100...175)	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.30 (0.22)
Tier 3		2007	5.0 (3.7)	-	4.0(3.0)	-	-*
Tier 1		1996	11.4(8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
Tier 2	130...225 (175...300)	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.20 (0.15)
Tier 3		2006	3.5 (2.6)	-	4.0(3.0)	-	-*
Tier 1		1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
Tier 2	225...450 (300...600)	2001	3.5(2.6)	-	6.4 (4.8)	-	0.20 (0.15)
Tier 3		2006	3.5 (2.6)	-	4.0 (3.0)	-	-
Tier 1		1996	11.4 (8.5)	-	-	9.2 (6.9)	0.54 (0.40)
Tier 2	450...560 (600...750)	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.20 (0.15)
Tier 3		2006	3.5 (2.6)	-	4.0 (3.0)	-	-*
Tier 1		2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
Tier 2	Over 560 (over 750)	2006	3.5 (2.6)	-	6.4 (4.8/)	-	0.20 (0.15)
Tier 4	56...130 (75...175)	2012-2014	5.0 (3.7)	0.19 (0.14)	-	0.4 (0.3)	0.02(0.015)
	130...560 (175...750)	2011-2014	3.5 (2.6)	0.19 (0.14)	-	0.4 (0.3)	0.02(0.015)
	Over 900 (1223)	2014	3.5 (2.6)	0.40 (0.30)	-	3.5 (2.6)	0.10 (0.07)
Tier 4 Final	130...560 (175...750)	-	3.5 (2.6)	0.19 (0.14)	-	0.4 (0.3)	0.02(0.015)

Note: * – not adopted; engines must meet Tier 2 PM standard; NMHC – non-methane hydrocarbons.

Table 3

RF emission standards for nonroad diesel engines

Standard	Power range	Net engine power, kW	CO	CH	NO _x	Particulate matter (PM)
GOST P 41.96-99	-	75 ≤ P < 130	5	1.3	9.2	0.70
	-	P ≥ 130	5	1.3	9.2	0.54
GOST P 41.96-05	-	75 ≤ P < 130	5	1.3	9.2	0.70
	-	P ≥ 130	5	1.3	9.2	0.54
	F*	75 ≤ P < 130	5.0	1.0	6.0	0.3
GOST P 41.96-11	E*	130 ≤ P ≤ 560	3.5	1.0	6.0	0.2
	F	75 ≤ P < 130	5.0	1.0	6.0	0.3
	E	130 ≤ P ≤ 560	3.5	1.0	6.0	0.2

Environmental Standards in Russia

In general, Russia keeps up with the EU emission standards. Environmental standards for heavy-duty nonroad equipment are regulated by GOST national standards [27-29]. The first standard GOST R41 96-99, equivalent to Stage I (Tier 1), was adopted in 1999, with subsequent, stricter regulations introduced by GOST R41 96-05 and GOST R41 96-11 (Table 3).

On 27 February 2008, a Technical Regulation was approved by Resolution No. 118 of the Government of the Russian Federation (as amended by Resolution No. 1076 of 30 December 2008), and came into effect on 27 August 2008, having established the diesel fuel sulphur content in the range between 10 and 500 ppm depending on the class. However, the diesel fuel containing 2,000 ppm of sulphur may be available on the

market for approximately three years (from 2011 to 2014, the dates vary for different fuel types, and this period is not limited for type 5 fuels). The use of low-grade diesel fuel dismissed in all developed countries, will therefore continue for quite a few years. Many openpits in Russia still use dump trucks, backhoe loaders and drill jumbos manufactured in the 1990s and equipped with engines of domestic make that fail to meet the latest world standards and stand at Stage 1-2. Outdated diesel fuel grades are better suited for such equipment and cost less.

Environmental Standards in North and South America

Canada [25]. On-Road Vehicle and Engine Emission Regulations (SOR/2003-2) are harmonised with the US standards, but with some

lagging behind, which entails a discrepancy between the standards of Canada and the US during the transition phase.

