Chapter 6
Measurements of Exhaust Emissions In-use Conditions

6.1 Testing Possibilities

The growth in the global vehicle number and in environmental pollution result in increased requirements with respect to reducing the exhaust emissions. State of the art techniques and technologies in all industries (including all modes of transport) induce ever-greater requirements as regards manufacturing of exhaust gas emission measurement devices. Recent studies under actual in-use conditions show that the emission of certain toxic substances is by several hundred percent greater than measured on test benches, and the range of measured values is incomparably greater than in steady-state tests [3, 7, 11]. Therefore, there is a visible trend speaking in favor of sanctioning emission testing under actual traffic conditions.

An analysis of global environmental trends shows that in order to efficiently reduce pollution it is necessary to measure toxic gas emissions under actual conditions. The Institute of Combustion Engines and Transport at Poznań University of Technology is in possession of a system of portable analyzers (Fig. 6.1) enabling exhaust gas emission measurements from vehicles not only in steady state, but also dynamically, e.g. during engine start, and also in transition phases between two processes (e.g. particulate filter regeneration). The portable analyzers unit allows making all-inclusive on-board measurements of the exhaust gas emissions, in real time and on road from vehicles running on different fuels (petrol, diesel, LPG, CNG, E85, etc.), as well as hybrid vehicles.

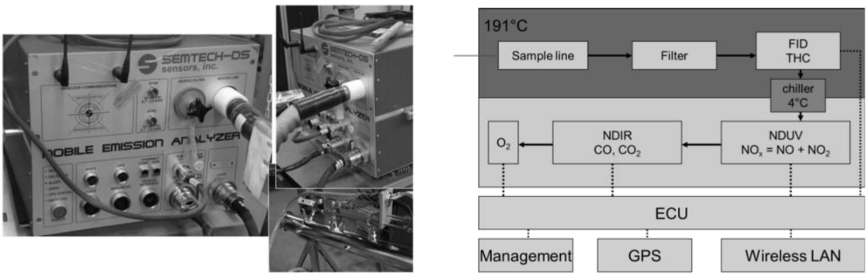

Fig. 6.1 Portable analyzer for gaseous compounds concentration measurement, incl. layout

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Studies held so far and their results pointed out to the need to improve the measurement of PM emission. Therefore, the Combustion Engines Laboratory received state-of-the-art equipment for PM measurements under actual conditions. The following devices were purchased: portable particle measurement device (PPMD) by Sensors Inc. (Fig. 6.2), AVL Particle Counter (Fig. 6.3) and Engine Exhaust Particle Sizer (Fig. 6.4).

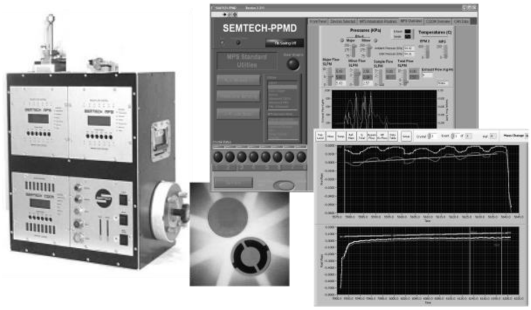


Fig. 6.2 Portable particle measuring device (PPMD) in use (Semtech)

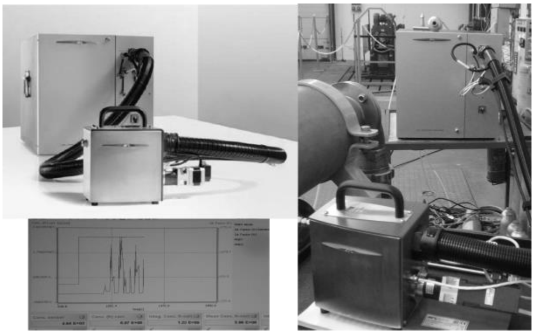


Fig. 6.3 AVL Particle Counter

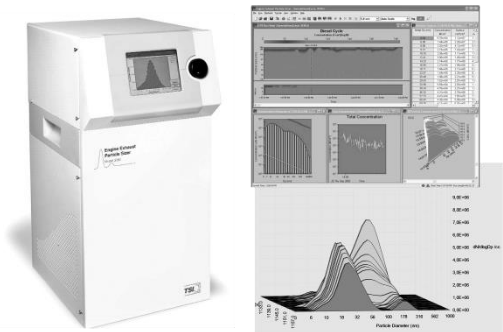


Fig. 6.4 TSI's engine exhaust particle sizer (EEPS)

Thus, the Laboratory can now measure particle sizes and numbers within a given size range and treat the sample as required for testing by means of a dilution tunnel. Such equipment enables not only steady-state, but also dynamic measurements, e.g. during engine start, and also in transition phases between two processes (e.g. particulate filter regeneration) (Fig. 6.5).

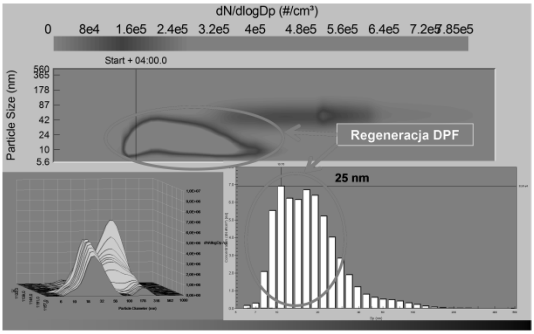


Fig. 6.5 Spectrum analysis of particle sizes during particulate filter regeneration

Legal regulations regarding exhaust gas toxicity will require measurement of the PM number discharged from vehicles. Thus, the above investment was in keeping with global changes in internal combustion engine testing. Together with the particle sizing device it forms complete testing equipment for measuring emissions from internal combustion engines tested not only on a test bench, but also in service. Remarkably, the above equipment – unique on a global scale – provides instant measurement results for all exhaust gas components, which allows one to quickly draw conclusions from the test. Thanks to the newly acquired equipment, the Laboratory can meet EU requirements on reducing the emissions of pollutants and on the validation of research on combustion processes.

6.2 Tests of Passenger Cars Fitted with Different Propulsion Systems

6.2.1 Conventional Drive Vehicles

Verification tests with respect to pollutant emissions from passenger vehicles fitted with internal combustion engines (SI, CI, CNG, Euro 4 compliant – Fig. 6.6) carried out under actual conditions were aimed at developing an on-board system for measuring exhaust emissions. Emission measurement under actual conditions (see results visualized in Fig. 6.7) and its comparison with data collected on a chassis dynamometer in the type approval test allows determining the emission factor. The emission factor answers the following question: is emission under actual conditions comparable to emission during type approval tests? Simultaneously, the said factor verifies driving conditions in the type approval test (developed decades ago) against actual vehicle traffic conditions.

Fig. 6.6 Passenger cars during on-road tests (fitted with various types of internal combustion engines and running on petrol, diesel and CNG)

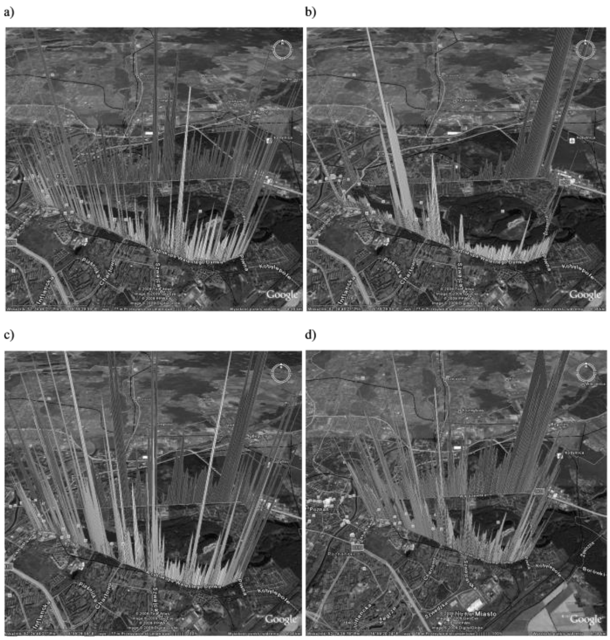


Fig. 6.7 Visualization of emission of pollutants measured during on-road tests: a) carbon monoxide, b) hydrocarbons, c) nitrogen oxides, d) carbon dioxide (the same scale was used for each compound); color codes: – SI, – CI, – CNG

The data on concentrations of each pollutant can be useful in identifying relationships describing the effect of the vehicle's dynamic performance on exhaust emissions. Such relationships are accounted for in an indirect way, by using the distribution of the entire range of vehicle speeds and the calculated acceleration range in actual traffic for the purpose of developing emission rate matrices. The data used are averaged within each speed and acceleration interval, thus providing characteristic information about the percentage of engine operation in each characteristic interval, e.g. engine speed – load (Fig. 6.8).

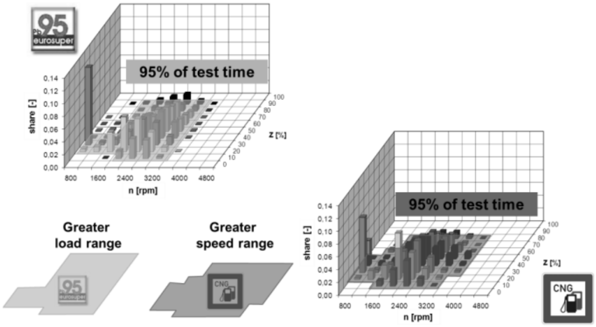


Fig. 6.8 Operation time percentages of a vehicle running on petrol and on CNG during tests under actual conditions

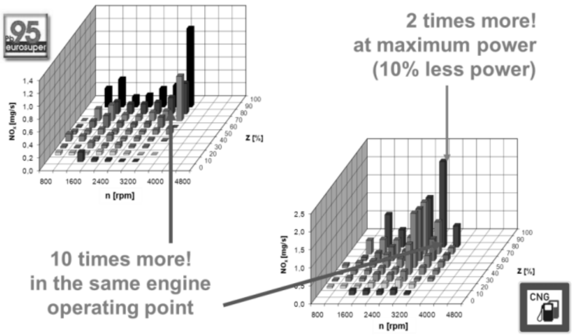


Fig. 6.9 Comparison of nitrogen oxide emission rate in testing under actual conditions (passenger cars)

The area of increased nitrogen oxide emission rate coincides with maximum vehicle speed and acceleration, i.e. with considerable engine loads. This phenomenon is linked to increased fuel consumption and greater engine speed. In the remaining intervals of engine operation for a vehicle running on petrol the emission rate is 0.1–0.3 mg/s, whereas for an engine running on CNG the same value grows to 0.5–1.5 mg/s. For average speed and acceleration values, the intensity of nitrogen oxide emissions from a vehicle running on CNG is 5 times greater than from a vehicle running on petrol. For the maximum power, the said intensity is over twice greater than for the petrol engine (even though the resultant power is by 10% smaller). Furthermore, in certain engine operating points the intensity of NO_X

emissions from the CNG engine is more than 10 times greater than from the petrol engine (Fig. 6.9).

Emission rate characteristics are used to calculate the multiplicity of emission increase (decrease) under actual conditions as compared to the type approval test. The emission factor of a given pollutant has been defined as:

$$k_j = \frac{e_{real,j}}{e_{\mathrm{NEDC},j}} \tag{6.1}$$

where: j – pollutant for which the emission factor has been defined,
$e_{real,j}$ – emission rate under actual conditions ([g/s]),
$e_{\mathrm{NEDC},j}$ – emission rate in the NEDC test ([g/s]).

Emission rate under actual conditions can be calculated using the characteristics of the vehicle drive time distribution $u(a,v)$ and the emission rate characteristic for the j pollutant $e_j(a,v)$ expressed in grams per second:

$$e_{real,j} = \sum_a \sum_v \left[u(a,v) \cdot e_j(a,v)\right] \tag{6.2}$$

In the absence of information on the vehicle's pollutant emission rate in the NEDC test, one can use the limits prescribed by the Euro exhaust gas standard applicable to the vehicle in question. The values of emission allowed for a given compound (stated in g/km) can be converted to emission rate (g/s), since the duration and the distance traveled during the type approval test are known (1180 seconds and 11,007 meters, respectively). The above relationships serve the purpose of determining emission factors for each pollutant for the vehicle in question (Fig. 6.10).

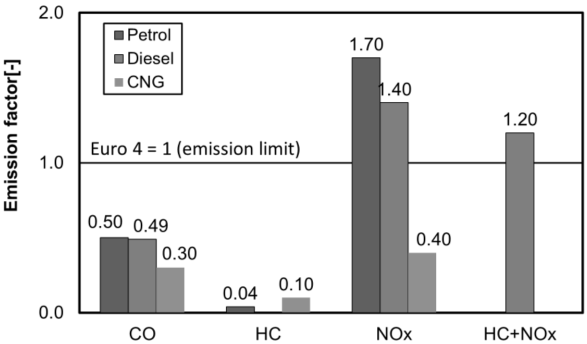


Fig. 6.10 Comparison of the emission factor using actual emission data in the NEDC test or using the limits prescribed in Euro 4

The emission factor for a vehicle running on petrol, diesel and CNG denotes the vehicle's emission under actual conditions as compared to the emission standard applicable to that vehicle. Emission factors for carbon monoxide (k_{CO} = 0.3–0.5) and hydrocarbons (k_{HC} = 0.04–0.1) for all tested vehicles indicate that the average emission of the said compounds does not exceed Euro 4. However, in the case of nitrogen oxides, only for vehicles running on CNG the emission factor is 0.4 (emission below the prescribed limit); for other vehicles the same factor equals k_{NO_x} = 1.4–1.7, so the average emission is by 40 to 70% above the limit prescribed in Euro 4. For the sum of HC + NO_X emissions (Euro 4 prescribes a limit for the sum of those compounds for CI engines) the emission factor is above 1 (k_{HC+NO_x} = 1.2), and thus the standard (to which the vehicle was type-approved) is exceeded by 20%.

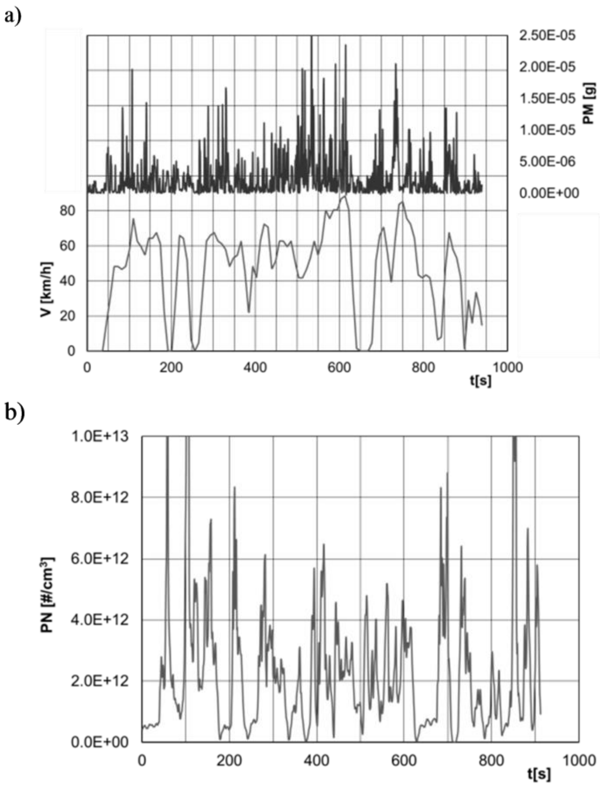
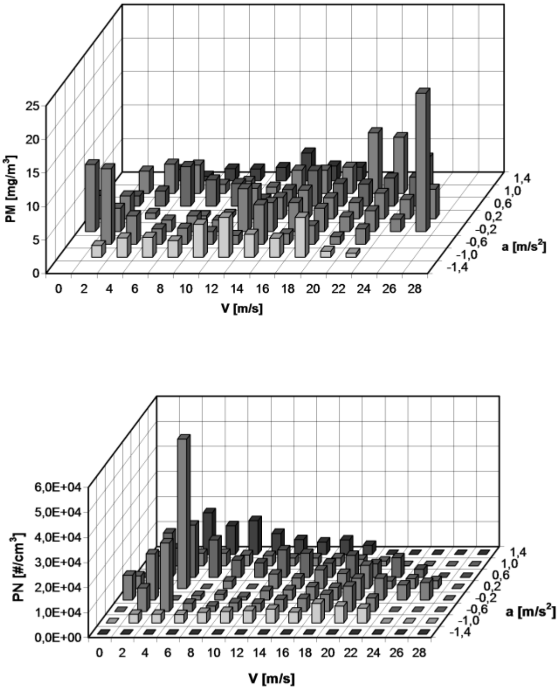


Fig. 6.11 Time traces from on-road tests: a) vehicle speed and PM mass, b) particle number

Vehicles can be compared not only in terms of gaseous compounds, but also in terms of mass and size emission of particulate matter [2, 10, 12]. PM mass (Fig. 6.11a,b) emitted in each tested interval is correlated with vehicle speed: greatest emissions have been observed at dynamic engine states (sudden acceleration). Particle numbers have been measured as well (Fig. 6.12a,b) – in this case, data a)



b)

Fig. 6.12 Distribution of PM mass (a) and particle number (b) against vehicle operating conditions in on-road tests

analysis shows *inter alia* a relationship with vehicle speed. However, this qualitative assertion does not provide any quantitative information – in order to obtain quantitative data, time density maps were used to determine mass and cumulative second-by-second emission, as a result of which the average emission of each of the discussed pollutants was determined.

The above data on vehicle speed and acceleration can also be analyzed against engine operation percentage. The said data were averaged for each engine speed and load interval, and then PM mass and particle number intensity matrices were developed. The areas of maximum concentration of particulates (Fig. 6.13a) as a function of engine speed and load are observed in several operating points of the engine. The greatest concentration occurs at a low engine speed (1200 rpm) and average (50%) engine load. Similarly high values of PM concentration can be observed at low engine load and high engine speed (10%, 2800 rpm, respectively); average load and low speed (40–50%, 800–1200 rpm) and high load (80–90%) and low and average (800 and 2400 rpm) speeds. Furthermore, characteristics of particle concentration as a function of engine speed and load were developed as well (Fig. 6.13b): the maximum value occurs at minimum speed (800 rpm) and average load (40%).

