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Impact of transportation on air quality: modern emission measurement methods and reduction perspectives

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Air pollution, one of the most critical environmental and health challenges, causes millions of premature deaths annually. Transportation, especially internal combustion vehicles, is a significant source of pollutants such as particulate matter, nitrogen oxides, carbon monoxide, and hydrocarbons. This article analyzes methods for measuring exhaust emissions in laboratories and real-world operating conditions, discussing their advantages and limitations. Traditional dynamometer tests conducted on test benches enable detailed analyses but do not fully reflect real-world operating conditions. These tests fail to account for factors such as driving style or variable weather conditions. Modern methods, such as Real Driving Emissions (RDE) tests using Portable Emissions Measurement Systems (PEMS), allow for emission measurements in real traffic conditions, although they are costly and time-consuming. Alternative approaches for measuring emissions during transit, such as remote sensing (tunnel, extractive, or open-path methods), enable quick and efficient studies on large vehicle samples, though they come with certain limitations, such as result precision or the influence of external conditions. The article also highlights research on rail vehicle emissions, which remain limited to laboratory engine tests. This underscores the need for further development of measurement technologies and the implementation of more advanced methods for better emission monitoring. Measurements play a crucial role in designing policies aimed at reducing pollution, such as low-emission zones or stricter exhaust emission standards. This is of critical importance for achieving climate goals, such as carbon neutrality.

Key words: *exhaust emission, RDE, PEMS, remote sensing, tunnel studies, extractive method, open-path system*

1. Introduction

The 2019 "State of Global Air" report, developed by U.S. research organizations – Health Effects Institute and the Institute for Health Metrics and Evaluation – states that air pollution was the fourth leading risk factor for premature death worldwide. It is estimated to have contributed to 6.67 million deaths within a year, accounting for nearly 12% of the global total (Fig. 1). It is the primary environmental risk factor for premature death, with its combined impact surpassed only by high blood pressure (10.8 million), smoking (8.71 million), and dietary risks (7.94 million). Each year, significantly more people worldwide die from exposure to air pollution than from road collisions, which are estimated to cause 1.28 million deaths annually. Additionally, air pollution contributes to a higher number of deaths than factors such as malnutrition, alcohol consumption, or lack of physical activity [44, 46].

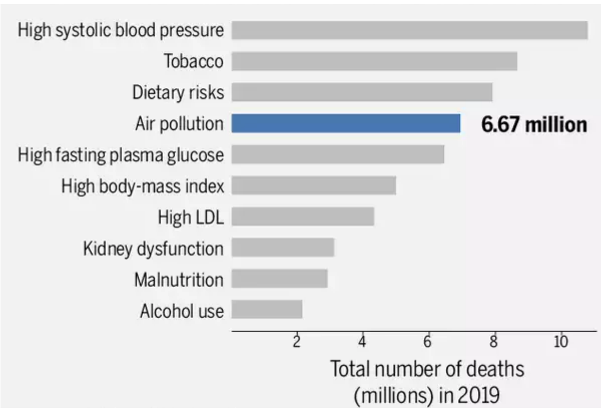

Fig. 1. Total number of deaths from all causes in 2019 [46]

Air pollution is a problem that negatively affects health and the environment in all countries worldwide, differing only in its severity (Fig. 2) [47]. The most vulnerable groups to the adverse effects of poor air quality include children, pregnant women, the elderly, and individuals with heart or lung diseases. Over 90% of the population still lives in areas where PM2.5 concentrations exceed the air quality standards set by the World Health Organization (WHO). Numerous current studies [44, 46] have unequivocally demonstrated that both short-term and long-term exposure to polluted air can contribute to serious health effects. These effects can include temporary or chronic diseases, mild or debilitating conditions, and even fatal outcomes.

Short-term exposure, lasting from several hours to a few days, can cause irritation of the ears, nose, and throat. These symptoms usually subside when pollution levels decrease. However, short-term exposure can also worsen the condition of the lower respiratory tract and lead to chronic illnesses such as allergies, asthma, chronic obstructive pulmonary disease (COPD), and bronchitis. For individuals with heart diseases, short-term exposure to PM2.5 can lead to arrhythmias, heart attacks, or even death. On the other hand, long-term exposure to air pollution, lasting from several months to several years, increases the risk of premature death due to chronic heart diseases, respiratory diseases, lung infections, lung cancer, diabetes, and other health problems. Additionally, growing scientific evidence indicates that exposure to polluted air during pregnancy can contribute to premature births, putting newborns at high risk of severe illnesses and mortality [44, 46, 66]. Numerous studies also suggest that air pollution may have neurological effects on children and cause neurodegenerative diseases in adulthood [44, 46, 66]. Considering these impacts, exposure to air pollution can significantly reduce life expectancy.