Mexico [25]. The first emission standards for heavy-duty diesel engines NOM-044-ECOL-1993 became effective in 1993. These standards were based on the US environmental regulations. Since February 2003, as an alternative, engines may also comply with the European standards. In 2006, new emission standards for heavy-duty truck engines were adopted, complying with US 2004 standards or equivalent to Euro 4. In 2018, the emission standards were aligned with Tier 5/Euro 5.

In South America [25], the regulatory framework limiting harmful diesel engine emissions is also based on the European and US standards.

Argentina. Engine emission standards for heavy-duty nonroad equipment are based on the European regulations.

In *Brazil*, the first standard was adopted in 1988. Most of these standards were equivalent to European regulations, yet the current PROCONVE L6 standard, although compliant with Euro 5, fails to stipulate the mandatory particulate matter or air emissions filters.

Chile. Where dual standards exist, engines must meet either the EU or the US requirements.

Peru. As of 1 January 2003, all new heavy-duty engines must comply with the Euro 2 standard, and with the Euro 3 standard effective since 2007.

Environmental Standards in Asia

In Asia [25], the regulatory framework for normalising diesel engine emissions is based on a combination of the European and the US standards, subject to regional specifics.

In *China*, vehicle emission control programmes were first introduced in the 1980s, and a nationwide standard (CNS) was adopted in the late 1990s. China has gradually been implementing stricter exhaust emission standards

for cars and heavy-duty trucks in line with the European regulations. China 1 standard followed Euro 1, China 2 was based on Euro 2, etc. These standards have already been introduced in major cities such as Beijing, Shanghai and Guangzhou [30, 31]. China 5 is the applicable national standard regulating the content of toxic substances in vehicle exhaust emissions in China. The Ministry of Environmental Protection is focused on developing China 6, a new standard regulating the content of harmful substances in exhaust gases. China 5 and 6 regulations are identical for all fuels and are more stringent compared to Euro 6.

Japan has its own regulatory framework that limits harmful emissions from diesel engines. The latest version of the 2009 standards stands between Tier 4 and Euro 5. Under these regulations, the limits for nitrogen oxide emissions from 56 to 560 kW diesel engines must be reduced to 0.4 g/kWh. For engines between 56 and 130 kW, the standards were introduced in 2015, while more powerful diesel engines were affected as early as in 2014. MOT/MOC standards were developed for nonroad diesel and generator set engines and are mostly aligned to the European Stage 4 and the US Tier 4 regulations. Furthermore, all vehicles in Japan are affected by the ‘fuel efficiency target’ programme. This is the world’s first program to cover not only cars, but also heavy-duty vehicles. Diesel fuel in Japan is affected by ‘The Law On Quality Control of Gasoline and Other Fuels’ and the industrial standard K 2204 ‘Diesel Fuel’.

India started adopting European emission and fuel regulations for light-duty and heavy-duty vehicles since 2000. Bharat Stage 3 standard is effective nationwide, while Delhi and 11 other major cities have already adopted Bharat Stage 4 regulations.

In *Malaysia, Indonesia, the Philippines, Vietnam and Thailand*, Euro 2 standards are still in force.

Table 4

EU Stage 5 emission standards for nonroad diesel & generator set engines

Engine type	Net power range, kWh	Date of introduction	Content of toxic substances in exhaust gas, g/(kWh)				
			CO	CH	NO _x	PM	PN, 1/kWh
All	130...560	2019	3.5	0.19 ^c	0.4	0.015	1·10 ¹²
All	> 560	2019	3.5	0.19 ^d	3.5	0.045	-
Generator sets	> 560	2019	3.5	0.19 ^a	0.67	0.035	-

South Korea. Earlier emission regulations for heavy-duty diesel truck engines were based on Japanese regulations and follow European standards since 2003. Korea’s first nonroad vehicle emission regulations came into force in 2004-2005 based on the US Tier 1 and Tier 2 standards. Emission standards based on the US Tier 3 requirements became effective in 2009 for construction machinery and in 2013 for agricultural equipment, while the Tier 4-based standard became effective from 2015.

In Asia, all environmental regulations as to the content of pollutants in exhaust gases also apply to diesel fuel, assuming a gradual reduction in its content of sulphur. Only in China, the adopted standards fail to apply to diesel fuel used for nonroad vehicles and generator sets.

