Chapter 2
Light-Duty Vehicles

Abstract This chapter presents the most important driving cycles used for testing passenger cars and light-duty trucks, which are all of the chassis-dynamometer type. European, U.S., Japanese, Australian and worldwide modal and transient cycles are presented, including those intended for battery and electric vehicles, with graphic illustration of the speed profiles together with a detailed historical background. Main technical specifications are provided, as well as identification of the shortcomings, and representative results from real vehicles operation. An extensive comparison of the most important legislated cycles is also presented and discussed at the end of the chapter.

Passenger cars and light-duty trucks/vans (collectively referred to as light-duty vehicles—LDVs), were the first vehicle types for which emission standards and test cycles were legislated in the late 60s, limited to gasoline engines. Initially, the employed cycles were modal but later evolved to more sophisticated transient form, and covered diesel-engined vehicles too. Both urban and suburban/motorway segments have been usually included it the test cycle, with varying duration, aggressiveness and maximum speed depending on the specific region. United States, Europe (through UNECE regulations) and Japan have been the pioneering regions in the world in legislating certification test cycles for LDVs. The most important of them, all of the chassis-dynamometer type, will be detailed in the following sections. The respective drive cycles for another light-vehicle category, namely motorcycles, are discussed in Chap. 3.

2.1 European Union

With a yearly production of more than 18.4 million vehicles (20 % of global motor vehicle production) in 2015, from which 98 % light duty, European Union (EU) is the second biggest car manufacturer in the world today after China. One out of four passenger cars sold worldwide is produced or imported in the EU [1]. It is not

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surprising then that the European regulations on automobile emissions affect the biggest manufacturers and many other non-European countries worldwide.

The legislative function in the European Union regarding emission regulations and test cycles/procedures is exercised in the form of directives or, more recently, regulations, by three regulating bodies:

(a) the European Parliament (elected by the peoples of the Member States),
(b) the Council of the EU (representing the governments of the EU Member States), and
(c) the European Commission (the executive body of the European Union responsible for proposing legislation and implementing decisions).

Through the years, the European Economic Community (EEC) and later the EU have produced a series of directives and regulations,[1] usually based upon the technical recommendations of the UNECE. The first emission limits were set in 1970 with Directive 70/220/EEC, concerning HC and CO emissions from gasoline vehicles; the limits (g/test) were defined with respect to the vehicle's reference weight. The directive applied to 'any vehicle with a positive-ignition engine, intended for use on the road, with or without bodywork, having at least four wheels, a permissible maximum weight of at least 400 kg and a maximum design speed at least 50 km/h, with the exception of agricultural tractors and machinery, and public works vehicles'. Directive 70/220/EEC harmonized draft national exhaust emission legislations from Germany ('Straßenverkehrs-Zulassungs-Ordnung' from 1968) and France ('Composition des gaz d'échappement émis par les véhicules automobiles équipés de moteur à essence' from 1969). These had been passed on to the Commission under the Standstill Agreement of 1969 General Program for the elimination of technical barriers to trade. With Directive 70/220/EEC, the first European test cycle, the ECE-15, was also legislated.

Since both Directive 70/220/EEC and its first amendment 74/290/EEC focused exclusively on HC and CO, the obvious reduction measure from the manufacturers was to adjust the SI engine operation towards lean mixtures. This, however, resulted in an increase in the emitted NO_x from gasoline passenger cars. As of October 1977 (Directive 77/102/EEC), NO_x emission limits were defined too, expressed as NO_2 equivalent g/test, again with respect to the vehicle's reference weight. Diesel engine emissions were covered from 1988 (Directive 88/76/EEC), with PM taken also into account (Directive 88/436/EEC), whereas fuel consumption measurement was introduced with Directive 80/1268/EEC [2].