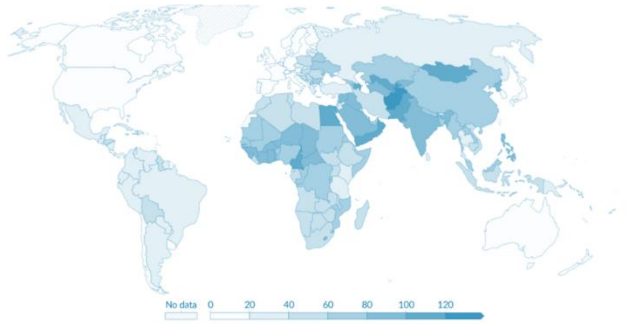

Fig. 2. Death rate attributed to ambient air pollution, 2019. Estimated annual number of deaths attributed to ambient air pollution per 100,000 people [66]

Reports on the state of global air also highlight the effects of pollution, which are the focus of the Global Burden of Disease Study (GBD) [45]. The GBD analysis estimates the societal burden in terms of years lived with illness and the number of deaths, most of which result from long-term exposure to air pollution. The study primarily examines mortality caused by five chronic non-communicable diseases, for which the strongest scientific evidence currently exists: diabetes, stroke, COPD, lung cancer, and ischemic heart disease, as well as one communicable disease – lower respiratory tract infections. Additionally, the estimates of particulate matter exposure include infant mortality caused by complications related to premature birth. The burden of diseases associated with air pollution is substantial, contributing significantly to the global percentage of deaths (Fig. 3) [45].

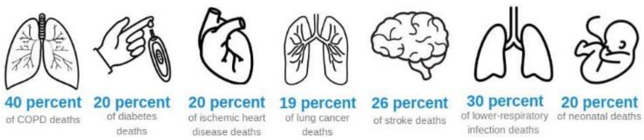

Fig. 3. Percentage of global deaths (by cause) attributed to air pollution in 2019 [45]

The impact of transport emissions on human health is not the only negative phenomenon. Significant amounts of emitted greenhouse gases (GHG) also have a strong impact on the environment. One of the results is global warming. Especially in the last 100 years, an enormous increase in the average global temperature was noted [52]. In this case, GHG emissions rose dramatically and were mainly caused by human activity. Faster warming process of the planet is causing weather anomalies and increasingly frequent, unpredictable, and dangerous phenomena such as hurricanes, tornadoes, droughts, and fires. Thus, paying attention to the growing negative trends in the environment and counteracting them is a key element in stopping the process of environmental destruction and degradation [1].

2. European legal regulations concerning exhaust emissions

2.1. Regulations concerning passenger cars

The European Union regulations on pollutant emissions from passenger cars and light commercial vehicles are described in Directive 70/220/EEC [27], which underwent a series of amendments up to the year 2004. In 2007, it was repealed and replaced by Regulation (EC) No. 715/2007 of the European Parliament and of the Council [74]. The most important legal documents include:

– Euro 1 standard: Directive 91/441/EEC [28], Directive 93/59/EEC [29]
– Euro 2 standard: Directive 94/12/EEC [32], Directive 96/69/EEC [33]
– Euro 3/4 standard: Directive 98/69/EC [35] Directive 2002/80/EC [15]
– Euro 5/6 standard: Regulation (EC) No. 715/2007 [74], Regulation (EC) No. 692/2008 [19]
– WLTP/WLTC tests: Regulation (EU) 2017/1151 [22], Regulation (EU) 2017/1247 [24]
– RDE tests: Regulation (EU) 2016/427 [20], Regulation (EU) 2016/646 [21], Regulation (EU) 2017/1154 [23], Regulation (EU) 2018/1832 [25].

The above-mentioned documents, starting with Directive 91/441/EEC, apply to exhaust emissions, fuel vapor emissions, crankcase emissions, and the durability of emission control systems in all motor vehicles equipped with spark-ignition engines, as well as to exhaust emissions and the durability of emission control systems in category M1 and N1 vehicles (Table 1) equipped with compression-ignition engines.

Table 1. Vehicle categories [30]

Cat.	Description	Subcat.		Number of People	Weight Limit	
M	Passenger transport, minimum 4 wheels, passenger vehicles	M1		up to 9	–	
		M2		> 9	GVW ≤ 5 t[1)]	
		M3			GVW > 5 t	
N	Goods transport, minimum 4 wheels, light and heavy commercial vehicles	N1	CL1	not applicable	GVW ≤ 3.5 T	RM ≤ 1.305 t
			CL2			1.305 t < RM ≤ 1.76 t
			CL3			1.76 t < RM ≤ 3.5 T
		N2			3.5 t < GVW ≤ 12 t	
		N3			GVW > 12 t	

[1)] Until Euro 4: two subgroups: M1 DMC ≤ 2.5 t and M1 DMC 2.5 t < DMC ≤ 3.5 t
RM – Reference Mass
GVW – Gross Vehicle Weight

With the introduction of Directive 98/69/EC [35], the scope was expanded to include testing of exhaust emissions at normal and low ambient temperatures for spark-ignition engines, as well as verification of the proper functioning of onboard diagnostic (OBD) systems for both spark-ignition and compression-ignition engines (for categories M1 and

N2). Regulation (EU) 630/2012 [26] introduced additional requirements for mono- and bi-fuel gas vehicles and for flex-fuel vehicles running on a mixture of hydrogen and natural gas. At the manufacturer's request, type approval granted under these directives for category M1 and N1 vehicles equipped with compression-ignition engines may be extended to category M2 and N2 vehicles with a reference mass not exceeding 2840 kg, provided they meet the conditions for EEC type approval extension described in Directive 91/441/EEC [28].