Environmental Standards in other Countries

Most of the other countries adopt the standards introduced in the USA, Europe or Japan [25].

Australia and *New Zealand* apply Euro regulations that became effective almost concurrently with the European countries. European, American or Japanese certificates are valid in certain countries, which depends on the economic and political relations between the governments. Therefore, as of today, nonroad equipment and generator set engines are subject to regulations equivalent to Stage II standard in most countries.

Comparison of Environmental Standards

The EU Stage 4 and US Tier 4 Final standards are the latest environmental regulations in effect to limit harmful emissions from nonroad vehicle engines. They are comparable in classification and limit values, so that there is no need to produce different engines for each market in the context of globalisation.

However, the European Union is drafting new, more stringent emission regulations - Stage 5 [32-34] (Table 4), in compliance with the US Tier 5 standard.

The proposed Stage 5 standard will replace an existing, multilayered legal framework in the EU with one overarching regulation.

Stage 4 standard now applies to engines between 56 and 560 kW, and all generator sets will fall within the scope of Stage 5, regardless of power: under 19 kW and over 560 kW.

Of great concern to scientists is the particulate matter (PM) release by diesel engines. In its pure form, soot is non-toxic. However, the soot particles have a high adsorption capacity and carry toxic substances on their surface. Most hazardous are nanoparticles with a diameter of less than 50 nm that penetrate deeply into human lungs and contribute to the development of cardiovascular and cancer diseases [7, 17, 35, 36]. Soot may remain suspended in the air for a long time, thus extending the exposure time of toxic substances [6, 8]. Newer, more advanced models of diesel engines release fine particles in higher amounts compared to those made with the old technology [37].

In October 2014, the European Commission adopted the ‘Fuel Quality Directive’ that obliges fuel suppliers to reduce greenhouse gas intensity of transport fuels by a minimum of 6 % by 2020 [38]. Stage 5 regulation will therefore introduce

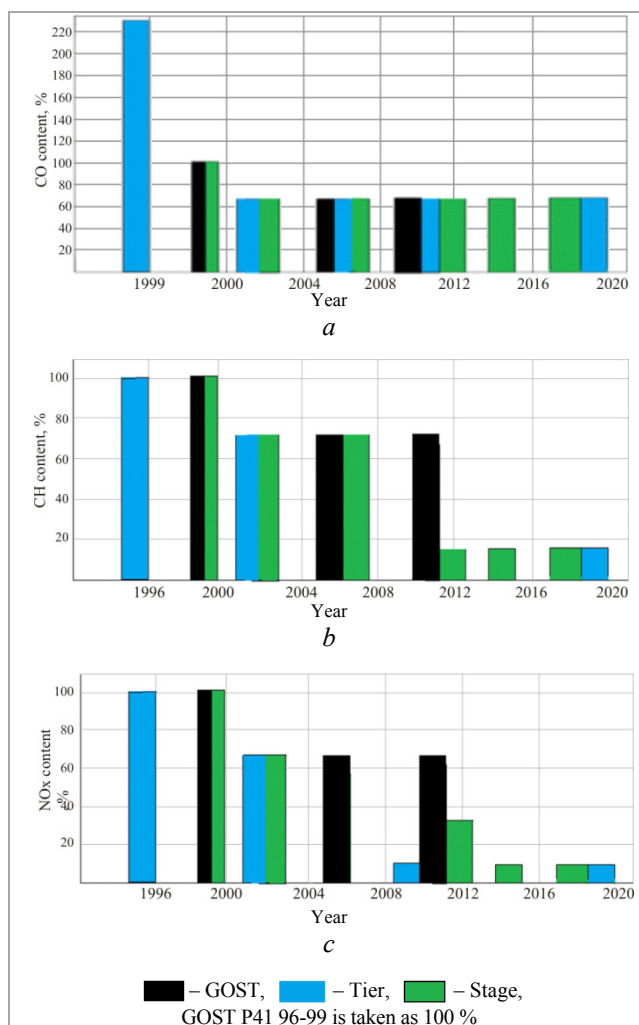


Fig. 1. Dynamics of changes in environmental content requirements: a – CO; b – CH; c – NO_x