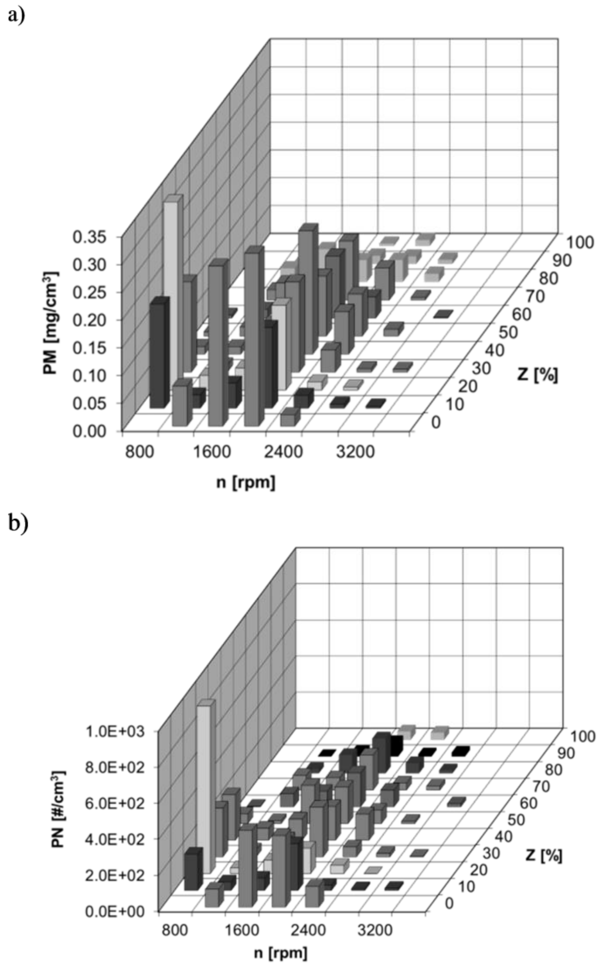


Fig. 6.13 Distribution of PM mass (a) and particle number (b) against engine operating conditions in on-road tests

On the basis of the above data particle concentration depending on engine load and speed has been visualized (Fig. 6.14). A characteristic distribution of particle sizes recorded in the tested engine operation states has been presented. To ensure graph comparability, a uniform scale on the particle concentration axis has been used. Each area determined by engine speed and load is characteristic for different spectral distribution of particles. The greatest number of the smallest particles is emitted when the engine is operating at high loads and average speeds (Fig. 6.14, area 8). Particles of greater diameters are regularly captured by the particulate filter.

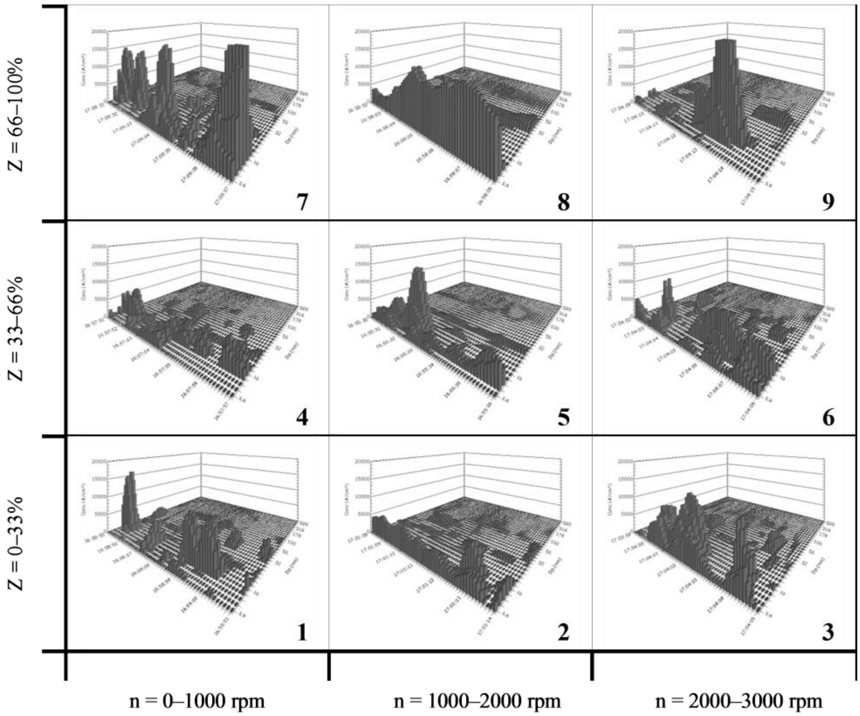


Fig. 6.14 Characteristics of particle concentration in different measurement points (the vertical axis scale denoting particle number per cubic centimeter is constant across all graphs)

An alternative approach to emission of PM and PN was presented using the example of SUV vehicles fitted with CI engines. Two vehicles were compared: vehicle A – without a particulate filter, conforming to Euro 4, and vehicle B – fitted with a particulate filter, conforming to Euro 5.

The methodology developed for the above test uses those engine operation ranges that are most commonly used under actual conditions. They correspond to four operation areas (Fig. 6.15): *1* – idling speed, *2* – medium engine speed – low load, *3* – medium engine speed – medium load, *4* – high engine speed – high load. The vehicles were fitted with different engines, which is why the working ranges are not identical (the compared areas were similar in terms of relative engine speed and relative load measured against maximum values). For vehicle A, most measurement points occur in the range of significant engine speeds and high load (area *4*). For vehicle B the points are distributed in a different manner: most of them coincide with medium speed and medium load (areas *2* and *3* in Fig. 6.15b) and with high engine speeds and high load (area *4* in Fig. 6.15b).

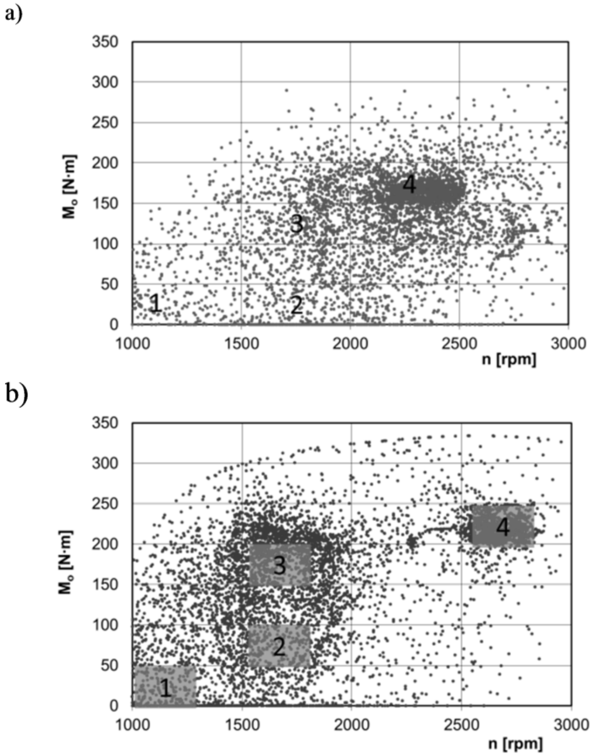


Fig. 6.15 Engine states in the coordinates of engine speed and load in on-road tests: a) vehicle A; b) vehicle B (the numbers denote operation areas for which PN size distribution was determined)

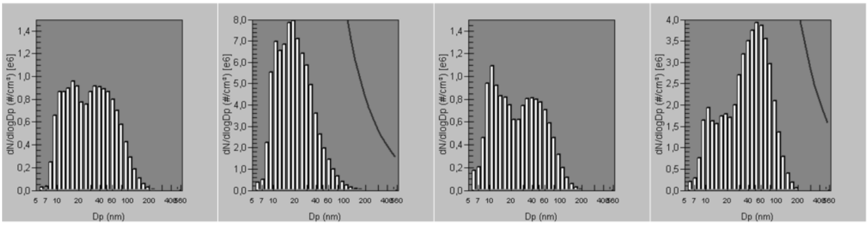
The said characteristic engine operating ranges were analyzed for average particle sizes (for vehicle A – without particulate filter, see Fig. 6.16a):

- range 1 (engine idling speed) – particle diameters in the range 10–100 nm are distributed evenly, particles of approx. 60 to 80 nm are the most numerous; particle concentration for the operating range in each size interval equals 0.8–1×10^6 cm^{-3}, which results from a high excess air coefficient value and time necessary to burn a minimum fuel delivery;
- range 2 (average engine speed – low load) – particle diameters in the range 10–100 nm, with most particles of 20 nm; particle concentration for the size interval of approx. 20 nm (greatest share of such particles in exhaust gas) equals 7–8×10^6 cm^{-3};
- range 3 (average engine speed – average load) – particle diameters in the range 7–100 nm, with a domination of particles of approx. 10 nm and 40–60 nm; particle concentration for these size intervals is equal to 0.8–1×10^6 cm^{-3}; these values, similar to the idling speed range, result from high excess air (supercharged engine) and high fuel injection pressure (approx. 130 MPa);

- range 4 (high engine speed – high load) – particle diameters in the range 7–150 nm; with most particles of 40–100 nm; particle concentration for this size intervals is equal to 3.5–4×10^{6} cm^{-3}; characteristic particle size values for this range are greater than in the other ranges, which mostly results from a greater fuel delivery, lower excess air coefficient and shorter fuel burning time.

a)

1 2 3 4



b)

1 2 3 4

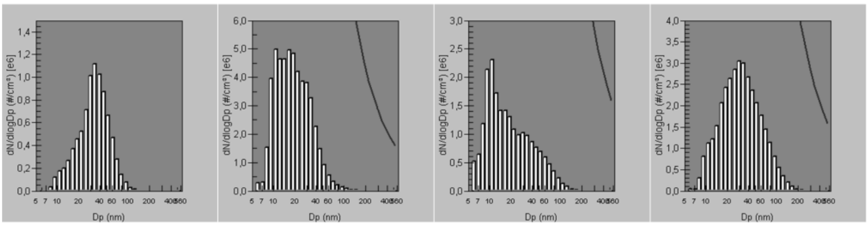


Fig. 6.16 Particle size distribution under actual traffic conditions for a vehicle without (a) and with (b) particulate filter (operating ranges are defined in Fig. 6.15): *1* – idling speed, *2* – medium engine speed – low load, *3* – medium engine speed – medium load, *4* – high engine speed – high load

For vehicle B fitted with the particulate filter, the particle size analysis (Fig. 6.16b) is different in terms of both size range and concentration values (particle numbers are smaller in most size intervals):

- range 1 (engine idling speed) – the characteristic particle diameter (most common for all particles) is approximately 30 nm; particle concentration for this range is 1×10^{6} cm^{-3};
- range 2 (medium engine speed – low load) – particle dimensions of 10–30 nm; particle concentration for this range: 4–5×10^{6} cm^{-3};
- range 3 (medium engine speed – medium load) – particle dimensions of 10–100 nm, with 10 nm being the most common; particle concentration for this range: 1.5–2.2×10^{6} cm^{-3};
- range 4 (high engine speed – high load) – particle dimensions of 10–150 nm; most particles in the range of 30–50 nm; particle concentration for this diameter range: 3×10^{6} cm^{-3}.

On-road tests enable watching the particulate filter regeneration process (driving on a highway, vehicle speed of approx. 120 km/h – Fig. 6.17). Particle size analysis shows emissions of significant PM concentration during the said process: the beginning of regeneration is characteristic for higher concentration of particles sized 20–30 nm (approx. 8×10^5 cm^{-3}), whereas the final stage of the process is dominated by smaller particles, of approx. 10 nm in diameter (approx. 1.3×10^6 cm^{-3}. The first regeneration period (the initial 3 to 4 minutes) is characterized by a greater range of sizes (7–100 nm); in the next stage (4 to 10 minutes) the range of particle sizes is less diversified (5–25 nm). It should be noted that no significant particle mass was recorded in this period. Standard PM emissions prescribed in Euro 5 take particulate filter regeneration into account, which means that the prescribed limit must not be exceeded, whether or not the process is taking place [43, 51].

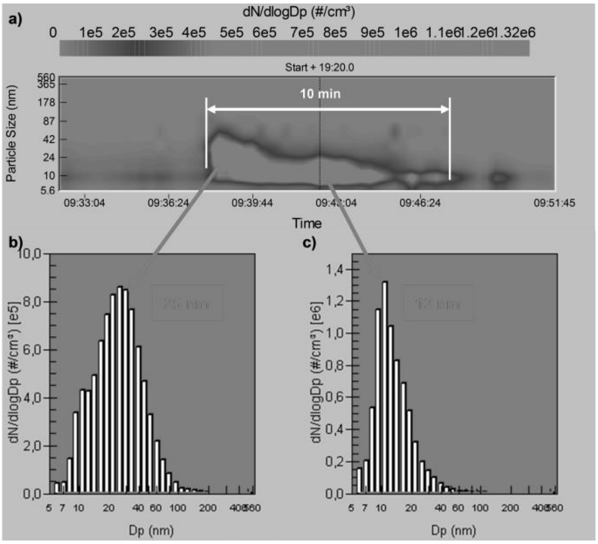


Fig. 6.17 Recorded particulate filter regeneration process

The emission factor k_{PM} regarding PM can be calculated as:

- instantaneous value (shown in green in Figure 6.18) – such a value is characterized by significant variability, as it is measured on a second-by-second basis,
- cumulative value for the entire test, calculated as the current emission of a given pollutant (cumulatively from the beginning of the test) compared to the standard value; this value is shown in blue in Fig. 6.18,
- value for the entire test, comparing emissions in an on-road test under actual conditions to the standard value.

The emission factor for a given pollutant can be anything in the range <0,∞). This means that if emission from a vehicle does not exceed the prescribed limit, the factor is less than one, and if the limit is exceeded, the factor is above one. If the actual emission is equal to the prescribed limit, the factor will be equal to 1.

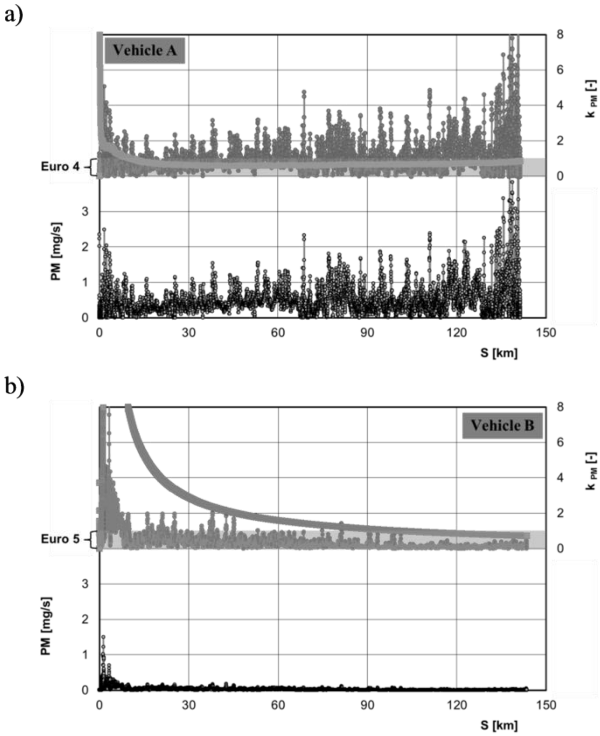


Fig. 6.18 PM emission rates in on-road tests of SUVs as a function of traveled distance: a) vehicle without particulate filter – Euro 4, b) vehicle with particulate filter – Euro 5

The PM emission factor variability differs between the vehicles: for vehicle A the value of $k < 1$ (in Euro 4 the PM limit is 25 mg/km) is achieved very rapidly, whereas for vehicle B the factor value dropped below one only after approximately 90 km, despite the use of a particulate filter; the underlying reason is that the PM emission limit in Euro 5 is very low (5 mg/km).

6.2.2 Vehicles Fitted with Start/Stop Systems

The global automotive industry is currently undergoing profound changes linked to such issues as environmental pollution, global warming, generation of waste or aging societies in the developed countries. Therefore, environmental aspects have become a priority.

In the recent years an increasing amount of attention has been paid to the hybrid technology. The hybrid system is defined as a propulsion with two different energy sources or two different propulsion sources. Contemporary hybrid electric vehicles (HEVs) can be divided into three classes, differing in terms of functionality: *micro hybrid*, *mild* and *full hybrid*.

Due to a relatively low power of the additional (secondary) energy source, start/stop systems are classified as micro hybrid. The purpose of such systems is to automatically switch off the combustion engine whenever the vehicle comes to a stop. To make that possible, a number of conditions must be satisfied simultaneously. The engine is restarted when the driver wants the car to move again. Start/stop systems offer significant fuel economy gains – an average of 10% in urban cycle, and up to 20% in particularly unfavorable driving conditions, e.g. in congested cities.

So far, this solution has been introduced by most global manufacturers of passenger cars, although its use in trucks is not unheard of. However, many questions related to the emission of pollutants from such vehicles' engines have arisen. Those questions have been inspired by the need to justify the use of start/stop systems and to answer the question whether or not lower fuel consumption is accompanied by lower emission of pollutants. It needs to be stressed that start/stop systems are activated only if the engine has achieved a preset working temperature. The measurements were made under actual conditions (on-road urban cycle test).

The tested vehicle was a passenger car (Mercedes A 150 BlueEfficiency) fitted with a start/stop system, as shown in Fig. 6.19 (also showing the testing equipment). The key technical parameters are presented in Table 6.1. On-road exhaust gas emission was measured under actual conditions, in city traffic in Poznań, Poland.

Fig. 6.19 SEMTECH DS fitted in the vehicle for testing

To better reflect actual conditions, two routes were selected: route 1 – around Lake Malta (faster, with fewer traffic lights) and route 2 – a loop going through the very center of the city (Fig. 6.20). Tests were carried out in the afternoon hours, in moderate traffic. The conditions were selected so as to avoid major changes over short periods and to be able to compare the emission of pollutants from the vehicle on both routes.

Table 6.1 Technical parameters of the vehicle

Parameter	Value
Engine	A 150
Number of cylinders	4, in-line
Displacement [cm^3]	1498
Compression ratio [–]	11.0
Maximum power: [kW @ rpm]	70 @ 5200
Maximum torque: [N·m @ rpm]	140 @ 3500–4000
Maximum speed [km/h]	175
Acceleration [s]: 0–100 km/h	12.6
Fuel consumption [dm^3/100 km] urban cycle / extra-urban cycle / mixed cycle	7.4–7.8 / 5.1–5.5 / 5.8–6.2*
CO_2 emission [g/km]	139–149*
Starter motor	1 – classical, high-power, 2 – starter/ alternator
Alternator	starter/alternator (electric machine)
Battery	main (classical 70 A·h), backup (12 A·h)
Transmission	Manual, 5-gear
Exhaust gas emission standard	Euro 5

* Fuel consumption information is provided for comparison; consumption was measured in accordance with 80/1268/EEC, recently amended by 204/3/EEC. Actual consumption may be higher.