Emission standards for passenger cars and light commercial vehicles apply to all vehicles in categories M1, M2, N1, and N2 with a reference mass not exceeding 2610 kg (or up to 2840 kg in the case of extended type approval), equipped with either spark-ignition or compression-ignition engines. Petrol-fueled engines must meet requirements for total hydrocarbons and methane (THC), non-methane hydrocarbons (NMHC), nitrogen oxides (NO_x), and carbon monoxide (CO). Compression-ignition engines, on the other hand, must meet standards for nitrogen oxides (NO_x), the sum of hydrocarbons and nitrogen oxides (HC + NO_x), and carbon monoxide (CO). Additionally, starting with Euro 5b for CI (compression-ignition) engines and with Euro 6 for SI (spark-ignition) engines with direct fuel injection (DI), vehicles are also required to undergo testing for particulate mass (PM) and particle number (PN) [56]. Table 2 presents the limit values for Euro 5–6 standards for passenger vehicles approved under category M1.

In order to obtain type approval, all internal combustion vehicles covered by the latest legal regulations must meet specific requirements and undergo the following tests:

Table 2. Euro 5–6 emission standards for M1 vehicles [30]

Standard		Euro 5a	Euro 5b/b+	Euro 6b, 6c	Euro 6d-Temp, 6d
		(WE) 715/2007 (WE) 692/2008			
Date		TA[1] 9/2009, FR[2] 1/2011	TA[1] 9/2011, FR[2] 1/2013	TA[1] 9/2014,(6b) FR[2] 9/2015(6b) FR[2]09/2018 (6c)	TA[1] 9/2017 (6d-Temp) TA[1] 1/220, (6d) FR[2] 1/2021 (6d)
Test type		Modified ECE + EUDC			WLTC + RDE
Engine type		Spark ignition			
THC	g/km	0.1	0.1	0.1	0.1
NMHC	g/km	0.068	0.068	0.068	0.068
NO_x	g/km	0.06	0.06	0.06	0.06
CO	g/km	1.0	1.0	1.0	1.0
PM[3][4]	g/km	0.005[6]	0.005[6]	0.005	0.005
PN[3][4]	1/km	–	–	6×10^{11} [5]	6×10^{11} [5]
Engine type		Compression ignition			
NO_x	g/km	0.18	0.18	0.08	0.08
HC+NO_x	g/km	0.23	0.23	0.17	0.17
CO	g/km	0.5	0.5	0.5	0.5
PM	g/km	0.005[6]	0.005[6]	0.005[6]	0.005[6]
PN	1/km	–	6×10^{11}	6×10^{11}	6×10^{11}

1) TA – Type Approval
2) FR – First Registration (approval for use)
3) Test procedure defined in Regulation No. 83 (UNECE)
4) Applies only to vehicles with direct injection gasoline engines (DI)
5) 6,0×1012 1/km during the first three years after the Euro 6 standard comes into force
6) 0,0045 g/km using the PMP (Particulate Measuring Protocol) measurement procedure

- Type 1 test – measurement of the average emission of gaseous compounds and particulate matter (PM and PN) from the vehicle's exhaust system
- Type 1A test – measurement of the average emission of gaseous compounds and particulate matter from the vehicle's exhaust system under real-world driving conditions
- Type 2 test – measurement of CO emissions at idle
- Type 3 test – measurement of crankcase gas emissions
- Type 4 test – measurement of fuel vapor emissions
- Type 5 test – verification of the durability of emission control systems
- Type 6 test – measurement of exhaust emissions at low ambient temperatures
- In-use compliance check
- Verification of the proper functioning of the OBD system
- Measurement of CO_2 emissions and fuel consumption
- Measurement of exhaust smoke opacity.

The values of emitted pollutants are primarily measured under laboratory conditions (for passenger cars, on a chassis dynamometer) using a strictly defined type-approval test designed to reflect normal driving conditions. However, with the adoption of Commission Regulation (EU) 2016/427 [20] of 10 March 2016, amending Regulation (EC) No 692/2008 [19] with regard to pollutant emissions from passenger cars and light commercial vehicles (Euro 6), provisions concerning emissions testing under real driving conditions were introduced – RDE (Real Driving Emission).

These guidelines were further supplemented by Regulations (EU) 2016/646 [21], 2017/1151 [23], and 2018/1832 [25]. Pollutants emitted during RDE tests must be recorded at a frequency of one second and calculated using strictly defined methods. Additionally, final values must be corrected using appropriate conformity factors (CF) in accordance with the guidelines set out in the above-mentioned regulations.

The emission of toxic pollutants during any real driving emissions test conducted in compliance with the requirements of the aforementioned legal acts, throughout the entire lifetime of vehicles approved under Regulation (EC) No 715/2007 [74], must not exceed the following Not-To-Exceed (NTE) values for individual exhaust compounds, which are dependent on the CF defined as:

$$\mathrm{NTE_j} = \mathrm{CF_j} \cdot \mathrm{EURO\ 6} \tag{1}$$

where: j – the pollutant for which the emission index is defined, NTE – Not-To-Exceed emission limit, CFj – Conformity Factor – operational conformity factor for a given pollutant, EURO 6 – limit value for a given toxic compound defined by the Euro 6 standard.

The vehicle operational CF for pollutant emissions is determined across all measurement windows for each exhaust gas component. It represents the multiplier by which pollutant emissions under real driving conditions may increase (or decrease) relative to the type-approval test, and is expressed by the following formula:

$$\mathrm{CF} = \frac{\mathrm{M_{RDE,j}}}{\mathrm{M_{test,j}}} \tag{2}$$

where: j – pollutant for which the CF index is defined, MRDE,j – on-road emission of the harmful exhaust compound obtained under real driving conditions during the RDE test [g/km], Mtest,j – on-road emission of the harmful exhaust compound obtained during the type-approval test [g/km].