The 'Euro' standards began in 1992, a few months before the European Union was established through the Treaty of Maastricht, with Euro 1 for passenger cars (Directive 91/441/EEC). This triggered the use of catalysts in cars and unleaded gasoline with a delay of more than a decade compared to the United States; evaporative emission standards were covered too. Light-duty trucks followed two years later, in 1993 (Directive 93/59/EEC). In September 2014, the last stage, Euro 6,

[1]EU directives and regulations can be accessed online through http://eur-lex.europa.eu.

came into force (Regulations 715/2007/EC and 692/2008/EC). Nowadays, the controlled pollutants from LDVs are mass emissions of CO, NO_x, HC/NMHC and PM, as well as particle number (see also Fig. 1.3). Passenger cars fall into categories M_1 and M_2, with light-duty vans into categories N_1 and N_2; reference mass for all these vehicles is lower than 2610 kg. Light-duty vans of category N_1 are further divided into three classes, I, II and III depending on the reference weight [3]. Detailed analysis of the complicated EU environmental policy-making and the often conflicting objectives between Member States and between car makers that led to the formulation of the EU automobile emission legislation is available in [4].

2.1.1 European Driving Cycle ECE+EUDC/NEDC

The driving cycles that have been employed for many decades in the European Union for the certification of passenger cars and LD vans were the ECE (initially) and the ECE+EUDC beginning with the Euro 1 emission standard in 1992, from 2000 known as NEDC. Although originally intended for gasoline-engined vehicles, the cycles have been also employed for the testing of diesel-engined vehicles, as well as to estimate the electric power consumption and driving range of hybrid and battery-electric cars. It is the intention of the EU authorities to adopt the WLTC (Sect. 2.5) from September 2017 together with the Euro 6c standard.

Work about emission test procedures for automobiles started in Europe in the mid 50s. For example in Germany, the VDA sub-committee 'Abgase von Otto-Motoren' (Exhaust gases from gasoline engines) was assigned to establish emission standards, evaluate possibilities for pollutant reduction, and develop necessary measurement techniques. Until October 1958, the German Ministry of Traffic had distributed various research assignments on automobile emissions, for example air quality measurements in German cities, and pollutant reduction in the exhaust gas from gasoline engines. However, it soon became clear that these activities had to be coordinated with similar ones conducted at the time in Sweden and France, in order for the results to be more effective [2].

In France, research on the early development of a cycle to simulate Paris driving is reported in [5]. Two routes, a north–south (8.4 km) and an east–west (11.25 km) were selected, and continuous traces of engine speed, inlet manifold vacuum, brake usage, and gear selection were recorded in two vehicles driven over the routes. Analysis of the resulting traces yielded data similar to that obtained in a Los Angeles research of 1957 (Sect. 2.2.1). An 11-mode cycle was then constructed by UTAC (Union Techniques de l' Automobile, du Motorcycle et du Cycle), which contained mode times as indicated in Table 2.1, and further detailed in Table 2.2 also showing weighting factors for continuous emissions analysis. Under the auspices of the UNECE, GRPA (later GRPE) carried out studies of driving patterns in ten European cities and recommended modifications to the UTAC cycle [2, 6].

The driving cycle discussion had been monitored by the WP.29 working group, which in its 20th session on December 20, 1965, assigned the BPICA ('Bureau

Table 2.1 Comparison between Paris driving, UTAC cycle and ECE-15 cycle [6]

Mode	Proportion of time in driving mode (%)		
	Paris	UTAC	ECE-15
Acceleration	32	15.6	18.5
Cruise	13	52	32.3
Deceleration	22	13.4	18.5
Idle	33	19	30.7

Early results from Germany in 1965 showed a markedly higher percentage of idling in German cities of the order of 45 %, but this figure was subsequently revised to 35 % [2]

Table 2.2 UTAC cycle modes and weighting factors [6]

Mode	Speed (km/h)	Weighting factor (%)
1	Idle	7.3
2	0–20	33.1
3	20	6.4
4	20–40	36.2
5	40	3.3
6	40–25	7.1
7	25	0
8	25–60	5.2
9	60	1.1
10	60–25	0.3
11	25–0	0

Permanent International des Constructeurs d'Automobile') to propose a unified European driving cycle. The first draft of this cycle was presented by BPICA during the 1st session of the GRPA in Paris on July 6–8, 1966. After some modifications,—e.g., a reduction of the average speed from 21.2 to 18.9 km/h which was requested by Great Britain—and after an evaluation in the London laboratories of the BPICA, the cycle was eventually accepted during GRPA's 2nd session on January 9–11, 1967 [2]. The resulting cycle was the ECE-15, which was the first drive cycle to be legislated in the EU (EEC at the time), and is illustrated in Fig. 2.1. The name ECE-15 corresponds to UNECE Regulation No. 15 published in April 11, 1969.[2]

The cycle was adopted by the European Economic Community initially on 20 March 1970 (Directive 70/220/EEC) concerning CO and HC emissions from

[2]Regulation No. 15 was replaced by No. 83, which introduced the extra urban segment of the cycle, No. 84 as regards fuel consumption measurement, and No. 101 as regards CO_2 emission and fuel consumption measurement. The above UN regulations, as well as the respective EU documents, provide detailed information on the driving cycle, i.e., the exact gear-shift strategy, guidelines for the measuring procedure, calibration of the test equipment, reference fuels as well as detailed description of all the applicable type-approval documents.