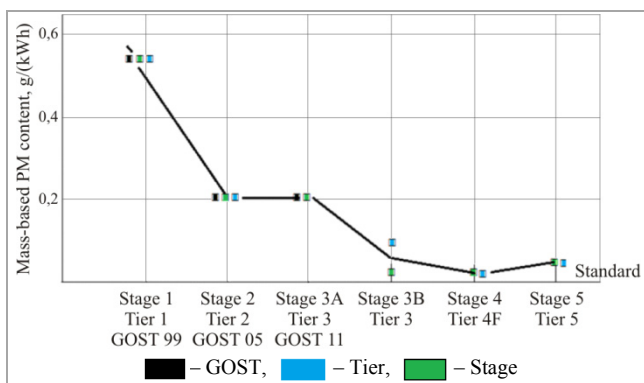


Fig. 2. Change in PM content of diesel engine combustion gas by standards

the latest restrictions on the mass-based PM, particle number (PN) and NO_x emission limits in engine exhaust gases (see Table 4). The PN limit was introduced to force the use of filtering technologies for particulate matter (soot), such as active (controlled) regeneration filters, on all engines covered by these standards.

It should be noted that fundamental changes shall be introduced to the US environmental standards to harmonise Stage 5 with Tier 5. The point is that Stage 5 sets a PN limit in emissions and forces to install a diesel particulate filter (DPF) to meet these requirements, whereas Tier 4 standards can be met without it.

Environmental protection is one of mankind paramount concerns, as human lives, health and well-being depend on its solution. In the context of globalisation, the issue of air pollution by harmful substances from car exhausts is no longer relevant for developed countries only, but is becoming a global issue that requires joint efforts from many countries. The environmental requirements to engine and fuel quality are therefore increasingly tightening (Figure 1).

The US Tier 4 and Tier 4 Final regulations correspond to lower particle number limits for nonroad engines compared to the EU Stage 3B and 4, respectively. However, the US standards fail to require the use of diesel particulate filters. EU Stage V proposes a new, lower limit of particulate matter (reaching 0.015 g/kWh for engines between 130 kW and 560 kW). This is 25 % lower than the Tier 4 Final requirement. The particulate matter content limits, as well as the new PN requirements proposed by the EU, will increase the likelihood of diesel particulate filters being used to significantly reduce soot emissions from nonroad engines in the power range between 19 and 560 kW [25, 39]. The proposed Stage V

nonroad engine standard may be a new best practice for the rest of the world to follow.

The PM limit of Stage 5 is 97 % lower than that of Stage 1, and the the hydrocarbon (CH) + nitrogen oxides (NO_x) limit is 94 % lower (Figure 2). Using diesel NRE engines in the range between 130 and 560 kW, the PM limit is lowered to 0.015 g/kWh, i.e. a reduction of 40 % compared to the previous Stage 4 limit (0.025 g/kWh).

The increase in the PN limit of Stage 5 (Tier 5) standards is due to the fact that previous standards applied to engines under 560 kW, while Stage 5 (Tier 5) covers engines over 560 kW.

Harmonisation of engine emission regulations between countries is stipulated by rapidly developing international economic relations, as well the necessity to stand up for purity of environment.

The EU has adopted a series of seven directives over the past two decades to address emissions from non-road engines. Current EU regulation of emissions from these engines consists of various annexes that have been amended eight times since adoption in 1997. These directives left it up to individual EU member states to modify standards to achieve the intended outcomes, which resulted in 28 national standards currently in effect.

In addition to the 28 national laws, regional amendments set supplementary requirements on the engines sold and used in targeted areas, reflecting more stringent requirements than European law. For example, Germany [40], Austria [41] and the Netherlands [42] have adopted national standards requiring mandatory diesel particulate filters on heavy-duty construction equipment.

Conclusions

Human health and the environmental protection are paramount for the mankind. The problem of air pollution from combustion gases from mining and nonroad vehicles in the context of globalisation is no longer applicable to individual countries only, but is becoming a universal concern. The joint efforts of many countries are therefore being a requisite. Being an influencer in this regard, the European Union frequently introduces updates and stringent regulations. Most countries are guided by similar exhaust gas pollutant content regulations, follow the trend and update their emission standards.

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