Chapter 7
Conclusions

Since 2005 the European Union has gradually introduced a new legislation package on the emission of pollutants from vehicles in type-approval category M (passenger cars and buses) and N (trucks), consisting of the following [2, 3]:

- Euro 5 and Euro 6 standards for light-duty vehicles, replacing the previous Euro 4 standards,
- Euro VI standards for heavy-duty vehicles, replacing the previous Euro V standards.

The new legislation constitutes an important element of the EU's Clean Air for Europe strategy. The introduced changes relating to inspecting vehicles' compliance are in keeping with the legislative trends observed since the introduction of Euro 1 and Euro I, including the following:

- increased number of limited pollutants,
- more stringent emission requirements (standards),
- increased number of tests,
- extended mileage corresponding to the vehicle life, over which emission parameters should be sustained.

Stricter requirements have been introduced first of all with respect to limited tailpipe emissions under normal environmental conditions. Particular emphasis has been placed on particulate matter. From now on, limits apply not only to PM mass, but also to particle number. The previously prescribed PM limits for vehicles fitted with CI engines have been dramatically reduced, by 5 to 12 times for light-duty vehicles and by 2 to 3 times for heavy-duty vehicles. The requirements have also been extended to include vehicles with SI engines (in the case of light-duty vehicles, only direct injection SI engines are affected).

Nitrogen oxides are another pollutant on which the new legislation concentrates. For heavy-duty vehicles (with both CI and SI engines) the prescribed limits are now over 4 times lower than in Euro V. The reduction rate of the same limits for light-duty vehicles is clearly lower. For SI engines, the limits are identical for Euro 5 and Euro 6, and by approximately 25% lower than under Euro 4. For CI engines the reduction depends on the standard (28% for Euro 5 and 68% for Euro 6).

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Emphasis on nitrogen oxides and PM emissions resulted from the fact that the relative growth of the requirements in their case (i.e. between the first set of legislation and Euro 4 for light-duty vehicles/Euro V for heavy-duty vehicles) was significantly slower than for other limited pollutants. For NO_X this is particularly true for vehicles with CI engines.

Table 7.1 Limits of emission of pollutants from vehicles in category M1 of MLM ≤ 2500 kg, fitted with SI engines under the first legislation compared against Euro 4 limits and newly introduced EU limits

Pollutant	Euro 4 legislation			Euro 6 legislation	
	A	B	C	D	E
CO	25÷50	3÷65	100÷180	25÷50	40÷80
HC	20÷30	40÷55	100÷140	20÷30	60÷85
NO_X	31÷48	50÷70	100÷170	41÷64	85÷120

A – relationship between limits prescribed in the first legislation and in the previously applicable legislation (Euro 4).

B – severity of the previously applicable legislation (Euro 4) calculated as the ratio of the corrected prescribed limit in the first legislation to the Euro 4 limit.

C – the ratio of average emission in type I test of uncontrolled vehicles prior to the introduction of the first legislation to the emission from vehicles type-approved in accordance with Euro 4.

D – relationship between limits prescribed in the first legislation and in the new legislation (Euro 6).

E – severity of the new legislation (Euro 6) calculated as the ratio of the corrected prescribed limit in the first legislation to the Euro 6 limit.

The severity of emission limits depends not only on the values prescribed in the legislation, but also on inspection schemes and testing methodology. Table 7.1 shows the accumulated effect of all these factors for category M1, selected by way of example only.

For heavy-duty vehicles, specific emissions of hydrocarbons (THC or NMHC) have also been significantly reduced, both for CI and SI engines. Euro VI limits are by approximately 3.5 lower than Euro V limits. For light-duty vehicles fitted with SI engines, the limits prescribed for THC under Euro 5 and Euro 6 do not differ from those introduced by Euro 4 [11].