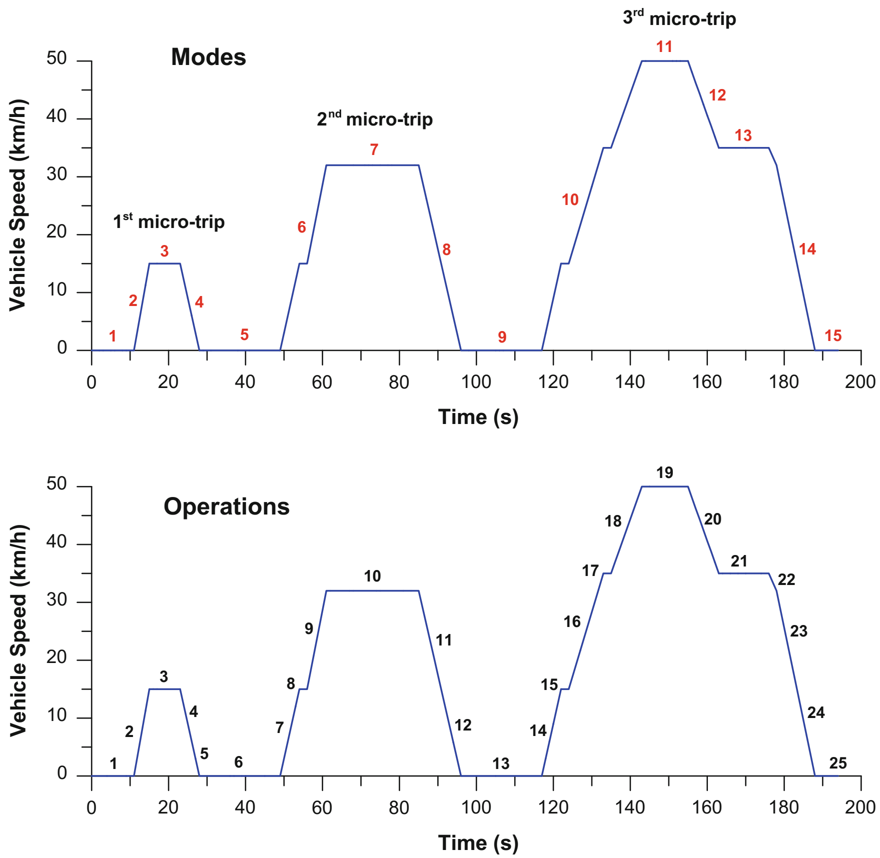

Fig. 2.1 Speed profile of the ECE-15; the *upper sub-diagram* identifies the 15 modes of the cycle and the *lower sub-diagram* the operations to be followed by the driver (for example, mode *10* consists of accelerations (operations) No. *14*, *16* and *18* and gear changes No. *15* and *17*). Notice that the points the gears are to be changed are explicitly defined in the legislation. During the certification procedure, the ECE-15 is run four times consecutively

gasoline cars only using the single bag measuring procedure; the concept of modal weighting in the UTAC cycle from Table 2.2 was abandoned in favor of collection of all the exhaust gases from the cycle. The sampling method changed in 1983 to constant volume sampling (Directive 83/351/EEC), and from the late 80s covered diesel-engined vehicles too.