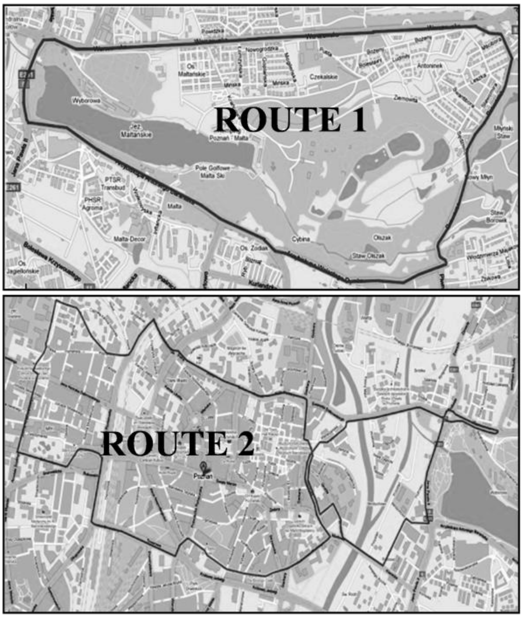


Fig. 6.20 Vehicle routes in emission tests (ROUTE 1 – urban area; ROUTE 2 – city center)

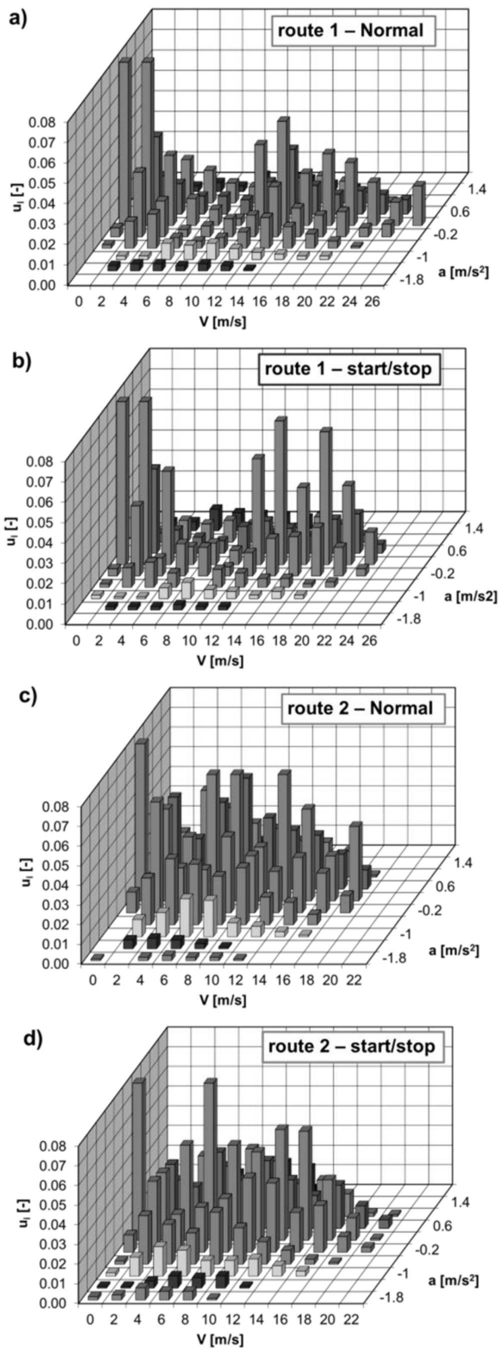


Fig. 6.21 Percentages of vehicle operation in speed and acceleration ranges: a) route 1 – Normal, b) route 1 – start/stop, c) route 2 – Normal, d) route 2 – start/stop

The tests consisted of measuring the concentration of pollutants (CO, CO_2, HC, NO_X) and exhaust gas flow rate and subsequently computing the data from the OBD system to determine emission of the said compounds.

The test involved measurements of emission of pollutants. In addition, signals from the OBD (e.g. engine speed and load, vehicle speed) were recorded for comparative purposes. Some of the signals were used to determine time density maps showing the percentage of the time of the engine work in actual operation.

To verify the degree of similarity between each cycle, the percentages of the engine work time (as a function of vehicle speed and acceleration) were also compared (Fig. 6.21). For both cycles in route 1 the greatest share of the engine work was that of minimum and average speeds and minimum acceleration. For route 2 (city center area), the engine work percentages were distributed more evenly across the entire range of speeds with low to medium acceleration.

Particular attention should be drawn to the fact that measurements were carried out in actual city traffic, i.e. at very changeable and varied conditions. Despite that, a comparison of the data shown above allows one to conclude that the results collected from each cycle were highly similar in terms of transient traffic conditions. Although the percentages of the vehicle work differed slightly from one another, the general characteristic trends were maintained.

In addition, the test included comparisons of acceleration ranges, constant speeds, braking and stops, average speeds, average fuel consumption and distance traveled (Fig. 6.22). The differences proved insignificant, which enabled an effective comparison of the emissions in each cycle.

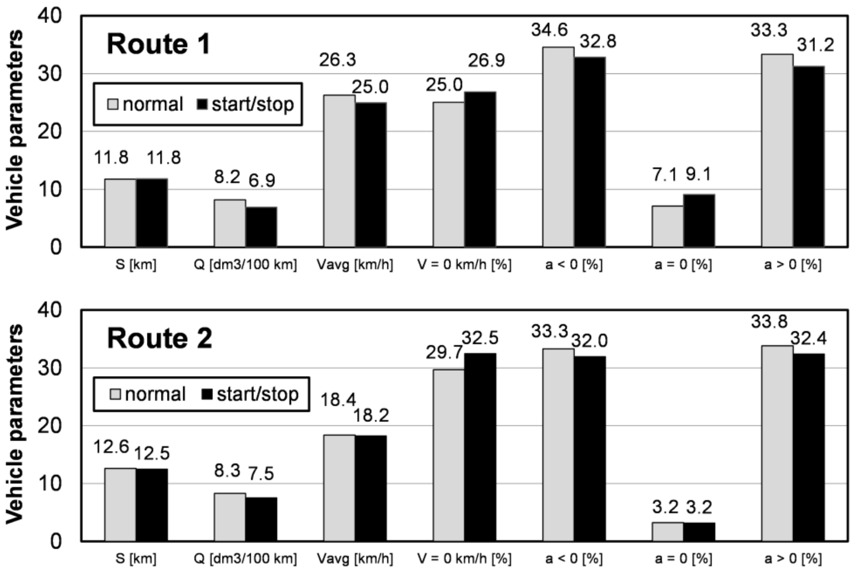


Fig. 6.22 Comparison of driving conditions in on-road tests on two routes in normal and start/stop mode

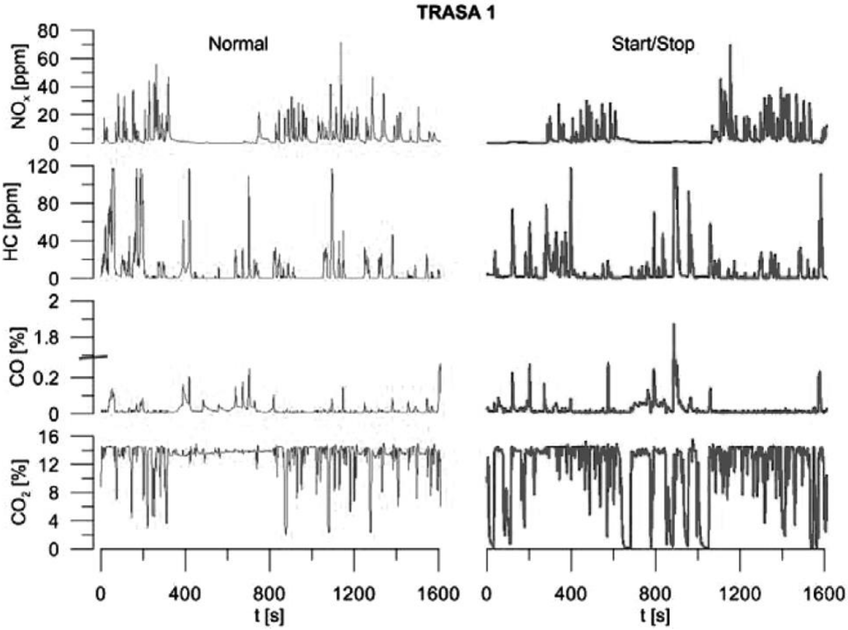


Fig. 6.23 Concentration of exhaust gas components on route 1

The recorded concentrations and the emission of CO_2, CO, HC and NO_X (calculated on the basis of exhaust gas emission) are shown to enable comparing all cycles against their respective durations (Figs. 6.23 and 6.24). The results mostly depend on cycle characteristics. Carbon dioxide concentrations are closely related to fuel consumption, acceleration and braking. The start/stop cycles are characteristic because when the system is off, carbon dioxide concentration drops to zero. The nearly constant cycle characteristics on route 1 in normal mode denotes heavy traffic (frequent stops, congestion). The same route traveled in the start/stop mode had remarkably frequent engine switch-offs. Both cycles are characteristic for high variability of emission patterns. Carbon monoxide emissions are significant across the entire cycles and vary only slightly. Simultaneously, the time of a very high CO concentration (e.g. during high engine loads) is short, which is determined by the catalytic converter. For start/stop cycles in routes 1 and 2, the concentration grows dramatically on engine restart (Figs. 6.23 and 6.24). This is related to a temperature drop in the catalytic converter during stoppage. The emission of hydrocarbons is similar to that of CO. However, there is clearly less HC than carbon monoxide. Nitrogen oxide concentrations are correlated with vehicle speed, and the emission pattern follows the one for carbon dioxide. The amount of NO_X is closely related to the engine temperature that changes depending on the operation mode. At idling speed or if the engine is switched off the temperature drops, and so does nitrogen oxide concentration.

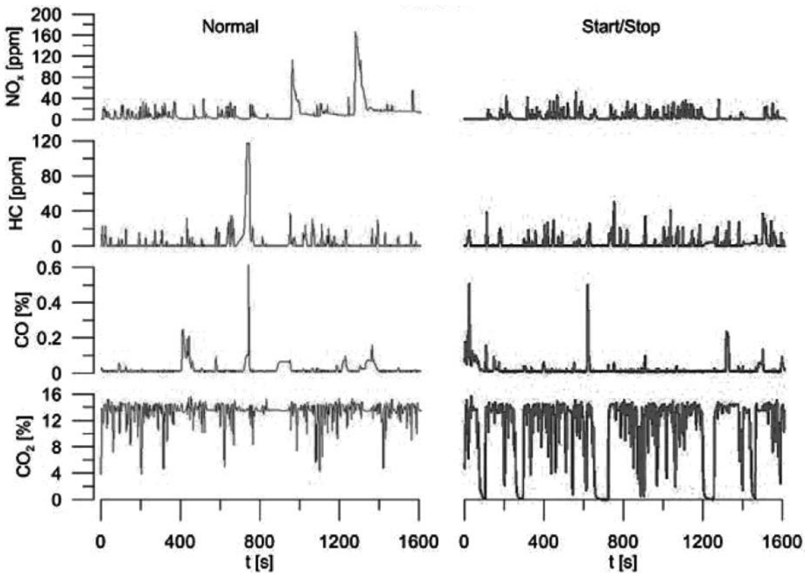


Fig. 6.24 Concentration of exhaust gas components on route 2 (city center)

The comparison shown in Fig. 6.25 indicates that the aggregated mass of carbon dioxide is greater for route 2 (city center), irrespectively of the mode used. Simultaneously, the comparison shows that start/stop cycles are characteristic for lower aggregated CO_2 mass for both routes. The aggregated CO_2 mass for route 1 is 2283 g in normal mode and 1933 g in start/stop mode, as compared to 3099 g in normal mode and 2702 g in start/stop mode for route 2. The emission pattern for aggregated CO_2 mass is nearly linear for both start/stop cycles, unlike the same pattern in normal mode cycles, where sudden peaks of aggregated mass are visible, corresponding to changes in road conditions. Such peaks indicate that the vehicle was at a standstill but the engine was on, thus consuming fuel and emitting CO_2. In such a case it is more beneficial to switch off the engine. Obviously, the lower aggregated carbon dioxide emission directly affects the fuel consumption during the test. As already presented (Tab. 6.2), lower fuel consumption was recorded in start/stop cycles. In route 1 it was reduced from 8.2 to 6.9 dm^3/100 km, and from 8.3 to 7.5 dm^3/100 km in route 2 (city center).

The total aggregated carbon monoxide mass emitted during the test (Fig. 6.25) is the only parameter negatively affected by the start/stop system. On route 1 in the normal mode the said mass is 2508 mg, as compared to 2553 mg in the start/stop mode. Largely, CO emission rate depends on the vehicle load, but it is also affected by the number of engine starts and the thermal profile of the catalytic converter. The surge of the aggregated mass in the start/stop mode in route 1 results from on-road congestion and very frequent engine switch-offs. While the aggregated CO mass in route 2 in both modes (normal and start/stop) amounted to 2779 mg and 2412 mg respectively, it is likely that for a greater number of engine start/stop operations the said value will be greater for the start/stop mode.

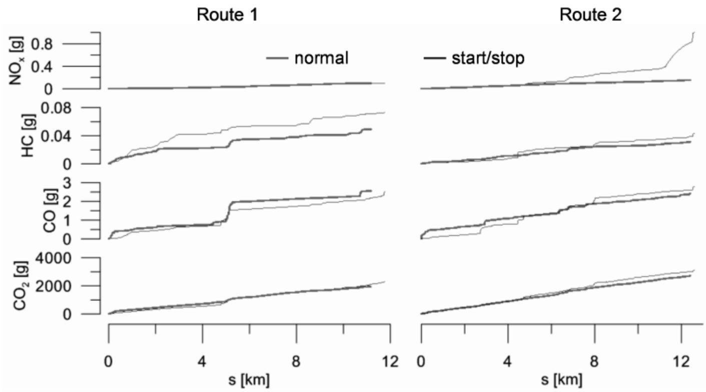


Fig. 6.25 Mass of pollutants on both routes, shown against speed profiles

A comparison of the total aggregated mass of hydrocarbons emitted during the test shows that emission values are greater for route 1, irrespectively of the mode. The underlying reason is that route 1 is faster, which means that engine and vehicle speeds are greater. Such conditions are accompanied by increased HC emission. The aggregated HC emission in route 1 in normal mode equals 72 mg (49 mg in start/stop mode), as compared to 43 mg and 31 mg in route 2. The comparison also shows that the aggregated mass of nitrogen oxides emitted in route 1 was almost identical for both modes (98 mg). Therefore, the start/stop system does not affect NO_X emission in any significant way. However, in down-town traffic (route 2), the aggregated NO_X emission reached a dramatically high level of 1.003 g in the normal mode, as compared to 0.151 g in the start/stop mode. In this particular case, by switching off the engine the start/stop system significantly reduced the aggregated nitrogen oxide mass.

On the basis of recorded data and aggregated emission levels, emissions of each pollutant were determined and compared for both driving modes. This exercise showed dependencies indicating that in route 1 only carbon monoxide emission was greater than in the normal mode. Nitrogen oxide emission was at the same level, and the emissions of the remaining compounds (hydrocarbons and carbon dioxide) were lower. The comparison also shows that in route 2 (city center), emissions of all pollutants were lower in the start/stop mode. The start/stop system effectively reduced the vehicle's emissions.

The emission values were also used to calculate relative emissions for each mode. The results for the normal mode (deactivated start/stop system) were assumed to be the base emission (100%). This comparison shows the tangible benefits of using the start/stop system. For route 1, the relative CO emission is by 1.4% greater in the start/stop mode, while NO_X emission is at the same level. The other emissions (HC and CO_2) are lower than in the normal mode, by 33.3% and 15.8%, respectively. For route 2 (city center) the following relative emission values were arrived at: emissions in the start/stop mode were by 12.7% lower for CO, 15% lower for HC, 85% lower for NO_X and 11.7% lower for CO_2.

Table 6.2 Summary of test results and their comparison against normal mode

Route	Operation mode	Emissions [g/km]				Fuel consumption [dm^3/100 km]
		CO_2	CO	HC	NO_X	
1	normal	194	0.213	0.006	0.008	8.17
	start/stop	164	0.216	0.004	0.008	6.88
Difference		30	–0.003	0.002	0.0	1.29
Savings		15.8%	–1.4%	33.3%	0.0%	15.8%
2	normal	245	0.221	0.004	0.080	8.28
	start/stop	216	0.193	0.003	0.012	7.53
Difference		29	0.028	0.001	0.068	0.75
Savings		11.7%	12.7%	15%	85%	9%

The comparison of emission performance in normal and start/stop modes shows the benefits offered by start/stop systems. An analysis of the test results shows that emission levels in the on-road test vary depending on the vehicle operation mode. The comparison takes into account both emission of each pollutant and fuel consumption expressed in dm^3/100 km. Table 6.2 presents the results of normal and start/stop mode operation.

The recent interest taken by car manufacturers in vehicles fitted with start/stop systems has been caused *inter alia* by EU regulations on the emission of pollutants, applicable to all vehicles. This policy is obviously positive and it testifies an increasing social awareness of environmental hazards caused by human activity. The growing global number of vehicles and environmental pollution both result in stricter requirements with respect to emission limits. The leading passenger car manufacturers declare that start/stop systems effectively reduce both emissions and fuel consumption. An analysis of the results discussed above leads one to conclude that the said declaration is true. Operation in the start/stop mode yielded significantly lower emissions and fuel consumption as compared to normal mode operation on the same route. The reduction amounted to 15% in one of the routes (comparable values are declared by the manufacturer). Car manufacturers rightly declare that the start/stop system does not affect the driver in any way, and on top of that it improves his/her comfort by reducing noise and vibration at standstill. During the test there were no issues related to the system's performance – the engine was switched off whenever possible. Furthermore – contrary to the manufacturer's recommendation – the test was carried out with the A/C system on, which did not affect the start/stop function. The vehicle ensured comfortable climate, and yet both emissions and fuel consumption were reduced.

When comparing a conventional vehicle with one fitted with the start/stop system one should also consider the cost factor. Most manufacturers already treat the start/stop system as a standard feature and do not collect extra charges. Therefore, the system brings both environmental and economic benefits from the very beginning of the vehicle's service. In addition, at certain traffic conditions, those benefits can be even greater than those observed during the test.

6.2.3 Hybrid Vehicles

Hybrid propulsion is one where two different vehicle power sources are available. Currently known combinations of such sources include gas turbines, CI and SI engines coupled with flywheels, batteries and ultracapacitators. Irrespectively of the combination, hybrid drives can be arranged in series or in parallel, or in a mixed arrangement.

Serial arrangements are the simplest hybrid configuration. Engine power is transmitted to wheels via an electric motor, which receives energy from batteries or a generator powered by a combustion engine. The amount of energy provided by the batteries or the generator is determined by a computer. The batteries are charged by the engine/generator set or by the energy recovery system activated during braking. The demand for power from the combustion engine is lower than in the conventional drive, which is why the engine itself is physically smaller. In serial arrangements, loads are generally greater than in parallel arrangements. Therefore, batteries must offer greater power. Due to the battery pack size and the necessity to install the generator, the cost of in-series systems is relatively high, making them more expensive than parallel systems.