The values of the vehicle operational CF for the respective pollutants are presented in Table 3. These values are subject to periodic review and are updated as PEMS (Portable Emission Measurement Systems) procedures or technologies improve. With the introduction of the temporary Euro 6d-TEMP standard, a CF value of 2.1 for NO_x and 1.5 for PN was adopted (1 + a margin for PN = 0.5). In the subsequent stage (Euro 6d), the CF for NO_x was reduced to 1.43 (1 + a margin for NO_x = 0.43), while the CF for PN remained unchanged. The margin is a parameter that accounts for the additional measurement uncertainty of equipment used to measure harmful exhaust compounds under real driving conditions. This parameter is reviewed annually.

Table 3. Conformity factors for emissions [30]

	NO_x CF	PN CF	CO
Euro 6d-TEMPT	2.1	1.5 (1 + margin = 0.5)	Must be measured and recorded
Euro 6d	1.43 (1 + margin = 0.43)	1.5 (1 + margin = 0.5)	Must be measured and recorded

In the absence of information regarding pollutant emissions from a vehicle recorded during the type-approval test, it is possible to adopt the permissible values specified in the Euro emission standards applicable to the given vehicle. Emission indices (for individual pollutants) can be defined as the following types:

- Instantaneous – characterized by high variability, calculated for each second of the test
- Cumulative during the test – calculated as the running on-road emission of specific harmful exhaust compounds (from the start of the test to the current moment) relative to the normative value
- Overall, for the entire test, calculated as the ratio of on-road emissions in the RDE test to the normative value.

The validity of a completed run within an RDE test must be verified through a three-stage procedure as follows:

- STAGE A – verification of general requirements, boundary conditions, trip and operational requirements, as well as specifications for operational fluids, as defined in Regulation (EU) 2016/427 [20]
- STAGE B – verification of general driving dynamics requirements and the procedure for determining the cumulative positive altitude gain, as defined in Regulation (EU) 2016/427 [20]
- STAGE C – verification of dynamic driving conditions and calculation of the final emission value under real driving conditions using the moving averaging window method based on CO_2 mass, as defined in Regulation (EU) 2016/427 [20].

2.2. Regulations concerning rail vehicles

The regulations in force in Europe regarding the permissible emissions of harmful exhaust compounds from combustion engines used in vehicles of the NRMM category (Non-Road Mobile Machinery Emissions) are defined by the requirements set out in the Stage I–V standards. These regulations are specified in Directive 97/68/EC of the European Parliament and of the Council [37] and in subsequent amendments:

- Stage I/II standard: Directive 97/68/EC [34], Directive 2002/88/EC [36]
- Stage III/IV standard: Directive 2010/26/EU [17], Directive 2010/26/EC [16]
- Stage V standard: Regulation (EU) 2016/1628 [75], Regulation (EU) 2017/654 [127], Regulation (EU) 2018/989 [14], Regulation (EU) 2017/655 [12], Regulation (EU) 2018/987 [13].

In the European Union regulation, the following categories of engines used in traction vehicles have been defined:

a) Category NRE (Engines For Non-Road Mobile Machinery)
   - Engines for mobile machinery not intended for use on roads
   - Engines with a rated power of less than 560 kW
b) Category NRS (Spark Ignition Engines For Non-Road Mobile Machinery) – SI engines
   - Engines with a rated power below 56 kW
c) Category RLL (Railway Locomotives)
   - Engines used in locomotives
d) Category RLR (Railway Railcars)
   - Engines used in railcars
   - Engines used instead of RLL category engines under Stage V [38].

The first emission limits with the force of European Union law for the non-road vehicle group were introduced in the 1990s. The Stage standards were gradually implemented as increasingly strict regulations based on engine power (Tables 4–7). Type approval is granted when the power unit meets the requirements set out in the relevant directives and when the emission of toxic compounds in the exhaust gases complies with the limits defined by the applicable standard.

Table 4. Stage IIIA/B emission standards for locomotives and railcars [10]

Cat.	Power	Date	CO	HC	NO_x	PM
	[kW]		g/kWh			
Stage III A						
RC A	P > 130	2006	3.5	HC+NO_x = 4.0		0.2
RL A	130 ≤ P ≤ 560	2007	3.5	HC+NO_x = 4.0		0.2
RH A	P > 560	2009	3.5	0.5[1]	6.0[1]	0.2
Stage III B						
RC B	P > 130	2012	3.5	0.19	2.0	0.025
R B	P > 130	2012	3.5	HC+NO_x = 4.0		0.025

The emission of harmful exhaust compounds from NRMM vehicles in the European Union is assessed using two test cycles:

- NRSC (Non-Road Stationary Cycle) – a stationary test cycle used to measure toxic exhaust compounds (CO, HC, NO_x, PM) from non-road vehicles. It is applied under Stage I–V standards for CI engines operating at constant or variable speed with a net power output in the range of 19 kW ≤ P ≤ 560 kW. The NRSC test is also used to measure emissions from engines intended for use in locomotives and railcars (Stage IIIA/B).