The urban cycle ECE-15 or ECE (also known as urban driving cycle UDC) is illustrated in Fig. 2.1 and is a typical modal/'synthetic' cycle. Each micro-trip comprises an initial idling phase, acceleration—depending on the specific micro-trip, there are one or two intermediate gear changes—steady speed, and deceleration. Overall, the elementary urban cycle encompasses 15 modes and 25 operations to be followed by the driver. The cycle is repeated four times for a total duration of 13 min (4 × 195 = 780 s) and a total distance of 4045 m. The UDC is characterized by frequent gear changes, relatively low vehicle speeds (and loads) up to 50 km/h, and several stops, with a rather prolonged idling period of the order of 31 %; further, the cruise section is very high at 32 %. The average driving speed is quite low, at 18.7 km/h. It should be noted that, as is the case with all modal chassis-dynamometer cycles, the ECE-15 is defined in terms of specific modes and operations to be followed by the driver. From these modes, provided in tabular form in Directives 70/220/EEC and 91/441/EEC, the graphical illustration of Fig. 2.1 is derived.

After pressure from the Netherlands, who presented evidence that over 70 % of European mileage in the 80s was driven at vehicle speeds higher than 70 km/h, the extra urban driving cycle, EUDC, was introduced in 1989 by UNECE Regulation No. 83 and adopted by the European Community on June 26, 1991 (Directive 91/441/EEC). The cycle was a compromise between the West German and British proposals and that of the consultative Committee of Manufacturers of the Common Market [7, 8]. The modal EUDC, graphically illustrated in Fig. 2.2 from the tabulated driving operations detailed in Directive 91/441/EEC, represents extra urban driving, with much higher vehicle velocities up to 120 km/h maintained for 11 s, accounting thus for rural or motorway driving. The aim was to replicate in a more complete way the real ‘duty cycle’ of a typical passenger car. Total duration is 400 s, of which 332 s (83 %) is spent with the fourth or fifth gear engaged in the gearbox; interestingly, for 54 % of the time, the vehicle cruises. Overall, the EUDC comprises 13 modes, namely idle, accelerations, steady speed driving, and

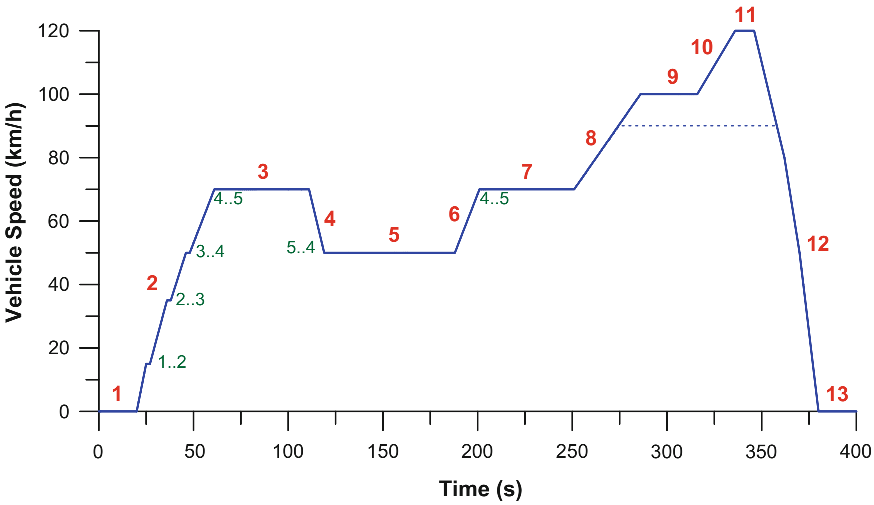

Fig. 2.2 Speed profile of the motorway EUDC segment with the dotted line corresponding to the low-powered version of the cycle (numbers from *1* to *13* denote the cycle modes; the gear changes throughout the cycle are also indicated for the case of a five-speed gearbox)

Table 2.3 ECE and EUDC breakdown by use of gears (in s) (Directive 91/441/EEC)

Cycle segment	Total	Idling	Idling, vehicle moving, clutch engaged on one combination	Gear shift	1st gear	2nd gear	3rd gear	4th gear	5th gear
UDC	195	60	9	8	24	53	41	–	–
EUDC	400	20	20	6	5	9	8	99	233

decelerations. Predictably, there are no intermediate idle periods in the cycle's speed trace but there is an idle phase of 20 s both at the beginning and the end. Table 2.3 provides some data for the urban ECE and motorway EUDC with reference to the time spent with each engaged gear.