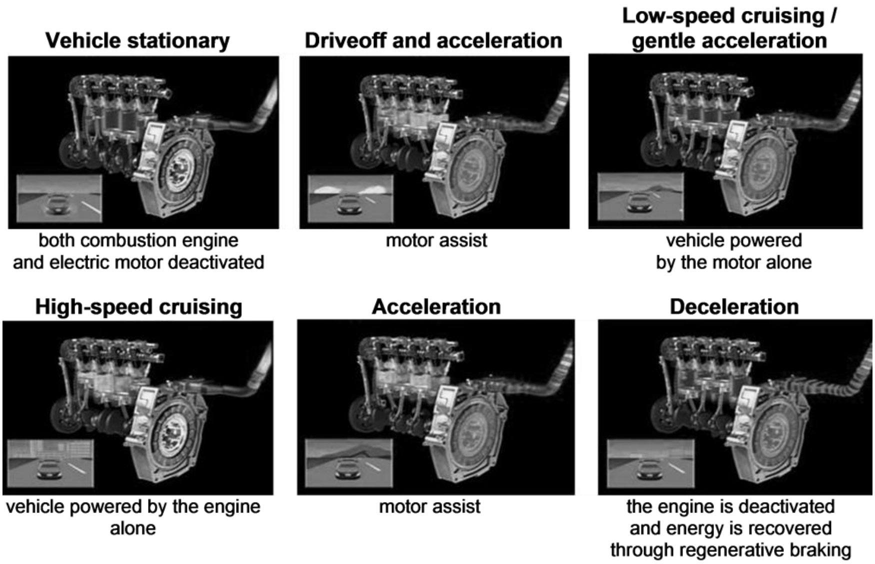


Fig. 6.26 Operating principle of Honda's IMA; examples of using a combustion engine and electric motor at different traffic conditions

In parallel systems the power used to propel wheels is generated both by the combustion engine and the electric motor. A control device makes the cooperation of the two possible. One example of such a system is Honda's IMA (Integrated Motor Assist, as shown in Fig. 6.26). In parallel hybrid systems, batteries are smaller to ensure efficient charging during braking. In addition, the battery can be charged by the combustion engine while running. Energy transmission to wheels is mechanical, which is why energy losses due to mechanical-to-electric conversion (and vice-versa) are reduced. As a result, the system is more efficient when the vehicle cruises at a constant speed (e.g. on a highway). However, the mechanical coupling of the engine and the wheels slightly increases energy losses in urban traffic (stop-and-go driving). At such conditions, the engine is required to provide power at different loads.

The above solution by the Japanese company is currently used in Honda Insight, Honda Civic Hybrid and Honda CR-Z. It is a light-weight version of the parallel hybrid system. The motor is fitted between the engine and the gearbox. Therefore, it can act as a starter, a battery-powered motor and a generator powered by the engine to charge the batteries. The i-VTEC engine makes it possible to control valve operation and deactivate cylinders while recovering energy during braking. At standstill the combustion engine is switched off (start/stop system), thus reducing emission of pollutants.

Split serial-parallel systems combine the advantages and disadvantages of serial and parallel drives. The combination of the two solutions makes it possible for the wheels to be driven directly by the combustion engine (parallel hybrid), with possible uncoupling if electric transmission (in-series hybrid) is preferred. This particular solution has been popularized by Toyota Prius. Owing to the system duality the engine works at optimum efficiency. At lower speeds the system works in-series, while at greater speeds (i.e. when the in-series arrangement loses its efficiency), the motor is activated to minimize losses. The system requires a generator, greater batteries and more computing power to synchronize both components – all of those make its production more expensive. However, the capacity of the split serial-parallel system is greater than that of either of the two single-mode systems working on its own.

The tests were carried out on two vehicles with different hybrid drives. The first one was a third-generation Toyota Prius HSD with a split hybrid drive (Fig. 6.27a), fitted with an in-line spark ignition engine with cylinder capacity of 1.8 dm^3. The combustion engine has a power of 73 kW and torque of 142 N·m. It is assisted by a 60 kW electric engine with a torque of 207 N·m.

The other test vehicle was a Honda CR-Z (Fig. 6.27b) featuring Honda IMA hybrid drive. Fitted with a manual transmission, it has a four-cylinder spark ignition engine of cylinder capacity of 1.5 dm^3, maximum power of 84 kW and a torque of 145 N·m. The drive system also includes a 10 kW electric motor producing 78 N·m of torque. Both vehicles were fitted with OBD II systems.

The distance traveled was 12.7 km. The route consisted of a typical urban and extra-urban section. On the latter, driving conditions were comparable to those on a highway (with maximum speed of approx. 120 km/h). The length of the extra-urban section was approx. 5.5 km. The average cruising speed was 35.7 km/h for Honda CRZ and 37.6 km/h for Toyota Prius.

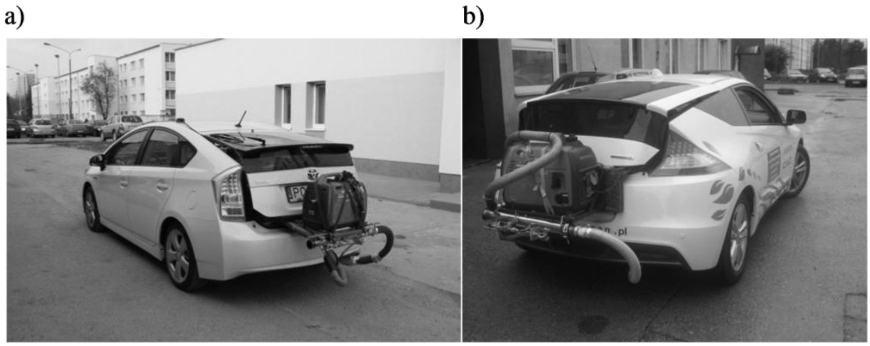


Fig. 6.27 Vehicles ready for testing: a) Toyota Prius, b) Honda CR-Z

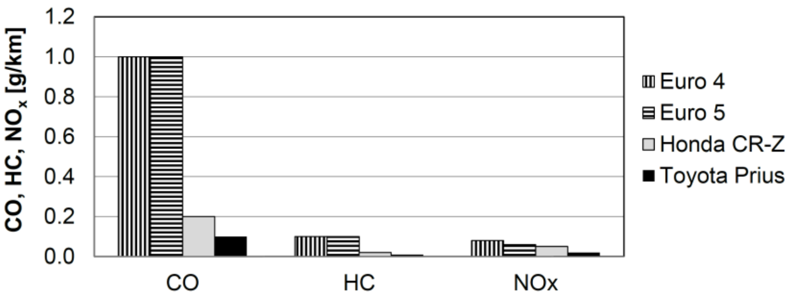


Fig. 6.28 Average emissions and Euro 4 / Euro 5 limits

The test of emissions showed that for both vehicles the values for each pollutant were far below the limits prescribed for Euro 5 vehicles (Fig. 6.28). Honda CR-Z generates CO also at standstill, which is why its emission of carbon monoxide is twice as high as that of Toyota Prius. The amount of hydrocarbons emitted from Honda CR-Z is also greater, unlike the emission of nitrogen oxides. The Toyota's hybrid drive is more advanced, which offers greater reduction of emissions. The possibility of running on the electric motor alone efficiently reduces the average emission of pollutants. Honda is more dynamic, and its drive is simpler, but running on the motor alone is not possible. Emissions from both vehicles exceed by 1/3 the average carbon dioxide values declared by the manufacturers. Contrary to type-approval tests, in-service tests under actual conditions are characteristic for variable traffic, which results in higher average CO_2 emissions.

6.3 Tests of Heavy-Duty Vehicles

For heavy-duty vehicles with maximum laden mass above 3500 kg (and for buses), the European legislation on reducing emissions was first introduced in the early 1980s. Like for light-duty vehicles, the requirements have since become more strict, and testing procedures have been modified. The progress in emission reduction has nonetheless been slower than in the case of passenger cars and other vehicles with maximum laden mass below 3500 kg. One of the reasons is that the legislation on heavy-duty vehicles was first introduced over ten years later. New heavy-duty vehicles emit approximately 5–15% of pollutants emitted by uncontrolled vehicles.

For many years the system of vehicle inspection in terms of the emission of pollutants consisted of type approval and checking production conformity. Currently, more and more emphasis is being placed on measuring specific emissions, particularly from heavy-duty vehicle engines in transient cycles. Such cycles simulate actual on-road conditions much more closely than steady-state cycles. In the new legislation, the "vehicle life" expressed as mileage has been significantly extended. Vehicles must meet emission requirements over the entire life. Trucks of maximum laden mass in excess of 16,000 kg will have to meet the requirements when the mileage is 700,000 km. Consequently, the quality requirements applicable to emission reducing devices (such as catalytic converters and particulate filters) will become much more stringent.

The route used for testing under actual conditions was divided into 4 basic cycles (Fig. 6.29): urban (referred to as "the city"); highway ("A2Max" and "A2Eco"); and mixed ("Road 92"). The highway section was additionally divided to consider different cruising speeds and driving styles, as follows:

- in the first half of the route the cruising speed was close to the vehicle maximum speed, i.e. approx. 90 km/h ("A2Max"),
- in the other half the cruising speed was approx. 75–80 km/h („A2Eco").

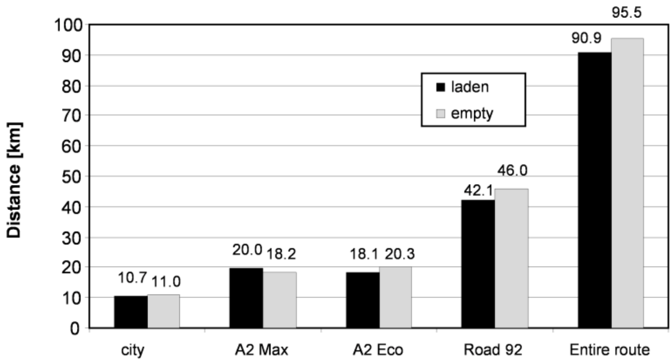


Fig. 6.29 Lengths of each test section

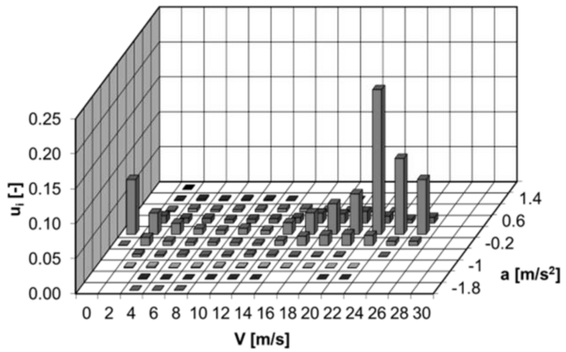
The vehicle carried a payload of approx. 10 tons. The route details are presented in Table 6.3.

To ascertain the degree of similarity between each run, operation time percentages as functions of speed and acceleration were compared (Fig. 6.30).

Table 6.3 Test overview (empty and laden run)

Test parameter	Empty run	Laden run
Time [s]	6184	5890
Average speed [km/h]	55.56	55.56
Distance [km]	95.5	90.9
Fuel consumption [dm^3/100 km]	17.59	22.67

a)



b)

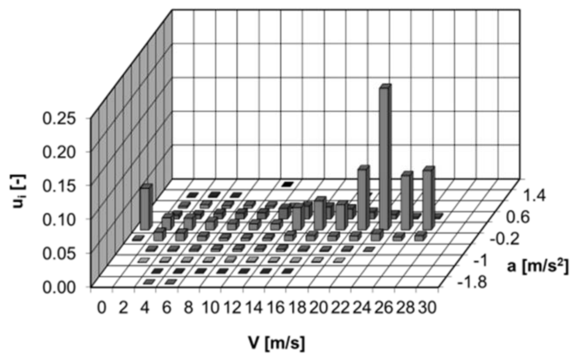


Fig. 6.30 Speed and acceleration dependent vehicle operation time percentages for empty run (a) and laden run (b)

Figure 6.31 presents some examples of nitrogen oxide emissions depending on the vehicle acceleration on each section of the route. Empty run is shown in blue, and laden run is shown in red. Concentration changes in line with the vehicle acceleration are clearly visible. Emission levels grow in line with the load. The trends of the said changes are particularly discernible when engine operation is stable, i.e. in the highway cycle (b, c).

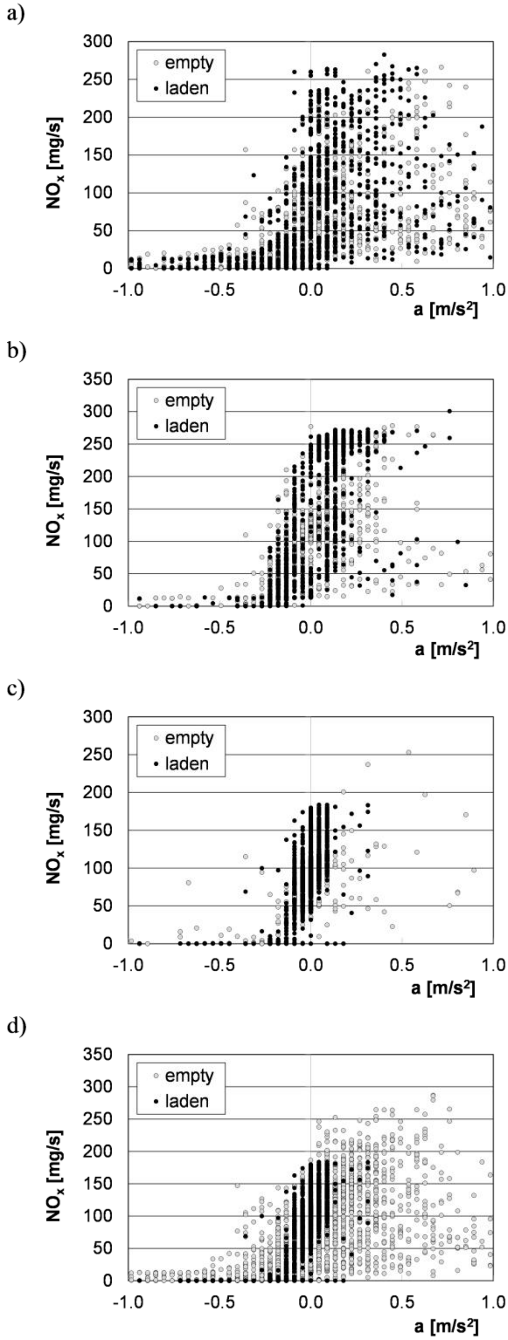


Fig. 6.31 NO_X concentration as a function of instantaneous acceleration: a) city cycle, b) A2Max cycle, c) A2Eco cycle, d) road 92 cycle

The data on the concentration of each pollutant was used to compare the dependencies reflecting the effect of the vehicle dynamic performance on emission rate under actual traffic conditions. The dynamic performance was taken into account indirectly, by applying speed and acceleration intervals calculated for actual traffic. On the basis of the results, an emission rate matrix was developed. The data was additionally broken down within each speed and acceleration interval, to show the characteristics of the emission of each pollutant (Fig. 6.32).

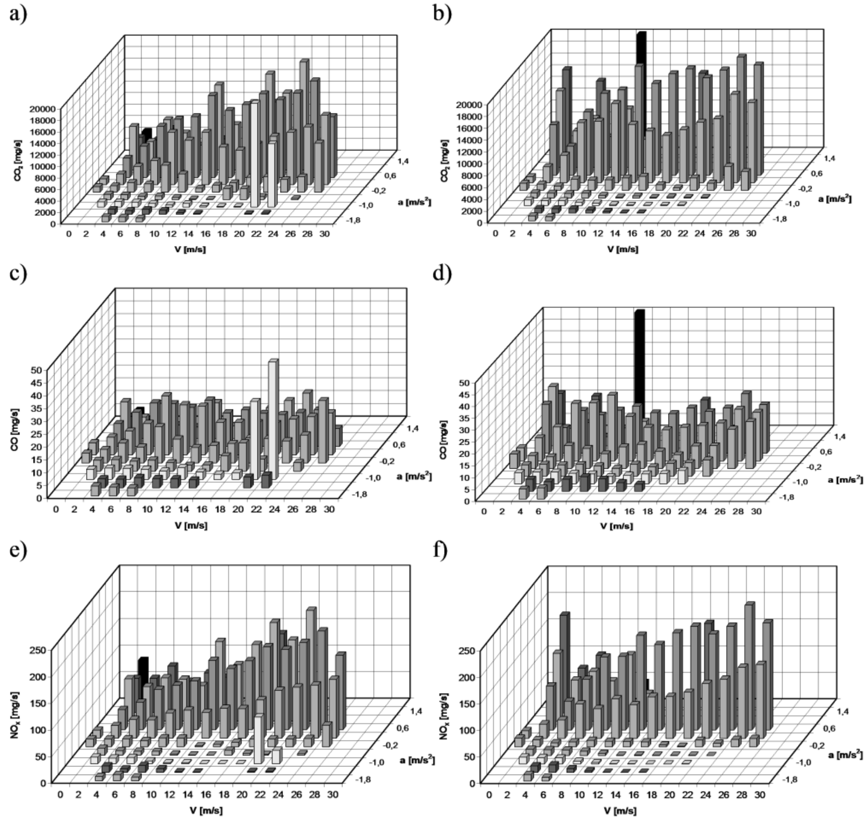


Fig. 6.32 Pollutant emission rates at various speed and acceleration intervals: a) CO_2 – empty, b) CO_2 – laden, c) CO – empty, d) CO – laden, e) NO_X – empty, f) NO_X – laden

Carbon dioxide emission rate (Figs. 6.32a and 6.32b) is similar for both runs (empty and laden): it grows as the vehicle speed and acceleration grow. However, the absolute levels of such emissions are different (much higher for the laden run). For both runs, speed growth (with the same acceleration values) is accompanied by almost linear growth of CO_2 emission rate. The maximum carbon monoxide emission rates (Figs. 6.32c and 6.32d) are observed for nearly all speed and acceleration values. Those rates are correlated with the vehicle acceleration. The area of elevated nitrogen oxide emission rates (Figs. 6.32e and 6.32f) coincides with the vehicle maximum speeds and significant acceleration (and thus – maximum engine load). This is closely related to an increased fuel dose and simultaneously increased engine speed. The growth tendency compared to vehicle acceleration is linear (in both runs).

Quantitative emission factors are also presented as the total aggregated mass of pollutants measured in the test. The emission of tested compounds and the distance traveled during the test were used to calculate the average emission of pollutants (Figs. 6.33–6.36).

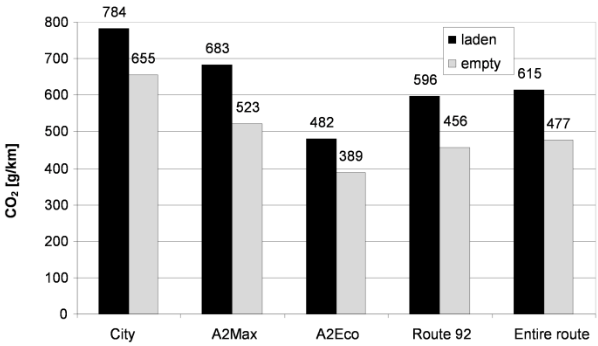


Fig. 6.33 Comparison of CO_2 emission in each cycle

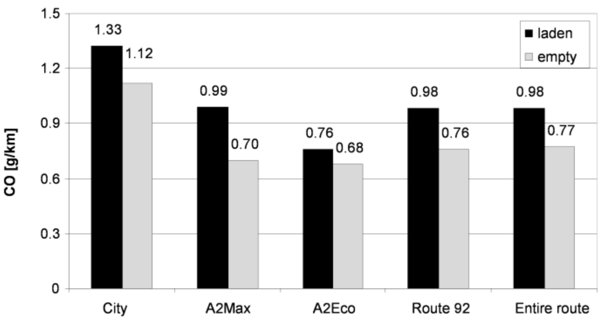


Fig. 6.34 Comparison of on CO emission in each cycle

Emission of carbon dioxide is greater for the laden run, irrespectively of the cycle. In the laden run, CO_2 emission for the entire route equals 615 g/km (477 g/km in the empty run). The greatest difference (160 g/km) was observed in the A2Max cycle. Such a large difference is caused by frequent accelerations triggered by the truck speed limiter and further deepened by the vehicle payload. The speed limiter requires the vehicle to accelerate frequently, as a result of which the engine works at maximum load.