– NRTC (Non-Road Transient Cycle) – a transient test cycle used to measure toxic exhaust compounds (CO, HC, NO_x, PM) from non-road vehicles. It is applied under Stage III B–V standards for compression ignition engines with a net power output in the range of 19 kW ≤ P ≤ 560 kW operating under variable speed conditions [17, 18, 37].

Table 5. Stage IIIA/B and Stage IV emission standards for rail vehicles [10]

Cat.	Power [kW]	Date	CO	HC	NO_x	PM
			g/kWh			
Stage III A						
H	130 ≤ P ≤ 560	2006	3.5	HC+NOx = 4.0		0.2
I	75 ≤ P < 130	2007	5.0	HC+NOx = 4.0		0.3
J	37 ≤ P < 75	2008	5.0	HC+NOx = 4.7		0.4
K	19 ≤ P < 37	2007	5.5	HC+NOx = 7.5		0.6
Stage III B						
L	130 ≤ P ≤ 560	2011	3.5	0.19	2.0	0.025
M	75 ≤ P < 130	2012	5.0	0.19	3.3	0.025
N	56 ≤ P < 75	2012	5.0	0.19	3.3	0.025
P	37 ≤ P < 56	2013	5.0	HC+NOx = 4.7		0.025
Stage IV						
Q	130 ≤ P ≤ 560	2014	3.5	0.19	0.4	0.025
R	56 ≤ P < 130	2014	5.0	0.19	0.4	0.025
[1] HC = 0.4 g/kWh, NO_x = 7.4 g/kWh for engines with power P > 2000 kW and displacement D > 5 dm³/cylinder						

Table 6. Stage V emission standards for engines of category NRE [10]

Cat.	Power [kW]	Date	CO	HC	NO_x	PM	PN
			g/kWh				1/kWh
NRE-v/c-1	P < 8[1)]	2019	8.0	HC+NO_x = 7.5		0.4	–
NRE-v/c-2	8 ≤ P < 19[1)]	2019	6.6	HC+NO_x = 7.5		0.4	–
NRE-v/c-3	19 ≤ P < 37[1)]	2019	5.0	HC+NO_x = 4.7		0.015	1×10^{12}
NRE-v/c-4	37 ≤ P < 56[1)]	2019	5.0	HC+NO_x = 4.7		0.015	1×10^{12}
NRE-v/c-5	56 ≤ P < 130[2)]	2019	5.0	0.19	0.4	0.015	1×10^{12}
NRE-v/c-6	130 ≤ P ≤ 560[2)]	2019	3.5	0.19	0.4	0.015	1×10^{12}
NRE-v/c-7	P > 560[2)]	2019	3.5	0.19	3.5	0.045	–
[1)] Ignition – CI [2)] Ignition – CI, SI							

Table 7. Stage V emission standards for locomotive and railcar propulsion systems [10]

Cat.	Power [kW]	Date	CO	HC	NO_x	PM	PN
			g/kWh				1/kWh
RC A	P > 0[1)]	2021	3.5	HC+NO_x = 4.0		0.025	–
RL A	P > 0[1)]	2021	3.5	0.19	2.0	0.025	1×10^{12}
[1)] Ignition – CI, SI							

In emission tests of exhaust systems, measurements are performed for gaseous compounds (CO, HC, NO_x) as well as PM. CO_2 is often used as a reference gas to determine the dilution level in both full-flow and partial-flow dilution systems. Additionally, it is recommended to monitor CO_2 concentrations due to their usefulness in detecting measurement issues during the test based on their readings. The stationary test cycle consists of a strictly defined number of engine speed and load phases, designed to represent the typical operating ranges of non-road mobile machinery engines. In all test phases, the concentrations of harmful exhaust compounds, exhaust gas flow rate, engine power, and the weighted average of measured values are determined. Pollutants from the vehicle's exhaust system are measured continuously by sampling undiluted exhaust gas under precisely defined operating conditions with a warmed-up engine. PM is measured by collecting the sample on a suitable filter, which is then diluted using conditioned ambient air. The PM sample can either be collected as a single sample for the entire test or as individual samples on separate filters for each test phase, with a weighted average then calculated for the whole test. The method for calculating the specific emission of pollutants (g/kWh), i.e., the number of grams of all measured harmful compounds per unit of work performed, is strictly defined. The NRSC includes various profiles that define how the measurement test is conducted for different types of equipment as specified in Directive 2004/26/EC [17, 18, 37].

3. Measurement of harmful exhaust emissions in laboratory tests

The primary tests for measuring exhaust emissions are dynamometer tests conducted under laboratory conditions. These measurements aim to simulate real-world vehicle operating conditions, with the resulting emission data often serving as input for models assessing the impact of road traffic on air quality. Laboratory measurements are divided into two groups. The first group consists of engine dynamometer tests, where the engine is mounted directly on a test bench and equipped with only the components necessary for its proper functioning. The second group involves chassis dynamometer tests, where vehicles are tested on rollers that simulate road conditions. The main advantage of laboratory tests is their ability to perform multiple measurement cycles at relatively low costs. However, the results are only approximate, as the tests do not account for factors such as road conditions, driver behaviour, or the quality of ambient air. Consequently, most test cycles conducted on dynamometers do not accurately reflect the actual operating conditions of vehicles in urban traffic [55]. Literature analyses confirm significant differences between parameters measured in laboratory and real-world conditions [3, 51, 88]. Additionally, most tests are conducted on new or minimally used engines, which are in much better technical condition than the majority of vehicles on the road. This highlights the need to consider the degree of wear and tear of tested vehicles, as it significantly impacts exhaust emissions. Numerous studies [6, 9, 62, 90–92] have demonstrated that old and worn-out vehicles pose the greatest threat to the environment and human health. As a result, several alternative methods have been developed in recent years to obtain more reliable results. One of the first approaches involved the creation of dynamic test cycles that simulate specific driving conditions [2, 83]. Another approach involved conducting tests under real-world operating conditions.