Attention should be drawn to the difference in the method of determining the emissions of hydrocarbons from light-duty and heavy-duty vehicles, introduced in the new legislation. For light-duty vehicles, separate limits apply only in the case of SI engines (for total hydrocarbons and non-methane hydrocarbons). For CI engines, the limit applies to the sum of total hydrocarbons and nitrogen oxides. For heavy-duty vehicles, the limits apply to:

- total hydrocarbons in the case of CI engines,
- non-methane hydrocarbons and methane in the case of SI engines.

The requirements regarding carbon monoxide have not changed either for light-duty or heavy-duty vehicles.

Apart from particle number, the newly added pollutants also include ammonia. The requirements for this particular pollutant apply to heavy-duty vehicles only, and the limit concerns its concentration in the exhaust gas, rather than emission.

The first legislation introduced in the early 1970s imposed limits on three pollutants only: carbon monoxide, total hydrocarbons and smoke opacity [5, 8]. Gradually, the number of limited pollutants has been increased and is now 9 (CO, THC, NMHC, MHC, NO_X, PM, PN, NH_3, CO_2).

The new legislation introduces not only stricter emission limits, but also significant changes in such areas as:

- division of vehicles into light-duty and heavy-duty,
- scope of application,
- testing.

The said changes significantly affect the severity of requirements.

The criterion of dividing vehicles in categories M and N into light-duty and heavy-duty is the reference mass, equal to 2610 kg, which replaced the previously used "maximum laden mass" equal to 3500 kg. However, the logic behind the above division is distorted by exceptions from the general rule. As a result, some vehicles with MLM > 3500 kg, previously classified as heavy-duty, are now considered to be light-duty.

Two important changes to the scope of application have been introduced:

- vehicles with RM > 2610 kg fitted with SI engines running on petrol are subject to heavy-duty legislation and must meet all the requirements stipulated therein,
- manufacturers are no longer allowed to choose the legislative scheme.

In the original legislation on emissions and emission-related vehicle parameters introduced in the early 1970s the following requirements were in effect [5, 7]:

- cold-start emissions at ambient temperature of 20–30°C,
- CO concentration at idling speed,
- engine crankcase emissions,
- smoke opacity.

For the purpose of assessing regulatory compliance, four tests were introduced. In the new legislation the number of tests has grown to eleven.

Particularly profound changes have been introduced for heavy-duty vehicles. As a general rule, the measurement methodology in each test should be identical to the one specified in the corresponding GTR (if available). Therefore, the tests previously used to measure emissions (ESC and ETC) have been replaced with WHSC (World Harmonized Steady-state Cycle) and WHTC (World Harmonized Transient Cycle), respectively. Smoke opacity test has been abolished after 40 years. The new tests, absent from the previous heavy-duty vehicles legislation, include [1]:

- measurement of engine crankcase emissions,
- off-cycle emission measurement (methodology in accordance with GTR 10),
- fuel consumption and CO_2 emission measurement.

The changes in testing schemes are less profound for light-duty vehicles. The newly introduced tests include measurement of electric energy consumption by electric vehicles and verification of the performance of the driver warning system preventing vehicle operation if the emission of nitrogen oxides is excessive. Measurement of particle number (PN) and significant changes to the PM emission measurement method have been introduced [6].

Emerging countries have been introducing stringent fuel and emission regulations following the developed countries from the view point of the emerging country's situation and energy reduction demand.

Although, to meet the stringent exhaust emission regulation, suitable fuel quality is required along with the engine technologies, there are mismatches between the emission regulations (Fig. 7.1) and fuel qualities in the market.