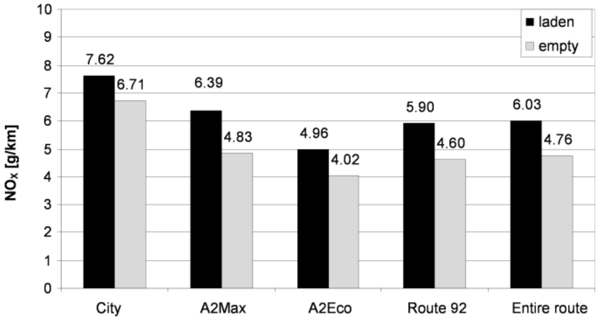


Fig. 6.35 Comparison of NO_X emission in each cycle

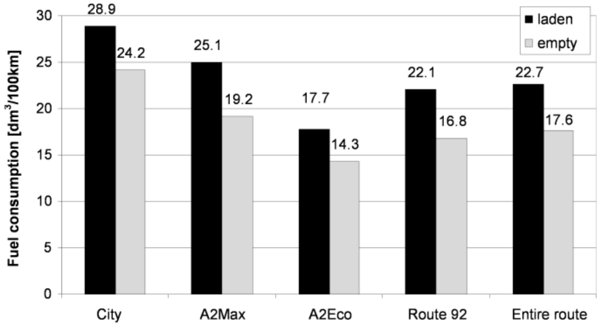


Fig. 6.36 Comparison of fuel consumption in each cycle

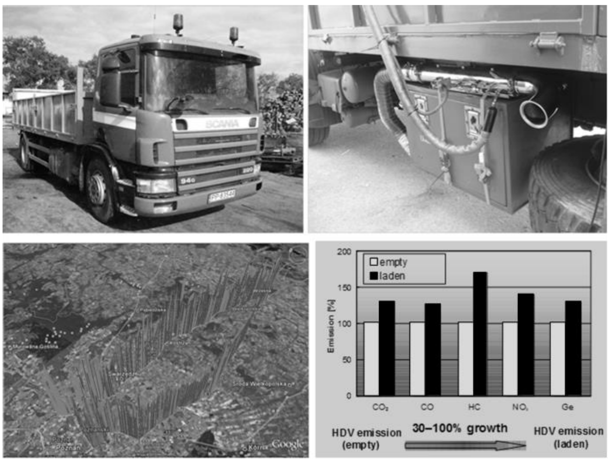


Fig. 6.37 Tests of exhaust emissions from empty and laden trucks

The smallest difference in on-road CO_2 emission is observed in A2Eco cycle (93 g/km), which results from very stable engine operation and cruising speeds within an adequate range. The lack of abrupt engine speed accelerations has a significant effect on fuel consumption and CO_2 emission. An analysis of carbon monoxide emission indicates that emission levels in A2Max and A2Eco cycles (empty runs) are similar (0.70 g/km and 0.68 g/km, respectively). For laden runs, however, the situation is different, as the respective values are 0.99 g/km and 0.76 g/km.

The significant effect of engine load on highway cycle emissions is discernible. The comparison presented in Fig. 6.35 indicates that NO_X emission is characterized by the greatest degree of stability (taking into account vehicle's payload) in the city cycle. Bearing in mind the conditions in which nitrogen oxides are generated (high temperature and pressure in the engine cylinder), the reason for such stability will be the stop-and-go nature of the city cycle.

A comparative analysis of emissions in each driving cycle indicates a 30% growth of emissions of each toxic component correlated with the engine load. The disproportion between the growth in emissions and the growth in vehicle mass is particularly remarkable. Emission values in the on-road test vary depending on the cycle and load. An analysis of the effect of the load on the emission of toxic component from trucks shows that in some cases emission values can be even doubled (Fig. 6.37).

6.4 Tests of City Buses

Due to the specific nature of their operation, city buses can be tested for emissions only under actual conditions, and the most adequate testing environment are city bus routes. By means of a portable exhaust emissions measurement system (PEMS) emissions from a hybrid and a conventional bus (Fig. 6.38) were measured under actual traffic conditions in Poznań, Poland. The tests involved buses operating on line 76 in the morning and at noon. Test conditions were selected so as to reflect the actual traffic conditions: the number of passengers on line 76 was equal to the average numbers for all city lines in Poznań. The tests were held for two days (Friday and Saturday), typical of high and low (respectively) number of passengers and high and average (respectively) traffic congestion. Each of the buses was a Solaris vehicle: one fitted with a hybrid drive (Hybrid H18), and one with a conventional drive.

Both buses were intentionally similar (18-meter, same number of passengers) and enabled comparison of functional and environmental performance under actual conditions (the engines of both buses were Euro V compliant).

Second-by-second emissions of CO, HC, NO_X and CO_2 in exhaust gas were measured by means of a portable measurement system. Engine speed and torque values were pulled from the vehicles' diagnostic system (CAN SAE J1939) and then used to calculate the emission as a function of the engine's specific energy. Vehicle location was recorded by means of a satellite navigation device, thus enabling cycle visualization and distance calculation. Some examples of information recorded during the cycle are shown in Fig. 6.39. The controller of the hybrid bus had a function of limiting transmission from the combustion engine during startup; until the vehicle reached a speed of 5 km/h, the engine was idling and the vehicle was powered by the electric motor alone, to reduce atmospheric emission of pollutants.

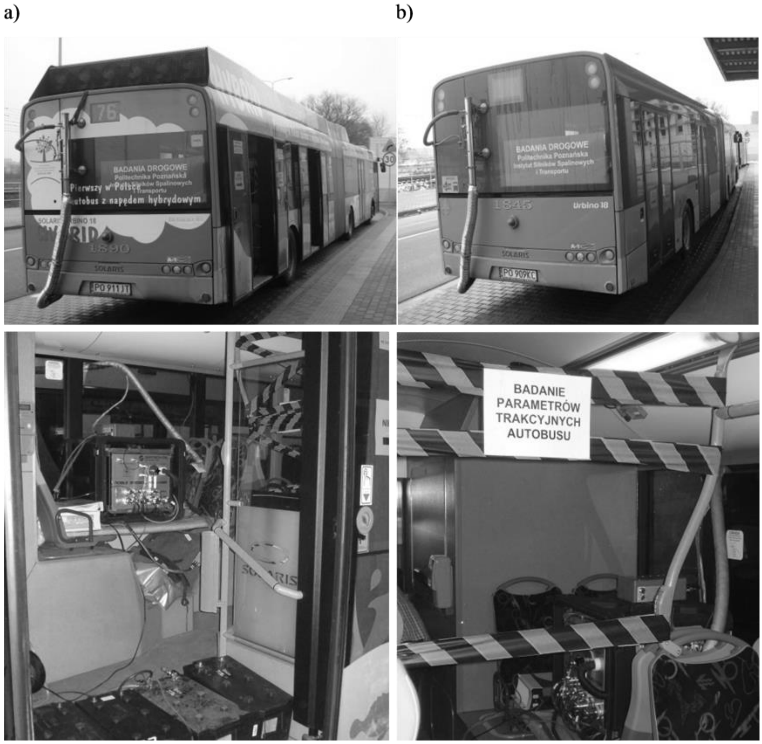


Fig. 6.38 Testing equipment for measuring toxic compunds (Semtech DS) fitted on a hybrid (a) and a conventional (b) bus

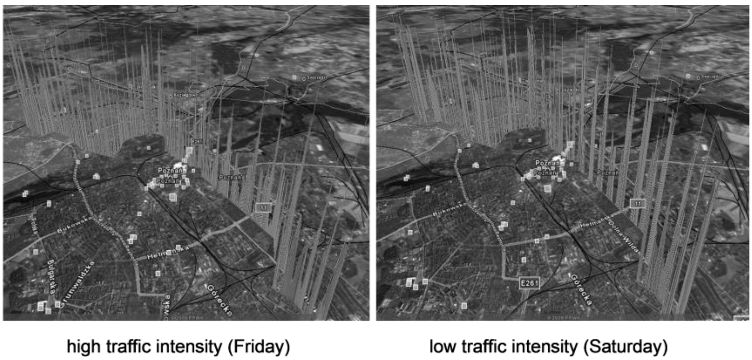


Fig. 6.39 Carbon dioxide recording (CO_2 emission rate projected on the bus route); color codes: green – hybrid bus; red – conventional-drive bus

For the hybrid vehicle, the values of carbon monoxide emission were similar in each cycle, whereas for the conventional-drive vehicle the differences between each cycle were significant (Fig. 6.40). The average emission value for the hybrid bus at high traffic intensity (Friday) was 3.2 g/km, as compared to 2.7 g/km (15% reduction) at low traffic intensity (Saturday). For the conventional-drive bus, the following values were measured: 8.7 and 7.3 g/km, respectively. The emission of carbon monoxide from the hybrid bus was thus approximately three times lower than from the conventional-drive bus.

Measurements of nitrogen oxide emission in each cycle were characterized by a low spread of the results for both buses (Fig. 6.41). The average value of emissions from the hybrid bus at high traffic intensity (Friday) was 19 g/km, as compared to 17 g/km (10% reduction) at low traffic intensity (Saturday). For the conventional-drive bus, the following values were measured: 9.9 and 7.3 g/km, respectively. The emission of nitrogen oxides from the hybrid bus was thus approximately two times higher than from the conventional-drive bus, which was primarily caused by the lower engine power in the hybrid bus.

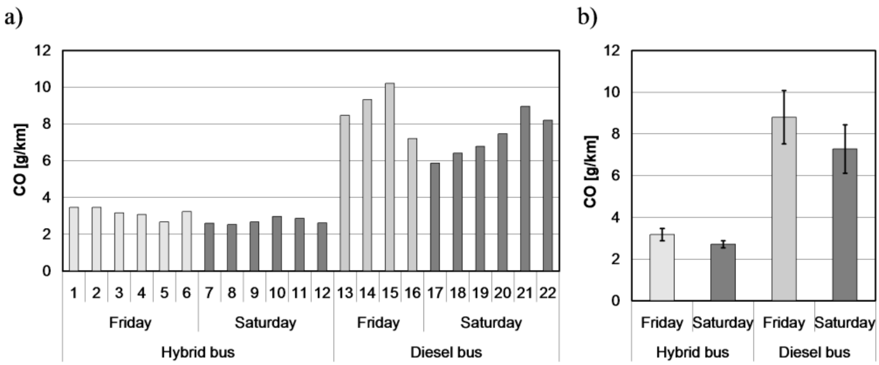


Fig. 6.40 Comparison of carbon monoxide emission from hybrid and conventional-drive buses: a) all runs, b); average values with measurement uncertainty

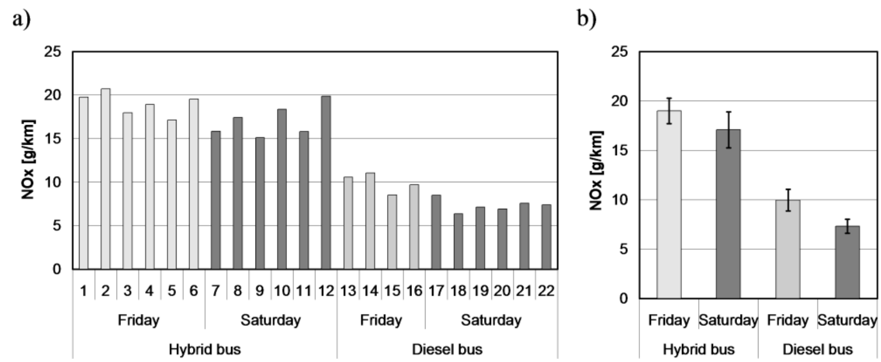


Fig. 6.41 Comparison of nitrogen oxide emission from hybrid and conventional-drive buses: a) all runs, b); average values with measurement uncertainty

The above results were used to compare emissions from buses operating under actual conditions in high traffic (Friday) and in low traffic (Saturday). Comparisons were made as regards specific emissions (the analysis consisted of comparing the mass of a given pollutant against the energy used in each cycle). The following results were arrived at for the hybrid bus as compared against the conventional-drive bus (Fig. 6.42):

- at high traffic intensity (tests on Friday): CO emission – 58% reduction, HC emission – 21% reduction, NO_X emission – 120% growth; CO_2 emission – 5% reduction, fuel consumption – 8% reduction;
- at low traffic intensity (tests on Saturday): CO emission – 61% reduction, HC emission – 73% reduction, NO_X emission – 143% growth; CO_2 emission – 5% reduction, fuel consumption – 8% reduction.

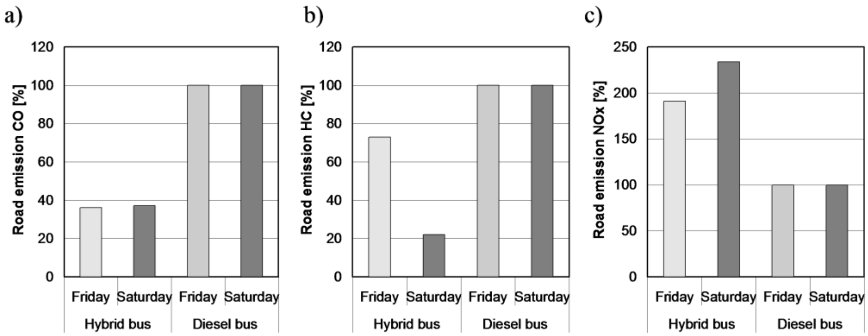


Fig. 6.42 Relative variations of specific emissions from the hybrid bus as compared to the conventional-drive bus (=100%): a) carbon monoxide, b) hydrocarbons, c) nitrogen oxides

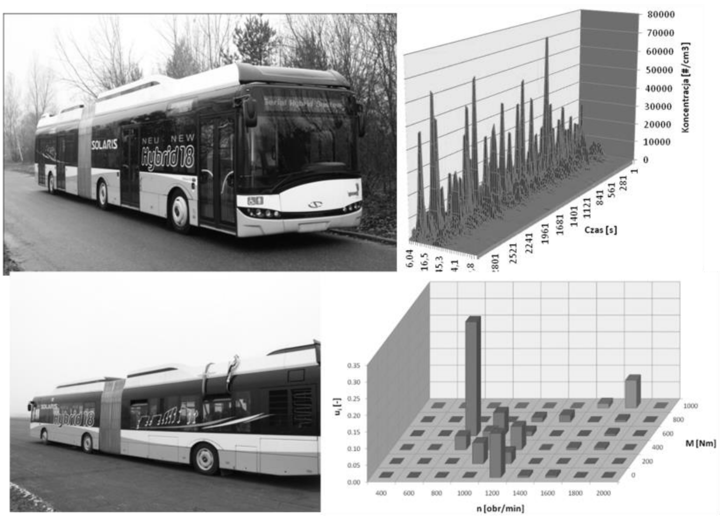


Fig. 6.43 Tests of an innovative bus with a serial hybrid drive

Some commercially available hybrid city buses come with a split serial-parallel system. However, such a system has certain limitations. As it is not compatible with the start/stop system, the engine cannot be switched off at standstill (e.g. on the bus stop or in other traffic situations, such as blocked cross-roads, congestion, etc.). The Solaris serial hybrid drive is not only environmentally friendly and attractive for its users, but also offers favorable power and emission performance. In particular, it makes it possible to reduce fuel consumption and thus emission of pollutants. It also makes it possible to reduce noise, which is particularly important in city conditions. Due to numerous advantages of the serial drive, the solution is highly competitive (Fig. 6.43).

Low emissions improve air quality in downtown areas, thus reducing environmental risks to inhabitants. An increasing number of European cities introduce low emission zones, where only vehicles with minimum emissions are allowed. The bus in question responds to such needs. In terms of technical and environmental performance it is ahead of its competitors and currently applicable exhaust emissions requirements. Lower noise emission improves the quality of life. The new hybrid bus is also characterized by lower noise levels both outside and inside the vehicle.

6.5 Tests of Non-road Vehicles

6.5.1 Pick-Up Trucks and Tractors

Transportation continues to be one of the primary sources of toxic exhaust gas emissions and fossil fuel consumption. Irrational use of agricultural tractors for transportation of goods negatively affects the environment and simultaneously increases fuel consumption as compared to transportation of the same goods using other means [6]. A delivery vehicle coupled with a trailer fitted with the innovative gooseneck coupling reduces haulage time, causes less traffic inconvenience thanks to higher speed and emits significantly less pollution.

Our tests were carried out using an agricultural tractor and a pick-up truck. The tractor (John Deere) engine is a state-of-the-art unit fitted with common rail injection system with maximum pressure of 160 MPa (with multiple injection and VGT turbocharger). The tests, carried out under actual operating conditions, showed that the truck's environmental performance was superior to that of the tractor (Fig. 6.44). An analysis of on-road emission from the entire vehicle demonstrated that the emissions from the tractor were many times greater than from the pick-up truck. The largest difference was observed in CO (over 25 times higher for the tractor), followed by HC (11 times higher) and NO_X (nearly 6 times higher).

Except for on-road CO emission from the pick-up truck, all other emissions from both the truck and the tractor were in excess of Euro 4 limits. Also fuel consumption (CO_2 emission) was greater in the case of the tractor (Fig. 6.45) – over three times the truck's consumption. When analyzing transportation of goods and participation in public traffic one should also take into account other parameters, such as time and speed. Both of them were disadvantageous for the tractor. The tractor cruising time was 72.6 minutes, as compared to 47.7 minutes for the truck. The average cruising speeds were 24.6 km/h and 37.3 km/h, respectively (Fig. 6.46). These two parameters are important from the perspective of traffic, as agricultural tractors usually cause stoppages and slow down the traffic.

Fig. 6.44 Tested vehicles

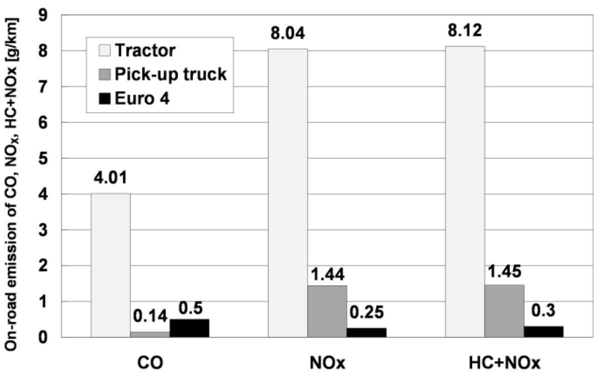


Fig. 6.45 On-road emissions from the pick-up truck and the tractor, tested under actual operating conditions

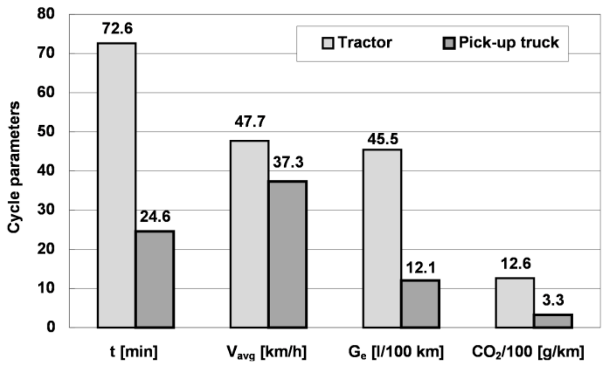


Fig. 6.46 Selected vehicle parameters in tests under actual traffic conditions

The tests indicate that the pick-up truck is a better solution for the transportation of goods weighing 4000 kg (and surely those weighing less). Pick-up trucks are characterized by a significantly lower emission of all toxic gaseous compounds and lower fuel consumption. Equally importantly, key traffic parameters also speak in favor of using pick-up trucks for the haulage of farming produce and materials. Truck transportation shortens travel time and uses less fuel, thus making it economically preferable. It also allows eliminating traffic disturbances caused by the low cruising speed of tractors.