4. Measurement of harmful exhaust emissions in real-world operating conditions

Homologation regulations currently mandate that emissions measurements for passenger cars must be conducted on the road, using specially designed RDE tests with PEMS [95]. The program for the RDE test is a development of the stationary World Wide Harmonised Light Vehicle Test

Procedure (WLTP). The WLTP test is performed on a car dynamometer and consists of four phases, which are different due to speed and driving dynamics. Phases in WLTP test are: low, medium, high, and extra-high. The test applies to passenger cars and delivery vans.

The driving test in the RDE procedure consists of a sequence of three driving stages: urban, rural, and motorway, which are classified based on instantaneous speed, with their proportions expressed as a percentage of the total driving distance (tab. 8). The test covers approximately (±10%) 34% urban driving with vehicle speeds not exceeding 60 km/h, 33% rural driving with speeds between 60 km/h and 90 km/h, and 33% motorway driving with vehicle speeds above 90 km/h. The total duration of the test is between 90 and 120 minutes, and the minimum distance covered in urban, rural, and motorway segments must be 16 km for each stage. Due to these requirements, such measurements are very time-consuming and require substantial financial resources.

Table 8. RDE test driving conditions [67]

Parameter	Requirements		
Segment	urban	rural	motorway
Duration of test	90–120 min		
Proportion of test time	29–44%	23–43%	23–43%
Minimum distance	16 km	16 km	16 km
Vehicle speed	v ≥ 60 km/h	60km/h < v ≤ 90 km/h	v > 90 km/h
Average vehicle speed	15–40 km/h	–	–
v > 100 km/h	–	–	≥ 5 min
v > 140 km/h	–	–	< 3% of motorway driving time
Stops during urban driving	6–30% of the urban segment time	–	–
Cumulative positive altitude gain	< 1200 m/100 km		
Difference in altitude (start vs. end)	≤ 100 m		

Real-world testing aims to verify the ecological performance of vehicles across a wide spectrum of operating conditions [96]. These measurements primarily focus on assessing the impact of applied powertrain systems and vehicle parameters on emissions of harmful substances and identifying differences between homologation procedures and real-world usage. Numerous global tests have demonstrated significant discrepancies between dynamometer-based laboratory tests and real-world road tests, particularly concerning nitrogen oxides [5, 42, 65]. Advancements in measurement equipment miniaturization have enabled increasingly precise studies in real-world operating conditions.

Moreover, the application potential of such devices continues to expand, allowing the inclusion of specific movement patterns for different vehicle types (road, off-road, including rail). However, there are certain limitations to using PEMS equipment. Primarily, the measurement analyzers must be installed on the test vehicle, and the measurement probes must be directly integrated into the exhaust system [64, 78, 87]. The installation process is often time-consuming, and it is not always feasible to use exhaust gas flow meters, which streamline the testing process. Consequently, flow characteristics often must be determined using data on intake manifold pressure, post-turbocharger temperature, and crankshaft rotational speed.

RDE procedures, however, cover only passenger cars and delivery vans, and there are no specific regulations yet for testing NRMM under real-world conditions. These vehicles, or more specifically their combustion engines, are only tested in laboratory conditions using engine dynamometers. The operational characteristics of engines for Stage standards are predetermined. For static tests, NRSC is tailored for specific engine groups, while the dynamic NRTC serves as a common test for all vehicle types. Both tests are mandatory, but they often fail to replicate real-world operating conditions. The latest regulations regarding NRMM emissions include provisions for real-world testing [31], but they lack defined research procedures or specific emission limits for harmful exhaust gases in such tests.

Real-world operating condition tests are a very modern solution designed to accurately reproduce the conditions prevailing during normal vehicle operations. However, such tests are primarily conducted on new vehicles that are being approved for road use, as mandated by homologation regulations. Older and more heavily used vehicles, which pose the greatest risk to the environment and human health, are typically only tested in research centres for scientific purposes or, more commonly, during inspections at Vehicle Inspection Stations. These inspections rely on basic and often imprecise equipment, which often yields unreliable results. As a result, there is ongoing development of measurement methods that do not require interference with the vehicle's structure and involve significantly lower financial costs [62, 90–92].

5. Remote sensing measurements

5.1. Tunnel studies

An alternative to PEMS-based testing is remote sensing measurements, which allow for the evaluation of vehicle emissions without the need to install equipment on the tested vehicles. These systems record instantaneous measurements of exhaust concentrations from passing vehicles, enabling the testing of a large number of vehicles in a short period and at low unit costs. Three main remote sensing systems can be distinguished: tunnel studies, the extractive method, and the open-path system. A comprehensive literature review revealed numerous solutions for measuring emissions from passenger cars and heavy vehicles, but there is a lack of research regarding such measurements for rail vehicles. Tunnel studies (Fig. 4) [48, 49, 81] are conducted for groups of vehicles, and harmful exhaust emissions are measured for the studied area.