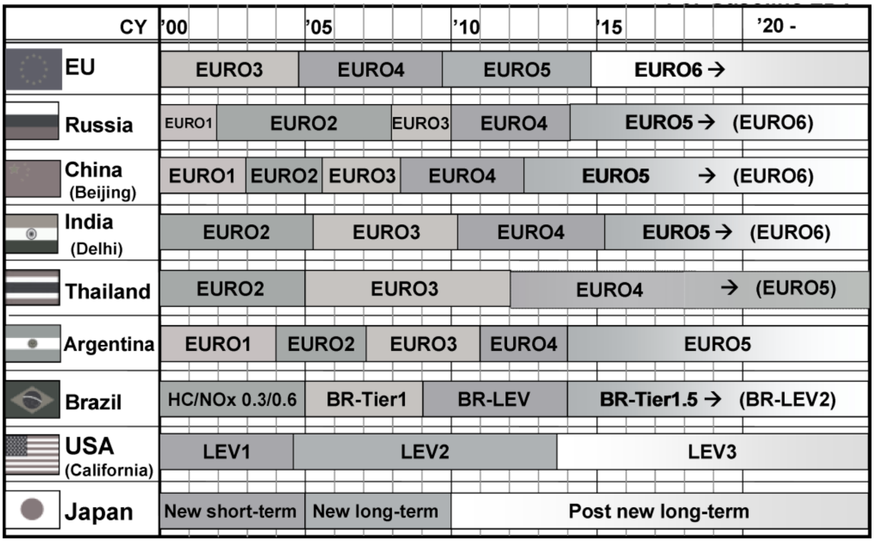

Fig. 7.1 Exhaust Emission Regulation [13, 14]

Currently a new method for testing emissions from light-duty vehicles is being developed. To that end, the GRPE (body in charge of drafting UN-ECE regulations) has set up the WLTP task force, responsible for developing (Fig. 7.2, Table 7.2):

- a new driving cycle,
- changes to the currently used emission measurement methodology.

It is expected that the WLTP will complete its project in 2014. As a result, a new GTR will be adopted, governing the method of testing emissions from light-duty vehicles.

World Light vehicle test procedure consists of 4 phases (Fig. 7.3): low phase, middle phase, high phase, extra-high phase. Objective:

- a test-cycle accepted worldwide to increase harmonization for the automotive sector at a global level,

Table 7.2 EU and USA Light Duty Passenger Car Emission Legislation

EU		USA	
EU Emission Legislation	EU and UN-ECE Technical Regulation	US Emission Legislation	US Technical Regulation
– EU-6b in 2014 and Euro-6c in 2017, – Limits are valid for all "normal driving" operations, not only for a certain drive cycle, – particle number (PN) also for spark ignition engines.	– test procedures and drive cycle shall be WLTP (World Light vehicle Test Procedure). WLTP Phase-1 should be finished within 2013, but is delayed, – real driving emissions (PEMS or random drive cycles).	– LEV-III (Low Emission Vehicle program III) will start in 2014, – US-EPA and CARB will harmonize their standards, – PM limits will be reduced by a factor 10, – PM measured for all engine and fuel types.	– test specifications CFR-1066 and CFR-1065 accordingly, replacing the current Part-40 CFR-86, – Medium Duty Vehicle (MDV) are tested on chassis dynamometers.

- the test cycle shall on average reflect the worldwide driving behavior of passenger cars and light duty commercial vehicles (based on driving data from the main Contracting parties including India, China, …),
- different gear shift points for PC and LDCV.

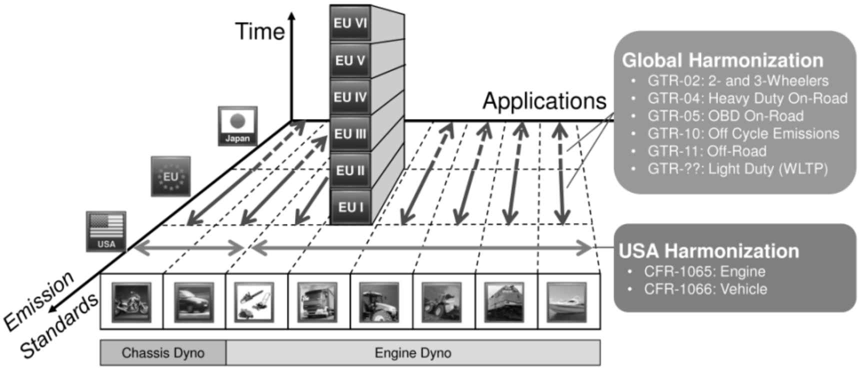

Fig. 7.2 Emission legislation: a complex 3-Dimensional matrix (application, region, level) [5]

In the new legislation, the method for testing in-service conformity of heavy-duty vehicles differs from the method used in type approval (Table 7.3). The engine dynamometer test is replaced with testing under actual traffic conditions.