6.5.2 Farming and Construction Machines

Tests of toxic emissions under actual operating conditions of farming machines (Figs. 6.47 and 6.48) (at fieldworks) show that the engines of those machines usually work at constant speeds (which reduces toxic emissions), and their load is variable – therefore, their typical operating conditions are different from those simulated on type-approval tests. The largest emissions were recorded at the time of engine parameter shifts (e.g. change of operating settings). Furthermore, it has been determined that emissions under actual operating conditions are well beyond applicable limits (particularly in the case of NO_X).

One of the largest group of non-road vehicles includes construction and earthworks machinery, most of which is fitted with turbocharged Diesel engines with direct fuel injection. Depending on the machine size and intended use, the engine power ranges from 40 to 1000 kW. In terms of technical design, such engines are different from traction engines.

Control systems of contemporary engines used in earthworks machines are highly specialized controllers fitted with electronic engine speed adjustment. Engines fitted with such control systems do not have any mechanical couplings. As a result, engine control parameters are much more superior (time of the power system response to load changes). Engine controllers are equipped with control and diagnostics software, measuring such parameters as charging pressure, coolant and air temperature, instantaneous amount of fuel injected to the cylinder, or the engine speed. Those parameters serve the purpose of determining the power generated by the engine. Once collected in the controller and then read out, they make it possible to identify actual engine load characteristics, the character of the machine's operation or the correctness of choices made by the operator. In modern earthworks and construction machines, propulsion systems are predominantly hydrokinetic and mechanical. Owing to their advantages they have replaced purely mechanical systems. Hydrokinetic and mechanical systems consist of the following key components: hydrokinetic clutch or transmission, gear box with friction clutches enabling power shifting, driving axles with spiral bevel gears and hub reduction gears.

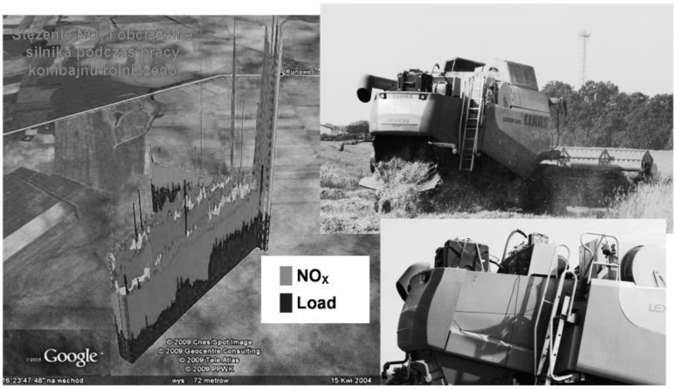


Fig. 6.47 The measurement of exhaust emissions from a harvester under actual operating conditions

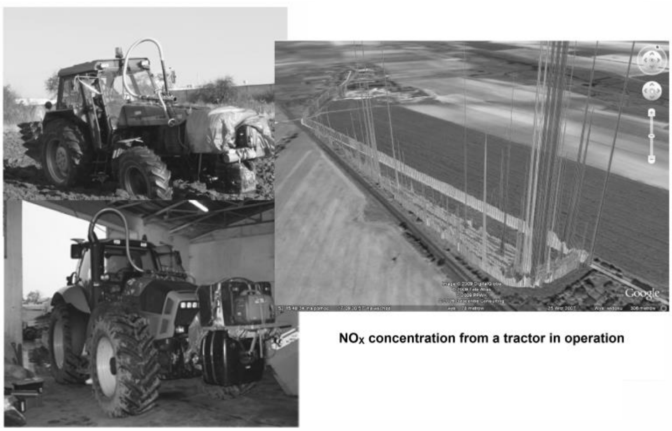


Fig. 6.48 The exhaust emission tests during fieldwork of an agricultural tractor

The analysis included several selected propulsion systems used in Caterpillar vehicles: D6N (bulldozer), D6R (bulldozer), and 325C (excavator). The vehicles were used at the newly built section of the A2 expressway in Poland. Each of them had worked on-site for 1500 to 2000 hours. They were powered with C-9 or 3126B engines (Fig. 6.49).

Fig. 6.49 Tested machines: Caterpillar bulldozer and excavator

The tests provided a response to the question whether or not the currently used type-approval test of heavy-duty machinery adequately reflects actual engine work conditions. An analysis of load histograms (Fig. 6.50) answers the above question and can be the first step to developing an on-site exhaust gas emission test. By relying on the information in the histograms one can adjust weight coefficients so as to give priority to those that find themselves in the right engine load interval, i.e. the one most commonly used under actual conditions.

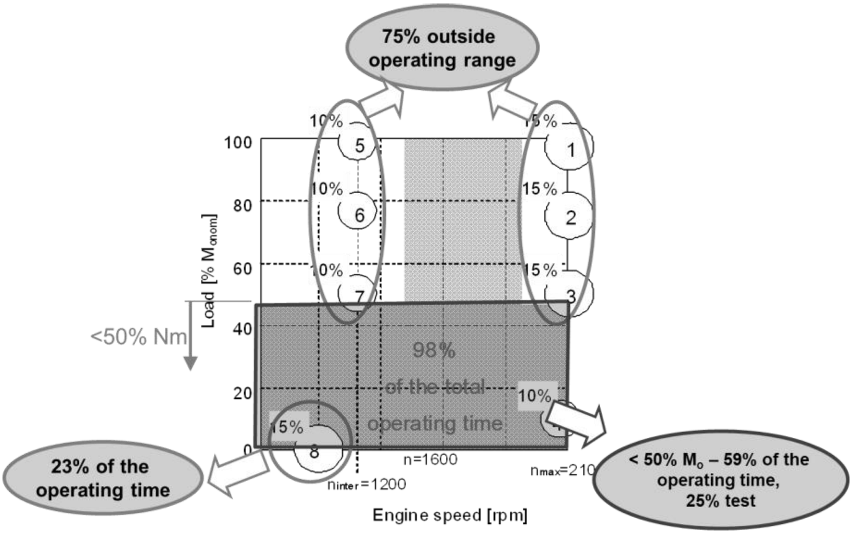


Fig. 6.50 Analysis of excavator operating conditions

A detailed analysis of engine operation histograms can provide a basis for developing proposals of field tests for various non-road vehicles. Such tests should take into account the prevailing range of engine operation. The ECE R96 test does not fully reflect the actual engine operating conditions. Excavator engines worked approximately 35% of the total operation time at the idling speed, with loads below 50%. The balance of the operation time featured average engine speeds of the crankshaft, corresponding to 60 to 70% of the maximum power. Meanwhile, in the ECE R96 test used for the engines in question, as many as four out of eight measurements are taken at the maximum crankshaft speed. This leads one to wonder whether ECE R96 measurement points should not be adjusted. However, such a claim should be based on the analysis of histograms from a greater number of engines (Fig. 6.51).

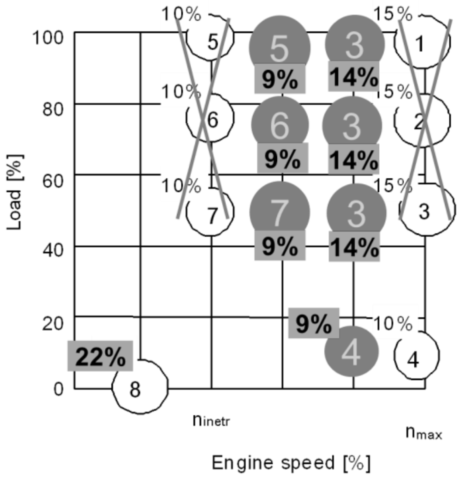


Fig. 6.51 Proposal of a new type-approval test for excavator engines

An analysis of time density characteristics for selected machines proves that certain points of the type-approval test are outside the prevailing scope of the operation. Therefore, engine time densities reflecting diverse operating conditions of each machine should be accounted for in type-approval tests (subdivision of category C1 into subcategories). Relying on the properties of hydraulic propulsion systems, exhaust gas emission could be measured in out-of-laboratory tests at controlled engine loads. Due to the lack of legal regulations governing specific emissions of toxic compounds from non-road vehicles, control tests of such machines should be introduced. Such tests would be followed by their extension to other groups of non-road vehicle engines, e.g. power-generating units, and by the development of testing procedures for out-of-laboratory tests controlling exhaust gas emissions from the engines of in-service non-road vehicles. Exhaust gas emission limits should be prescribed for such engines (Fig. 6.52).

Another group are special purpose machines, including *inter alia* forest harvesters. Measurements of specific emissions were carried out under actual operating conditions (tree felling, delimbing and tree cutting into 2-meter logs). Figure 6.53 shows the tested machine in operation, complete with test equipment. The machine worked in a predominantly pine wood. The diameter of felled trees ranged from 20 to 30 cm, distributed over a relatively small area of approx. 1 hectare (the distance travelled by the machine during the test was 2.3 km).

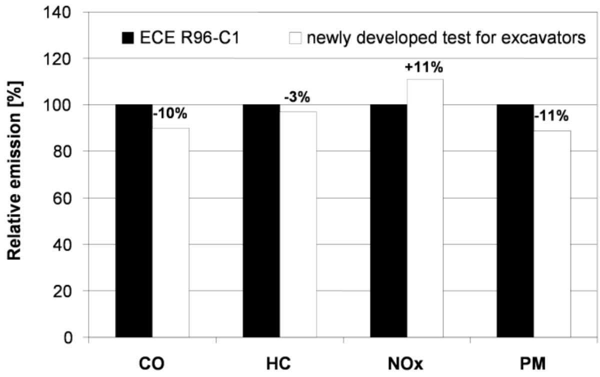


Fig. 6.52 Comparison of relative emission of pollutants measured in the ECE R96-C1 test and the newly proposed test for excavators

Fig. 6.53 A forest harvester felling trees

In many countries, tree felling involves heavy use of hand-held chainsaws powered by SI engines. Forest harvesters continue to be rather rare in many European countries, mostly in Central and Eastern Europe. For instance, in 2008 there were as few as 157 such harvesters in Poland, or 1 for every 580,000 hectares of woodland. For the purpose of a comparison, the test also included measurement of exhaust emissions from the engine of a hand-held chainsaw under actual operating conditions. The saw in question was fitted with a two-stroke SI engine of maximum power of 2.5 kW. Figure 6.54 shows the comparison of specific emissions from both engines (chainsaw and combine).

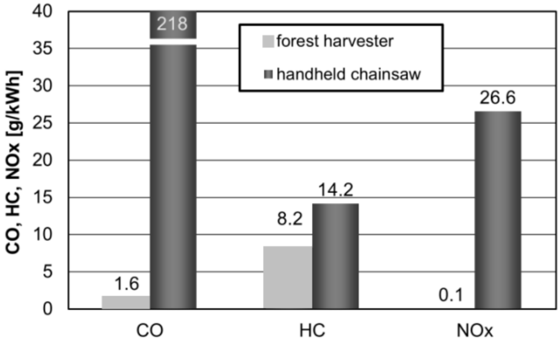


Fig. 6.54 Comparison of specific emissions of exhaust pollutants from the engines of a hand-held chainsaw and a forest harvester, measured under actual operating conditions

As regards the chainsaw, its specific emission of pollutants is significantly greater than for the harvester engine. For instance, specific NO_X emission is several hundred times greater, and CO emission is over one hundred times greater. The smallest difference was observed for HC. To visualize the difference in environmental performance, one should take into account the efficiency of both solutions. It is estimated that the efficiency of a harvester is equal to the efficiency of 4 chainsaws. Furthermore, another disadvantage of chainsaws is related to the health and safety of their operators.

6.5.3 Rail Vehicles

Over the recent years an increased number of rail vehicles (mostly locomotives) fitted with combustion engines have been imported to Poland. Their engines do not meet the statutory requirements as regards toxic emissions [4, 5]. The foregoing results mostly from the liberalization of railway transportation in Poland and the ensuing appearance of over thirty carriers (private carriers) from outside the former or current structures of the Polish Rail.

In most cases, the assessment of environmental performance is based on comparing the current status of a combustion engine (i.e. its emission factor) against limit values prescribed for engine or vehicle tests [1, 8]. In the Polish conditions of rail vehicles' operation the said tests take a slightly different form, because the rolling stock diversity significantly affects the vehicle's environmental performance. It is therefore necessary to address the issue of assessing emissions from rail vehicles under actual conditions. Therefore, any actions aimed at evaluating (and improving) actual emissions from rail vehicles are necessary and welcome.

Due to the fact that specific emissions of pollutants from most of the tested vehicles are measured in the ISO 8178-F test, environmental performance was analyzed in the phases of that very test. The results are presented as hour-by-hour emissions in the tested phases for each of the locomotives, to illustrate the differences in emitted masses of toxic compounds. Specific emission during the test is not a reliable indicator of emissions in this particular case, as it takes into account various coefficients of phase percentages, without addressing the specific operating conditions of a given locomotive. The actual hourly emission values recorded during operation can be presented by taking into account actual loads (histograms) or – in the absence of histograms – by using operation phase percentage coefficients derived from the ISO 8178-F test. In the latter case one should use the measured exhaust gas flow rates in each test phase, rather than the final specific emission values.

Environmental performance of a modernized BR231 fitted with a Caterpillar 3606 engine is presented below (Fig. 6.55). The said engine replaced an old 5D49 (the power of CAT3606 is by 10% lower than that of 5D49). Hourly emission of toxic compounds from the BR231 locomotive was determined taking into account the phase percentage coefficients derived from the ISO 8178-F test (Fig. 6.56).

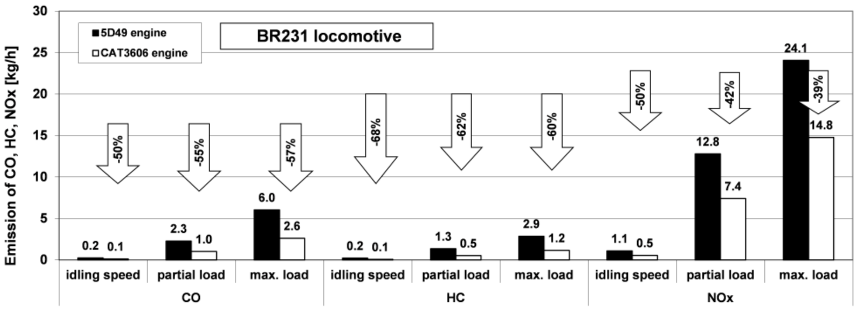


Fig. 6.55 Emission rate changes during one hour of locomotive operation, shown against different loads

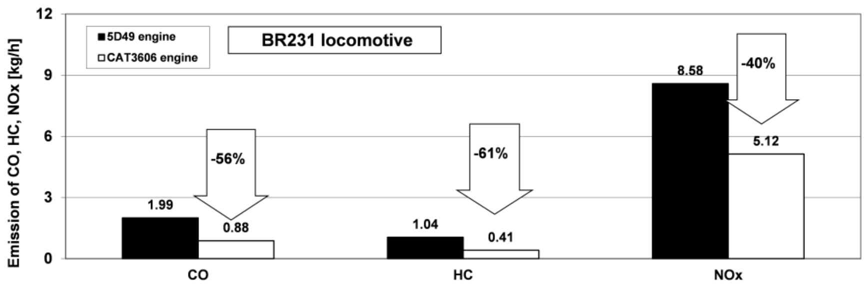


Fig. 6.56 Changes in the rate of emission of toxic compounds from a BR231 locomotive resulting from the engine replacement broken down by operating time percentages in accordance with the coefficients for the ISO 8178-F test

ST44 locomotives were modernized in stages. First, the main 14D40 two-stroke engine was replaced with a four-stroke engine (12CzN26/26) of the same cylinder capacity and power (V_{ss} = 150.6 dm^3, N_e = 1470 kW). In another locomotive, modernized by the company Rail Polska, another engine was used (654E3B, locomotive symbol: M62, engine power: N_e = 2238 kW, cylinder capacity: V_{ss} = 105.7 dm^3). The comparison of the environmental performance of both locomotives is presented in Fig. 6.57. The mass of toxic compounds was determined on the basis of the phase percentage coefficients derived from the ISO 8178-F test.

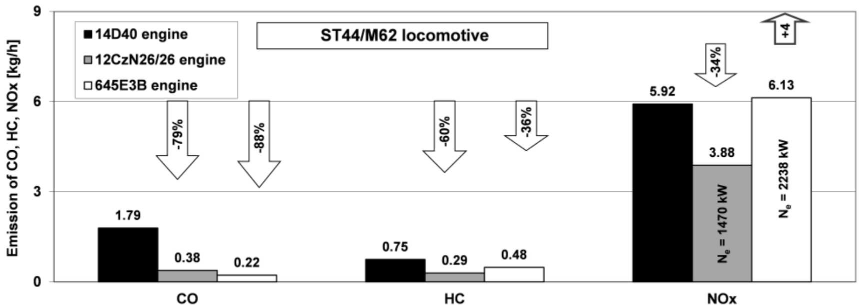


Fig. 6.57 Comparison of emission rates from 14D40, 12CzN26/26 and 654E3B engines fitted in modernized ST44 locomotives

Significant reduction in carbon monoxide emission rate positively affects the environmental performance of the modernized combustion-engine locomotives. Possible reduction of hydrocarbons ranges from 36% to 60%. The growth of nitrogen oxides emission in the case of the locomotive fitted with the 645E3B engine is linked to the engine power (50% more than the base power – 1470 kW).

Combustion-engine locomotives pulling passenger trains can be replaced with light rail vehicles. Frequent imports of such vehicles (fitted with more innovative combustion engines) for passenger transport (mostly regional), allows one to conclude that such engines will affect man's natural environment in a less negative way. Currently, MR/MRD traction units, Y traction rail vehicles as well as DH-1/DH-2 single and articulated vehicles are in use. The specific emissions from those vehicles [9] allow one to assume that emission rates will also be significantly reduced, owing to significantly smaller cylinder capacity as compared to traditional combustion-engine locomotives.

The benefits offered by light rail vehicles are illustrated by the toxic emission rates from an SP32 locomotive used in passenger transportation. The said locomotive is characterized by a relatively low power and small engine cylinder capacity. The relatively small cylinder capacity makes it possible to reduce toxic emissions, which positively affects the final results of the analysis (Fig. 6.58).

Attempts are being taken at neutralizing negative environmental influences of engines used in shunting locomotives by means of alternative fuels. As previously shown by these authors, toxic emission rates from such engines are greater than from an engine running on diesel. The respective emission rates are shown in Fig. 6.59.