In this type of research, a ventilation system is commonly used to collect samples. A reference gas sample is introduced prior to measurement. Air samples are collected at several measurement points, enabling the determination of average concentrations across a cross-section. These samples are stored in special bags or are sent directly to measurement devices at a defined flow rate. The collected pollutants are then analyzed using specific analyzers for measuring harmful exhaust gases. For CO_2 and CO measurements, NDIR (Non-Dispersive Infrared) analyzers or related technologies are commonly used [48, 57, 63]. NO_x measurements employ chemiluminescent detectors [48, 57, 63, 81], while HC is measured using a Flame Ionization Detector (FID) [57, 63, 85]. PM is analyzed using gravimetric methods [57, 58, 60]. Tunnel-based emission studies were first implemented in the late 1970s [68], and over time, these measurements have been widely adopted in the United States [40, 77, 79] and other countries [48, 58, 80, 86].

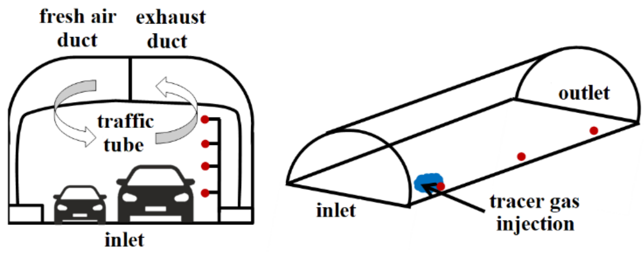

Fig. 4. Tunnel test method for exhaust gas sampling, where red dots (●) indicate the locations of measurement points [48, 49, 80]

The main advantage of tunnel studies is the location where the measurements are conducted. Tunnel walls and the use of air filtration systems act as barriers against external factors, such as pollution from vehicles outside the tunnel or from local stationary sources. Additionally, the tunnel's ventilation system facilitates the measurement of airflows. Another advantage of tunnel studies is the ease of setting up measurement equipment. However, research [50, 69] has shown that local emission models often significantly differ from real-world values, particularly for CO and HC results, which were found to be approximately half the actual values. This discrepancy raises concerns about the accuracy of the obtained measurement results.

5.2. Extractive method

Another type of remote sensing study is the extractive method (Fig. 4) [71, 72, 93]. This approach utilizes the principle of extractive remote sensing, where a sample of exhaust gas is collected and analysed by a specialized system. A test setup for this method can be mounted on a mobile research unit equipped with devices that capture exhaust gases. In this case, the test vehicle follows the analysed vehicle, capturing a portion of the emitted exhaust gases. The collected gases are then directed to specialized analysers for identification and measurement. Alternatively, stationary measurement points can be used, which continuously sample air, with the samples being taken near the vehicle's exhaust outlet. The extractive remote sensing technique is characterized by high precision due to the advanced technology of the analysers used.

However, a limitation of this method is the relatively small number of vehicles that can be tested simultaneously [8]. In most cases, extractive studies rely on specially adapted air monitoring systems that are modified by researchers [4, 41, 43]. The equipment used in these studies typically includes NDIR analysers for CO measurements [4, 11, 53], chemiluminescent analysers for NO [4, 11], and NDUV (Non-Dispersive Ultraviolet) analysers for O_3 [11], as well as optical particle counters for PM [11, 41, 89]. A review of the literature indicates that extractive studies have yet to define specific emission or concentration thresholds for the tested vehicles.

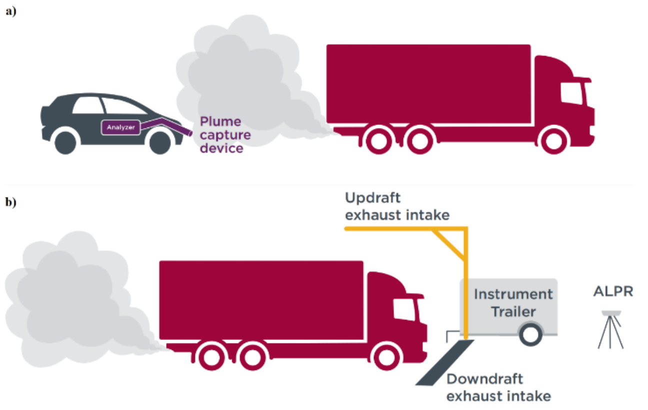

Fig. 5. Method of sampling exhaust gases using extraction remote sensing using a) mobile measuring point, b) stationary measuring point [8]

5.3. Open-path system

Another type of remote sensing system is the open-path method, which utilizes a light source and a detector placed either at the roadside or above the roadway (Fig. 5) [59, 94]. The light source, operating in the infrared or ultraviolet spectrum, is reflected by a mirror located on the opposite side of the road. Exhaust gases passing through the light beam absorb part of the radiation, allowing the concentrations of specific pollutants to be determined. This measurement occurs as the vehicle passes through the beam. The monitoring equipment also records environmental conditions, enabling the registration and control of surrounding air quality, which allows for the separation of background pollutants from those emitted by the analysed vehicle. This type of remote sensing station also facilitates the measurement of vehicle speed, acceleration, and the identification of license plates using cameras [8].