Table 7.3 EU and USA Heavy Duty on road legislation

EU		USA	
EU Emission Legislation	EU and UN-ECE Technical Regulation	US Emission Legislation	US Technical Regulation
– Euro VI has started 2013, in addition to Particulate Mass (PM) there is also a Particle Number (PN) limit for Diesel engines.	– GTR-4 (Global Test Procedure) from UN-ECE, – WHSC (World Harmonized Stationary Cycle), – WHTC (World Harmonized Transient Cycle), – "Real Driving Emissions" limits by: off cycle emissions (OCE) in a stationary engine test cycle, with 15 random modes; and "In-Service" in vehicle on-road tests with PEMS.	– harmonization between EPA and CARB regulations, – GHC (Green-House-Gases) CO_2, CH_4 and N_2O must be measured and reported.	– test procedure is based on CFR-1065, which is very different to old CFR-86 or EU: all calculations are based on mol, test system performance specs related to emission standard and not to device range, continuous analyzer w/o analog gains switch, low quench CLD analyzers required; – NTE (Not to Exceed) emission limits measured in the vehicle on-road with PEMS.

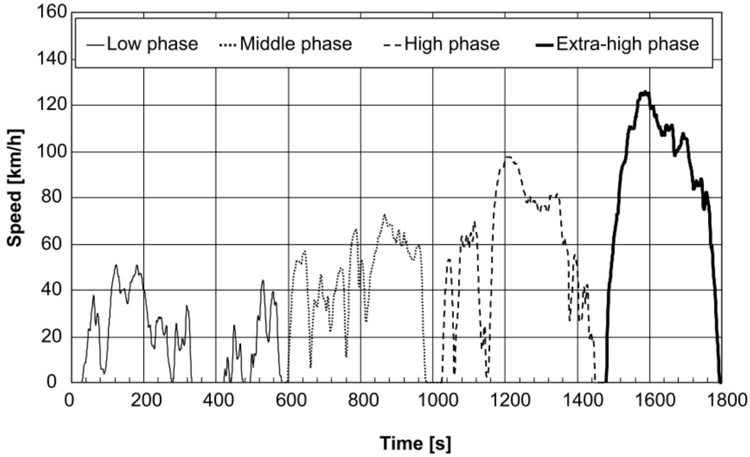

Fig. 7.3 WLTP driving cycle [5]

Emissions are measured by means of a portable emission measurement system (PEMS). This change marks a considerable shift from the previously binding principle (applicable to both light-duty and heavy-duty vehicles) that type-approval and in-service conformity methods should be identical [4, 9, 10].

State-of-the-art measurement solutions used for testing exhaust gas emissions make it possible to test vehicles under actual traffic conditions. The key drawback of such testing is the cost of the measuring equipment and its adaptation to the vehicle design. Such attempts are currently taken in all countries where environmental protection is a priority. The ultimate goal is to compare measurement options for different vehicles using different measuring devices. Consequently, the tendency to sanction emission measurements under actual operating conditions is discernible in Europe. This type of testing allows one to determine emissions of each pollutant under actual traffic conditions. Furthermore, it enables an assessment of the specific operating nature of a given vehicle in terms of engine load time density. Such information makes it possible to identify operating states of the propulsion system and their percentages in the total operation time. The data obtained in this way can be applied to steady-state testing procedures, which could facilitate optimization of operating points of engines used in various types of vehicles.