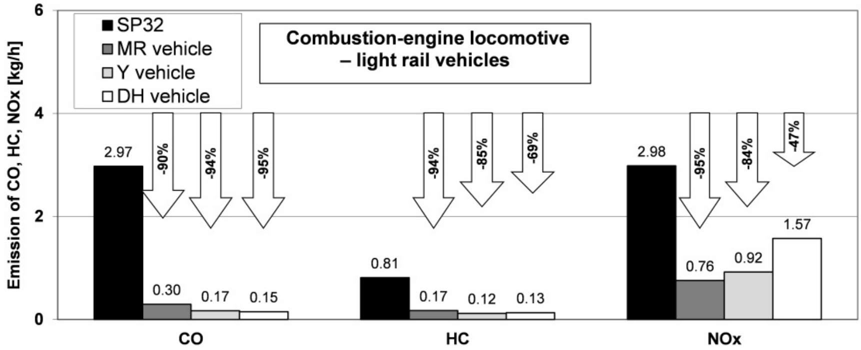


Fig. 6.58 Emission rates from light rail vehicles compared to a combustion-engine locomotive used in passenger transportation

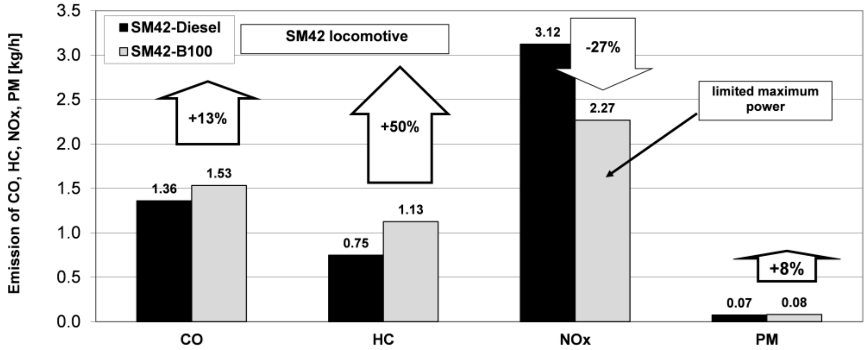


Fig. 6.59 Toxic emission rates of an SM42 engine running on diesel and on biofuel (B100) – shunting locomotive

Due to the lack of satisfactory reduction of emissions from shunting locomotives running on B100 fuel, the possibility to replace such locomotives with special-purpose rail vehicles was analyzed.

The comparison of heavy combustion-engine locomotives against light traction units shows significant differences in toxic emissions. This means that it is possible (and sometimes required) to replace worn out rolling stock with vehicles fitted with more innovative engines. While such engines usually have significantly less power and a smaller cylinder capacity, the vehicle's operating performance is not affected in any way.

Special-purpose rail vehicles are frequently based on technical designs of trucks (e.g. Iveco or Star – used for pulling and shunting on side-tracks), as well as tractors (Ursus, Crystal).

Road & rail tractor (Fig. 6.60) is used for shunting rail cars on both wide and narrow gauge tracks. The vehicle is based on Crystal tractor and is fitted with an additional creeping speed reducer and has a narrower wheel span. The rail version has been additionally equipped with a system enabling operation on tracks and coupling with a railway car (these systems were provided by TABOR Rail Vehicles Institute). The tractor can work both as a locomotive and as a vehicle for on-road towing.

Fig. 6.60 Tests of a Crystal tractor with the emission monitoring equipment installed. The tests were carried out at IPS Tabor in Poznan, Poland.

The environmental performance of the road & rail tractor was determined on the basis of on-track tests, by identifying pollution at the points of the ISO 8178-F test. Even though the engine is not used to propel typical rail vehicles, the measurements were carried out strictly in accordance with the said test, and specific emission values were compared to UIC 624 limits. The technical data of the tested engine contain information about its compliance with Euro IIIA and Tier 3 requirements. Therefore, Euro IIIA limits are also presented in the chart (Fig. 6.61). It should be stressed, however, that the said limit applies to measurements performed in the ISO 8178-C1 test. The C1 cycle applies to an 8-phase test, and not an F cycle (3-phase test), as mentioned above. Therefore, the limits are exceeded in the chart (even though the engine is in compliance). The inclusion of the said limits is important, because the engine specific exhaust emissions are low and the current UIC standards are met for all pollutants in the ISO 8178-F test. Our research shows that it is possible to achieve significant gains in fuel consumption if shunting operations are carried out by this type of vehicles, rather than by combustion-engine shunting locomotives. Fuel consumption at idling speed is 4.1 dm^3/100 km (equivalent), 15.3 dm^3/100 km at 50% load and 31.2 dm^3/100 km at maximum load.

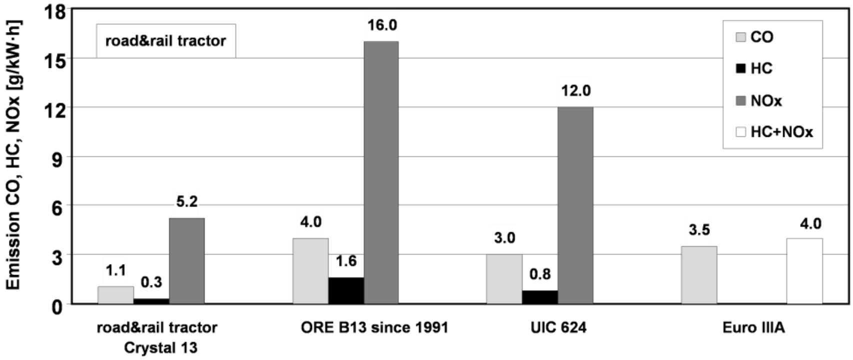


Fig. 6.61 Specific emissions of pollutants from a road&rail tractor compared to exhaust emission standards

The determined specific emission values made it possible to assess whether or not the replacement of combustion-engine shunting locomotives with road&rail tractors is reasonable. The following analysis presents the possibility of replacing shunting locomotives (exemplified by SM42 locomotive) with special-purpose rail vehicles (in this particular case: a road&rail tractor). The advantages of road&rail vehicles compared to shunting locomotives are as follows:

- the purchase price of a road&rail tractor is three times lower than the price of the cheapest shunting locomotive,
- the operating costs of a road&rail tractor are six times lower,
- traction properties are three times better,
- road&rail tractors can be operated by persons without railway operator's license (on private side-tracks),
- it is possible to mechanize cleaning operations of railway or tram infrastructure,
- it is possible to convert second-hand road vehicles to road&rail vehicles.

The rates of exhaust emissions (including particulate matter) from the road&rail tractor were compared to those from the SM43 shunting locomotive and are presented in Fig. 6.62. The simulations were based on the assumption that shunting operations carried out by the road&rail tractor take five times more time (reduction of the maximum number of pulled cars causes the operation time to grow five-fold).

An analysis of the operation of the locomotive and the road&rail tractor shows considerable savings in terms of atmospheric emissions of all toxic components of exhaust gases, amounting to at least 70% (by mass). This means that even though the operation time of the tractor is longer, during 2 hours of the SM42 locomotive operation it is possible to save the following amounts: over 2 kg of CO, 1.5 kg of hydrocarbons, 5 kg of nitrogen oxides and 100 g of particulate matter. By contrast, hourly emission of particulate matter from a passenger car (in a drive cycle) is approximately 2 g.

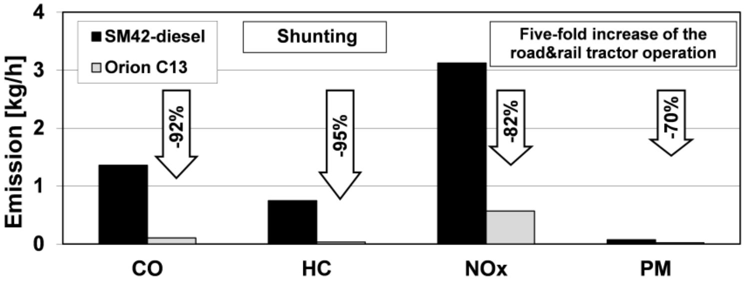


Fig. 6.62 Exhaust emissions from the SM42 locomotive and the road&rail tractor during shunting operations

The above alternatives for traditional track vehicles (modernization, replacement of traditional combustion engines with more modern ones, use of alternative fuels, introduction of railbuses and special-purpose vehicles) should be ranked in terms of environmental advantages offered by each of them. Therefore, the savings in toxic emissions resulting from each of the above alternatives were compared (Fig. 6.63). The comparison shows that locomotives used in cargo transportation generate 20 to 30% less specific emissions. Consequently, they can be replaced or decommissioned much later than locomotives used in passenger transportation. It also means that rolling stock upgrades are particularly necessary in passenger transportation. Modernization of the BR231 engine goes in the right direction as far as environmental protection is concerned. Emissions are reduced by approximately 1.7 (nitrogen oxides) to 2.5 (hydrocarbons). The replacement of obsolete two-stroke engines with modern four-stroke engines reduces emission rates by approximately 1.5 for nitrogen oxides to as much as 4.7 for carbon monoxide.

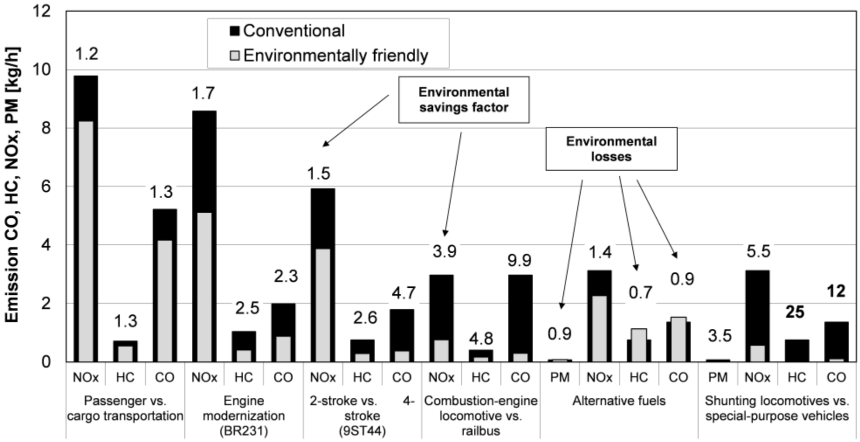


Fig. 6.63 Comparison of changes proposed in order to reduce the negative effect of rolling stock on the natural environment

The use of traction rail vehicles (railbuses) is very favorable, as it offers the following benefits: nearly 4-fold reduction in specific emissions of nitrogen oxides, 5-fold reduction in the emissions of hydrocarbons and an impressive 10-fold reduction in carbon monoxide emissions. Similarly beneficial is the replacement of shunting locomotives with special-purpose rail vehicles. The greatest reduction is possible for hydrocarbons – emissions from special-purpose vehicles (rail tractors) are 25 times lower. Carbon monoxide emission can be reduced 12-fold. Another remarkable benefit is the 3-fold reduction of PM emissions. The above figures take into account the fact that the operating time of the special-purpose vehicle is considerably longer (5×). If the operating time is reduced, the environmental advantages will be even greater.

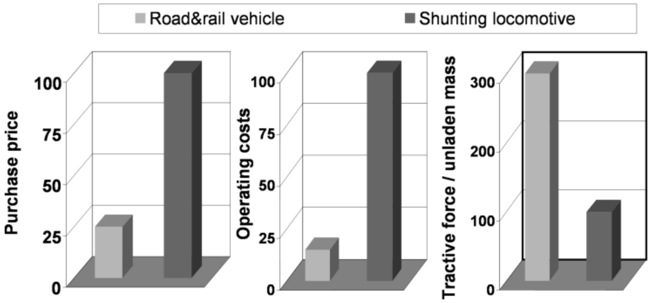


Fig. 6.64 Comparison of the advantages of rail&road vehicles and shunting locomotives

In addition, the economic effects of replacing shunting locomotives with road&rail vehicles (Fig. 6.64) are particularly striking: the purchase price of a road&rail tractor is three times lower than the price of the cheapest shunting locomotive, the operation costs are six times lower, and its traction properties are three times better; furthermore, operators without railway license can operate such vehicles on private side-tracks, it is possible to mechanize cleaning operations of railway or tram infrastructure, and second-hand road vehicles can be converted to road&rail vehicles. On top of that, attractive financing schemes are available for purchasing special-purpose vehicles.

The cost of purchasing a road&rail vehicle in order to replace a shunting locomotive will be regained in less than two years (assuming that work is carried out on a two-shift basis).

6.5.4 Special-Purpose Vehicles

Bearing in mind the specific nature of the operation of combat vehicles, it is set out to assess the way in which such vehicles are used and its effect on fuel consumption and specific emission of pollutants. Once these variables are known, it will be possible to evaluate the way in which combat vehicles are used. Thus far, no such tests had been made for combat vehicles. Poznan University of

Technology and Military Academy of Land Forces in Wroclaw were the first academic centers in Poland to tackle the issue in question.

The vehicle selected for testing for the purpose of evaluating emissions from combat vehicles was a Rosomak wheeled armored vehicle. Rosomak is a combat vehicle built by Finland's Patria Vehicles Oy. It is commonly referred to as an AMV (Armored Modular Vehicle). Poland chose this particular wheeled armored vehicle in a public procurement procedure. Built in a 8×8 arrangement with all-wheel drive, the vehicle can carry a total of 11 people. Suspension and power transmission systems are mounted on a longitudinal steel beam, constituting the vehicle main structural frame (Fig. 6.65).

Fig. 6.65 Measurement of exhaust gas pollutant emission from combat vehicles on military training grounds

The engine generates 294 kW of power in the standard mode and 360 kW of power in the overboost mode (more power through greater boost pressure). The maximum values coincide with the engine speed of 2100 rpm. The engine curves show that it is possible to increase the power by a maximum of 22.7% (which translates into a torque increase by 23%). These are maximum values at the engine performance curve shown in Fig. 6.66. Both of those values coincide with the engine speed of 1700 rpm.

The engines of military and special-purpose vehicles undergo the same testing procedures as the engines of non-road vehicles. This means that emissions are measured mostly in steady-state tests discussed in the preceding chapters. However, due to the specific operating conditions of military vehicles, their engines and powertrain systems are also tested for certain additional requirements.

Due to the specific operating conditions of combat vehicles it is set out to assess the way in which such vehicles are used and its effect on the specific emission of pollutants and particulate matter, as well as on the fuel consumption. Once these variables are known, it will be possible to evaluate the way in which combat vehicles are used. The ultimate goal was to determine the extent of change of the vehicle operating conditions depending on the area in which the vehicle is used.

The analysis of operating conditions was carried out: on access roads to the military training grounds (frequently in urban and extra-urban traffic – the results are also shown) and on the military training grounds (Fig. 6.67).

The time density matrices for each test phase were designed so that the torque value for each engine speed would correspond to actual loads. Normalization obtained from the readouts from the CAN network was transposed to actual values of the combustion engine. This procedure made it possible to refine the intervals and highlight the actual ranges of engine operation.

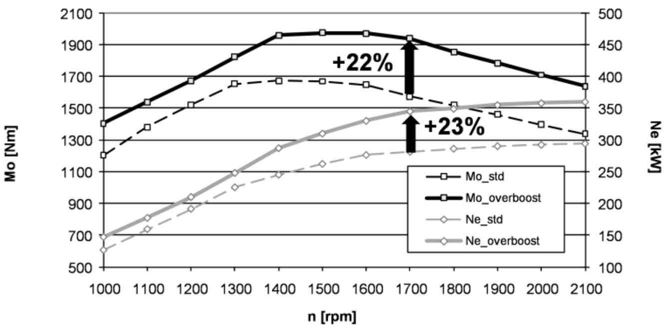


Fig. 6.66 Engine performance of Rosomak armored vehicle in the overboost mode

a) urban route b) access route c) military training ground

Fig. 6.67 Rosomak testing conditions

In urban traffic, the percentages of operation at idling speed and in the neutral gear (variable engine speeds with no load) are significant. Idling speed accounts for the greatest percentage (30%), which is typical of city traffic (Fig. 6.68). Partial loads (apart from innumerous cases of full load) are very rare. However, the greatest second-by-second fuel consumption coincides with high loads and engine speeds (Fig. 6.69). Specific fuel consumption equal to 200–250 g/kWh coincides with high engine speed and high load (Fig. 6.70). Despite the considerable idling speed percentage, the combat vehicle uses the entire operating range of its combustion engine even in urban traffic (Fig. 6.71).

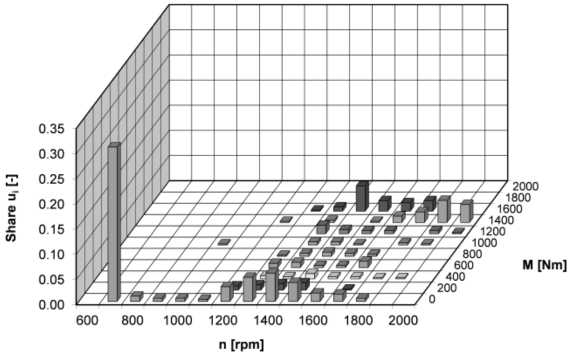


Fig. 6.68 Engine operation percentages (urban traffic)

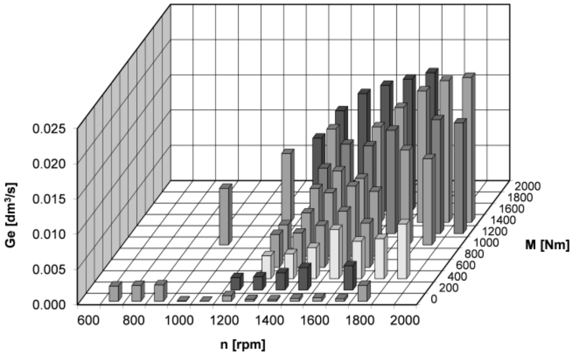


Fig. 6.69 Second-by-second fuel consumption (urban traffic)

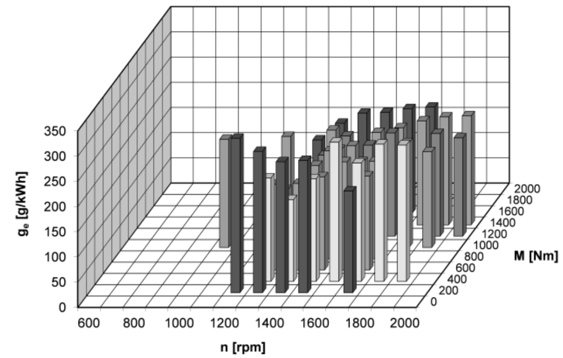


Fig. 6.70 Specific fuel consumption (urban traffic)

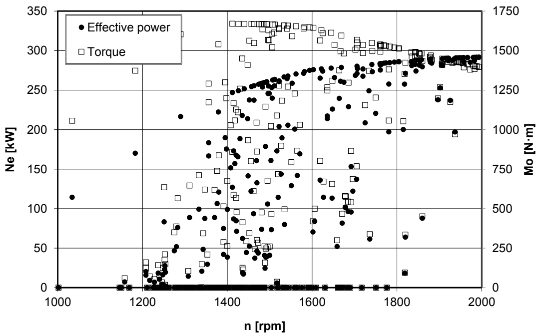


Fig. 6.71 Operating points in the engine operating field (urban traffic)

The combustion engine parameters change slightly on the access road to the training grounds (Fig. 6.72). In this setting, partial loads and high engine speeds are the dominating values, followed by engine in the neutral gear (variable engine speeds with minimum loads). Even though the maximum engine operation time in the extra-urban cycle corresponds to 600 rpm (its percentage is only 6%), this particular point is irrelevant when analyzing second-by-second fuel consumption (Fig. 6.73).