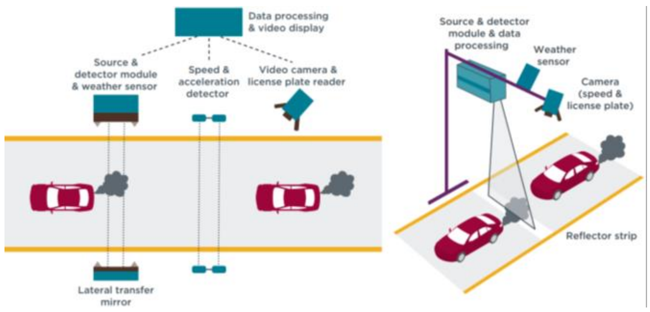

Fig. 6. Open path measurement scheme: a) configuration used at intersections, b) top-down detection system [8]

However, the open-path method has some limitations, such as differences in scanning time due to gaps between vehicles or variability in the composition of background air. Another issue is the significant uncertainty of results caused by the length of the measurement path, which often necessitates normalizing the data relative to CO_2 emissions [70, 73, 84]. Remote sensing studies of this type typically last several weeks or months, allowing data to be collected for a very large fleet of vehicles. Remote sensing devices are most commonly used to measure concentrations of CO, HC, NO, and PM. The scientific literature reports typical values for these pollutants as follows: CO ranging from 0.2% to 3.5% [54, 76, 82], HC ranging from 0.004% to 0.22% [54, 76, 82], and NO ranging from 35 ppm to 1000 ppm [54, 76, 82].

A review of the literature shows that for over a decade, researchers from various scientific institutions worldwide have been working on developing devices to assess emissions under both real-world and laboratory conditions [2, 3, 61, 65, 67]. However, the technologies developed so far remain insufficient. Given the persistent issue of harmful emissions from combustion vehicles, further research utilizing more advanced measurement technologies is necessary [7].

6. Summary

Due to the significant impact of transportation on air pollution, new regulations are being implemented to reduce harmful exhaust emissions. The European Union's primary goal is to introduce regulations for zero CO_2 emissions from vehicles by 2035. Intermediate emission reduction targets for 2030 have been set at 55% for passenger cars and 50% for commercial vehicles [39]. The final version of these regulations was approved by the European Parliament in February 2023. The overarching objective of these actions is to achieve a 90% reduction in greenhouse gas emissions from transportation by 2050 compared to 1990 levels, supporting the attainment of climate neutrality under the European Green Deal. However, transportation is the only sector where greenhouse gas emissions increased over the past three decades, rising by 33.5% between 1990 and 2019. Significant reductions in CO_2 emissions will therefore not be easy, as the rate of reduction has slowed.

Current forecasts indicate that emissions from the transportation sector will decrease by only 22% by 2050, far below the established goals [39]. Achieving the desired targets and addressing the health crisis caused by air pollution will require swift and comprehensive actions. In highly developed economies, various solutions are being implemented to improve air quality, such as establishing low-emission zones in city centres. The effectiveness of such zones can be assessed through remote sensing devices that measure harmful exhaust emissions from vehicles operating in these areas. The main advantage of such measurements is obtaining real-world data on the state of vehicles operating within a specific area, including compliance with legislative standards and the level of wear and tear of the vehicles. Remote sensing enables the determination of pollutant concentrations emitted by vehicles within and outside low-emission zones. This provides valuable insights into the actual impact of these zones in reducing automotive-related environmental pollution.

Additionally, this type of research can identify and exclude vehicles that excessively emit harmful substances, reducing their negative impact on the environment and public health. High-emission vehicles can then undergo diagnostics to identify the source of the issue. This approach encourages faster action from vehicle owners to repair or replace damaged components. In cases where repairs are not economically viable, the vehicles should be retired and replaced with modern, more environmentally friendly models. This strategy effectively reduces emissions and promotes more sustainable vehicle use. It is also essential to conduct similar studies in the non-road transport sector. Rail vehicles, especially older and heavily used units, are significant sources of harmful emissions, and research on their emissions remains limited and insufficient. Applying remote sensing systems to railways would, as with road vehicles, allow for the identification of units emitting excessive pollutants and enable corrective actions. A lack of action in the non-road vehicle sector risks the continued operation of vehicles that significantly exceed homologation limits, posing threats to human health and contributing to environmental degradation. Introducing remote sensing studies for rail vehicles is, therefore, not only necessary but also a critical step toward sustainable railway transport.

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Nomenclature

CF	conformity factors
CI	compression-ignition
CO	carbon monoxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
DI	direct fuel injection
FID	flame ionization detector
GBD	global burden of disease study
GHG	green house gases
HC	hydrocarbons
NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
NMHC	non-methane hydrocarbons
NO_x	nitrogen oxides
NRE	engines for non-road mobile machinery
NRMM	non-road mobile machinery
NRS	spark ignition engines for non-road mobile machinery
NRSC	non-road steady cycle
NRTC	non-road transient cycle
NTE	Not-To-Exceed emission limit
O_3	ozone
OBD	onboard diagnostic
PEMS	portable emissions measurement systems
PM	particulate mass
PN	particle number

RDE	real driving emission
SI	spark-ignition
THC	total hydrocarbons
WHO	World Health Organization
WLTP	World Wide Harmonised Light Vehicle Test Procedure

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