The present test campaign revealed the strengths and weaknesses of PEMS. In view of developing supplementary emission test procedures for light-duty vehicles, these can be summarized as follows:

1. Strengths:
   - PEMS measures real emissions from actual on-road driving,
   - PEMS can assure the proper design and operation of emission control technologies as well as the vehicle's energy consumption under a wide variety of normal operating conditions,
   - PEMS is suitable to test emissions from novel engine/after-treatment/powertrain technologies (e.g., parallel/serial (plug-in) hybrids or electric vehicles) as well as from alternative fuels,
   - PEMS provides measurements that can serve as basis for not-to-exceed emission limits, i.e., emission levels that should not be exceeded, regardless of driving and ambient conditions.
2. Weaknesses:
   - PEMS only to a very limited extent allow the reproducibility and comparability of individual test results due to the variability of on-road ambient and driving conditions,
   - PEMS only to a limited extent allows to reproducibility of cold start emissions,
   - The power consumption of PEMS is typically supplied by auxiliary batteries not to interfere with the vehicle operation. However, the weight of batteries and analytical equipment of approximately 80 kg may introduce a bias in the emission measurements, especially if conducted for small vehicles equipped with small engines.

Potentials for weight reductions of the equipment exist as technological improvements of the test equipment are very likely (both in terms modularity and size). Several practical considerations might support or limit the application of PEMS:

- PEMS allows a relatively long test campaigns of the duration of 2 hours,
- PEMS test procedures and equipment has been developed for testing the in-service conformity of heavy-duty vehicles and non-road machinery and has been proven to be reliable for light-duty vehicles as well,
- The modular composition of PEMS allows limiting the emissions screening to an absolute minimum. For instance, the THC measurements with a FID analyzer (that has high power consumption and requires a hydrogen/helium mixture) could be abolished because the correct functioning of oxidation and three-way catalysts can also be verified by analyzing the CO emissions only. Such an approach would substantially reduce the weight of the PEMS equipment.
- PEMS testing requires no detailed prescription of driving and ambient conditions; a prescription of key-features of test routes (e.g., percentage of driving in the city or motorway, test duration, road slope, driver's behavior) is, nevertheless, recommended to assure that PEMS testing covers the largest possible spectrum of driving conditions as it occurs during normal conditions of vehicle use.

The PEMS equipment is able to provide reliable and accurate on-road emission measurements for light-duty vehicles, even for vehicles that will be certified according to future emissions standards. This makes PEMS a suitable tool for identifying and updating emission factors of air pollution models. Furthermore, PEMS tests may be used as a supplemental emission test procedure next to standardized laboratory emission tests. The strengths of PEMS include the ability to detect the proper operation of emission control technologies under a wide variety of normal operating conditions, particularly during high-speed driving at speeds in excess of 130 km/h. PEMS also allows testing emissions from novel fuel/engine/aftertreatment/power-train technologies (e.g., parallel/serial (plug-in) hybrid vehicles). Such analyses have not yet been conducted but are envisaged. A major limitation of PEMS refers to its relatively heavy weight (PEMS unit, EFM, mounting devices, power supply) that may reach 80 kg (i.e., the weight of 1 person). As technological improvements of the test equipment are very likely (in terms modularity and size) the weight of the equipment could be reduced substantially in the future.

In conclusion, the present test campaign has resulted in the successful application of PEMS for light duty vehicles. The results of this test campaign indicate that on-road emissions might substantially exceed the emission levels identified during type approval in the laboratory.

The applied averaging window method implemented to check the emissions of heavy-duty engines offers a simple and straightforward way to average and analyze emissions data of light-duty vehicles. Based on this method, appropriate indicators could be developed to evaluate whether an averaging window (or any other data sub-set) can be classified as extreme (as opposed to normal) driving conditions. Such analysis could address specific driving situations, for instance cold start, steep road grades, or aggressive high-speed driving.

Future research should address not-to-exceed regulatory concepts and alternative metrics for defining emission limits: the current approach that expresses the emission limits as distance-specific quantities is problematic because it lacks a reference to actual engine parameters and only insufficiently accounts for the large variability of on-road driving conditions that may include long idling periods in congested traffic.

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