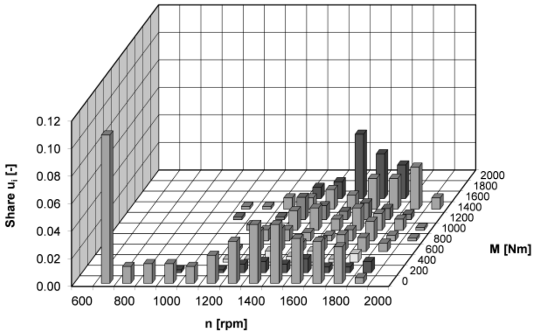


Fig. 6.72 Engine operation percentages (extra-urban traffic)

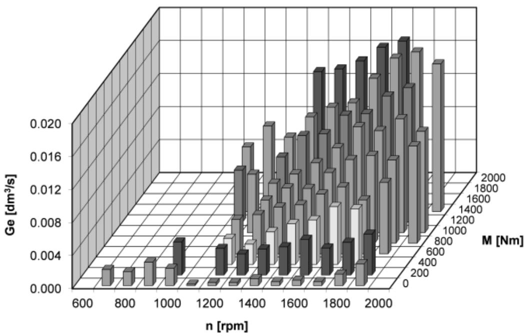


Fig. 6.73 Second-by-second fuel consumption (extra-urban traffic)

The average values of specific fuel consumption for this particular route amount to 300–400 g/kWh for the neutral gear and to 350–400 g/kWh when the engine works at greater loads. This shows that the efficiency of the combustion engine at its operating points is rather low (Fig. 6.74). The characteristics of the engine's operation indicate that it frequently works at maximum power with the speed ranging from 1400 to 2000 rpm (Fig. 6.75). One should expect the highest engine efficiency in these points (which is reflected by the specific fuel consumption).

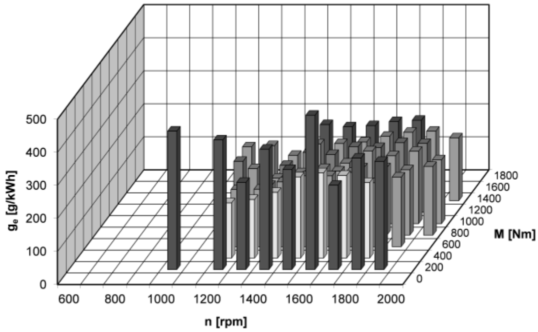


Fig. 6.74 Specific fuel consumption (extra-urban traffic)

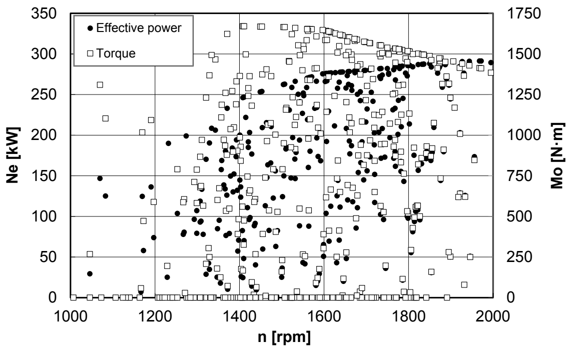


Fig. 6.75 Operating points in the general characteristics (extra-urban traffic)

Under the training grounds conditions, the engine operating characteristics were divided into two stages: standard power cycle and overboost power cycle. In the first cycle, changes in vehicle acceleration measured on the basis of the changes in the vehicle cruising speed were taken into account. The characteristics of these cycles (Figs. 6.76a and 6.76b) indicate that the shift from standard to overboost mode does not affect Rosomak's speed or acceleration profile in any significant way. However, the mode shift significantly affects the engine time density (Figs. 6.77a and 6.77b).

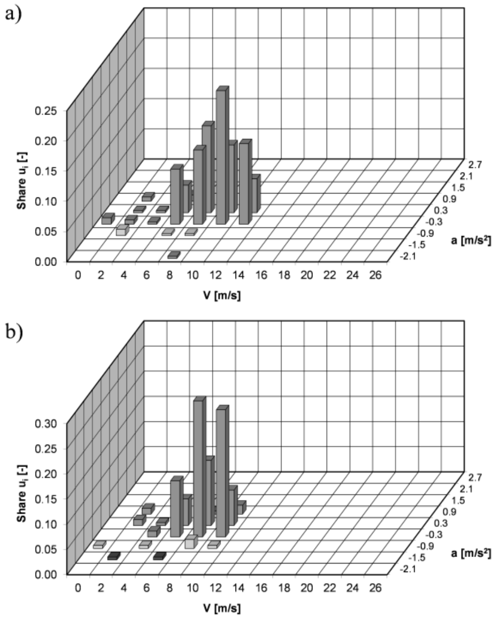


Fig. 6.76 Engine operation percentages (training grounds conditions) vehicle: a) in the standard mode, b) in the overboost mode

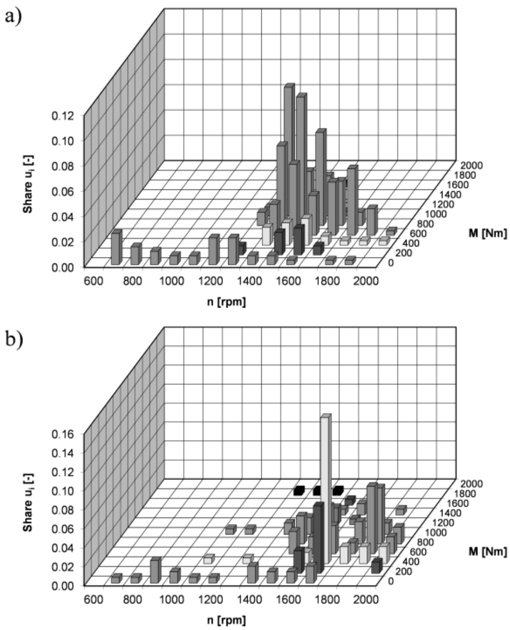


Fig. 6.77 Engine operation percentages (training grounds conditions) engine: a) in the standard mode, b) in the overboost mode

The overboost mode considerably narrows down the engine operating range. In that mode the engine works at greater speeds (1600 to 2000 rpm, as compared to 1400 to 1800 rpm in the standard mode), and the time percentages of those speeds grow significantly.

The standard mode is characteristic for lower second-by-second fuel consumption (Figs. 6.78a and 6.78b), as compared to the overboost mode: the differences measured at similar operating points amount to approximately 25% (e.g. the operating point at n–M_o: 1400–1400 in the standard mode yields fuel consumption of 0.010 dm^3/s, as compared to 0.014 dm^3/s in the overboost mode, which means a 40% growth).

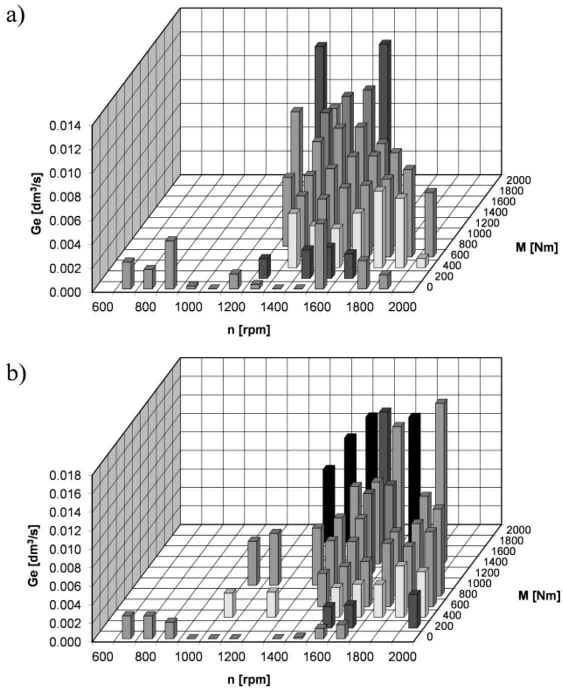


Fig. 6.78 Fuel consumption (training grounds conditions): a) second-by-second consumption in the standard mode, b) second-by-second consumption in the overboost mode

Small differences (or no differences at all) can be observed for the engine neutral gear (second-by-second fuel consumption in this range of engine speeds does not exceed 0.004 dm^3/s). As already mentioned, the overboost mode uses higher engine speeds and greater loads, which translates into differences in second-by-second fuel consumption. Consequently, mileage fuel consumption is also significantly greater for the overboost mode (Figs. 6.79a and 6.79b). Instantaneous fuel consumption equals 250–280 dm^3/h in the standard mode, whereas in the overboost mode it exceeds 350 dm^3/h. Much greater fuel consumption does affect the maximum engine torque and power.

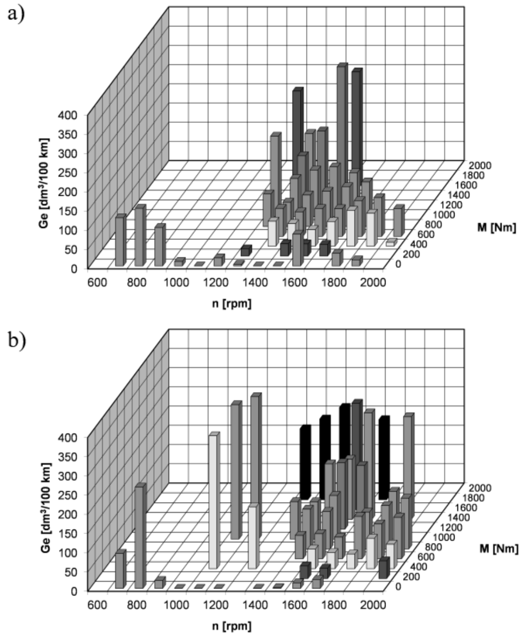


Fig. 6.79 Fuel consumption (training grounds conditions): a) mileage fuel consumption in the standard mode, b) mileage fuel consumption in the overboost mode

An analysis of specific fuel consumption pattern confirms that the fuel consumption is lower in the overboost mode, which results from lower hour-by-hour accumulation of fuel consumption in relation to increased power. The average specific fuel consumption values in the standard mode amount to 250–300 g/kWh (Fig. 6.80a), whereas they do not exceed 250 g/kWh in the overboost mode (Fig. 6.80b).

Figs. 6.81a and 6.81b clearly illustrate the differences in the engine operating points in both modes. The engine operating range in the overboost mode is much narrower, and engine speed and torque values are shifted upwards, while loads are generally lower. Another noticeable range is characteristic for partial loads and high engine speeds.

The changes between overboost and standard modes observed in on-road emissions were significantly greater than in specific emissions (Fig. 6.82). The greatest changes are related to on-road emission of CO (90%), PM (66%) and particle number (PN) – 130%. Changes in specific emissions of toxic compounds are by approximately 50% lower than changes in on-road emissions (overboost vs. standard mode). Engine operating conditions are important from the perspective of fuel consumption: 48% increase (from 48 to 70 dm^3/100 km) in the overboost mode (Fig. 6.83). Specific carbon dioxide emission is proportional to the mileage fuel consumption.

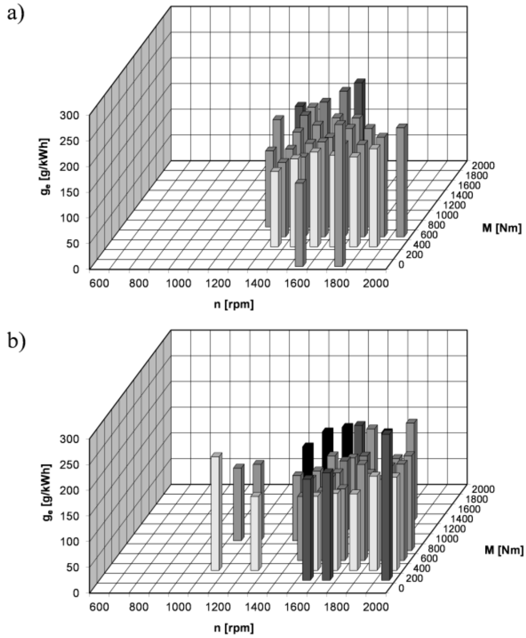


Fig. 6.80 Fuel consumption (training grounds conditions): a) standard mode, b) overboost mode

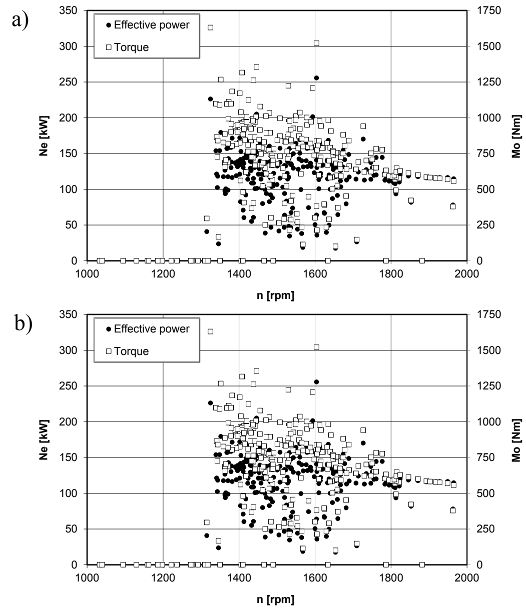


Fig. 6.81 Engine operation points (training grounds conditions): a) standard mode, b) overboost mode

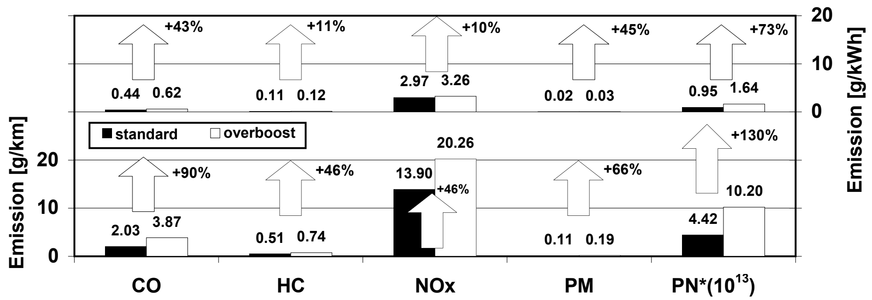


Fig. 6.82 On-road and specific emission of exhaust gas components from the engine of Rosomak combat vehicle (training grounds cycle, standard and overboost modes)

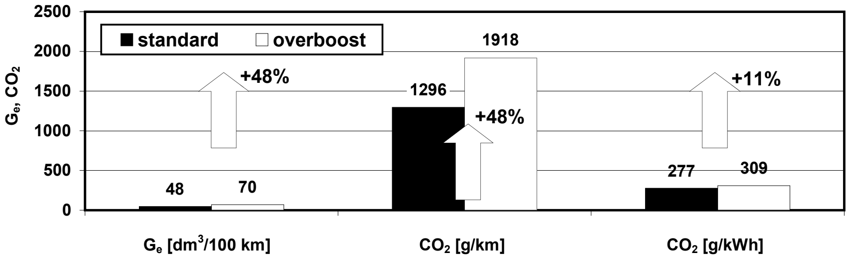


Fig. 6.83 Mileage fuel consumption and on-road and specific carbon dioxide emission from the engine of Rosomak combat vehicle (training grounds cycle, standard and overboost modes)

Tests under actual conditions are necessary to determine the emissions from a combat vehicle. The study discussed above was carried out for that very purpose. However, the knowledge of emission assessment criteria for such a vehicle allows one to compare the emission factors without the need to carry out time and effort consuming tests. Therefore, the operating conditions of combat vehicles were analyzed in order to develop a control test. The following assumptions were made:

- the test should be representative of the measurements under training grounds conditions; the results of specific emissions in a steady-state test should be similar to the training grounds measurements;
- the test should be similar to the test used for HDV engines; the number of test phases should not be greater than 3 and the phases should be selected similarly to the ISO 8178-F cycle (idling speed, partial load and maximum load);
- only the overboost mode is assessed, because it offers conditions similar to combat conditions; it is the only mode where the maximum values of the operating field are achieved.

On the basis of the above assumptions and the time density, the engine operating field was divided into three areas (Fig. 6.84): idling and minimum engine speeds (area 1), partial loads (area 2) and maximum loads (area 3). Area 3 is characteristic for a slightly smaller range of engine speeds.

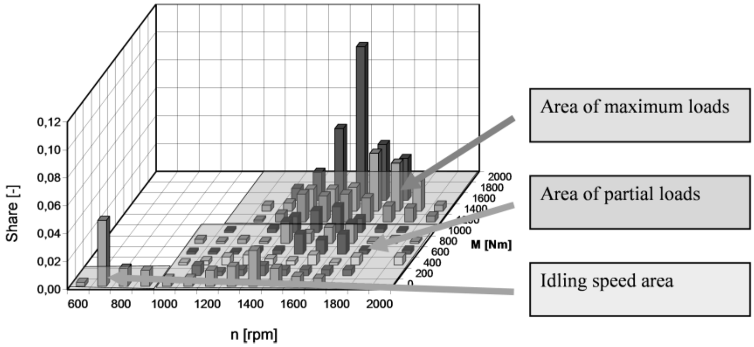


Fig. 6.84 Test phase selection methodology based on engine time density during the training grounds cycle

By adding up time density percentages for each area it was possible to identify the percentages of each phase in the test, which are as follows:

- idling speed phase – 6%,
- partial load phase – 49%,
- maximum power phase – 45%.

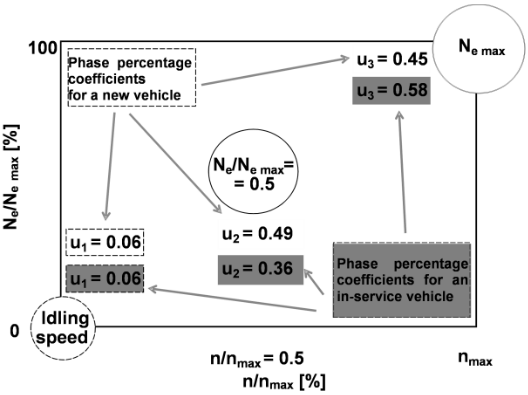


Fig. 6.85 Choice of phases and phase percentages in the test for a new vehicle and an in-service vehicle

The test discussed above made it possible to arrive at specific emissions of each exhaust component as presented in Fig. 6.85. The specific emission values identified in the test are lower than those under actual training grounds conditions. However, in spite of the small discrepancy (8 to 13%) in the measured emissions of each compound the test can be considered as representative of the training grounds conditions. The smallest discrepancy was observed for PM emissions, and the largest one for carbon dioxide.

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