Upon introduction of the EUDC in 1991, the full version of the European driving cycle was formulated, demonstrated in Fig. 2.3; it comprised two parts: the urban ECE segment formed the first part and the motorway EUDC the second. An alternative version of the EUDC was also defined at that time, where the maximum vehicle speed during the cycle was limited to 90 km/h. This was employed for low-powered vehicles having a maximum engine power less than 30 kW, or 30 kW/t for LD vans, and a maximum vehicle speed lower than 130 km/h. According to Directive 93/59/EEC, the low-powered version of the cycle was to be employed until 1 July 1994 for M-category vehicles, 1 January 1996 for N_1-category Class I, and 1 January 1997 for N_1-category Classes II and III. After that dates, vehicles which do not attain the acceleration and maximum speed values required in the cycle must be operated with the accelerator control fully depressed until they once again reach the required operating curve.

Beginning with emission standard Euro 1 in 1992, passenger cars in Europe were tested on the combined ECE+EUDC, Fig. 2.3, using the CVS system. This combined version of the urban ECE and the motorway EUDC is known as MVEG-A.[3] The cycle has a total duration of 1180 s (=4 × 195 + 400) with 11 km traveled distance. It is the Type I test in the type approval, as originally defined in Directive 70/220/EEC.

For compliance with the Euro 1 and 2 emission standards, the vehicle (run-in and driven for at least 3000 km) was kept for at least 6 h before the test in a room with a constant temperature between 20 and 30 °C. Especially for compression-ignition engined vehicles, and with regard to their PM measurement, Directive 91/441/EEC established a further preconditioning requirement. Specifically, the motorway EUDC part of the cycle was to be run three times between 6 and 36 h prior to the test. After the preconditioning, the vehicle was started and kept idle for 40 s before the cycle was run and the emissions sampled. During the test, the cell temperature was

[3]The Motor Vehicle Emissions Group—MVEG, has been an expert working group that played a central role in the development of the European automobile emission regulations.

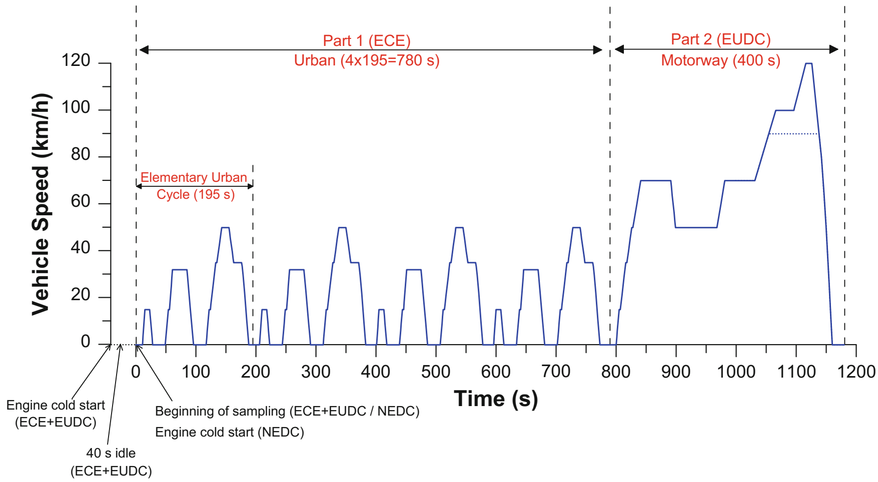

Fig. 2.3 Speed profile of the ECE+EUDC/NEDC driving cycle valid in the EEC/EU from 1970 to 2017 (*dotted line* designates the low-powered version of the cycle). Initially, there was a 40-s idling period before the cycle commenced (and sampling began), hence total duration was often cited as 1220 s. From 2000 onwards, the cycle runs and the sampling begins with the engine cold started (NEDC). A tolerance of ±2 km/h between indicated and theoretical speed is allowed as well a time tolerance of ±1 s at certain operations during the cycle

again between 20 and 30 °C, and the absolute humidity between 5.5 and 12.2 g of water per kg dry air. Directive 98/69/EC of October 13, 1998, implemented a slight but important change in the procedure, valid from the year 2000 with the transition to emission standard Euro 3. Emission sampling commences now immediately, i.e., without the 40-s warm-up period. This slightly modified cold-started procedure is known as the New European Driving cycle (NEDC) or MVEG-B, Fig. 2.3. Obviously, the first UDC run is responsible for higher amount of pollutants compared to the other three, as during the first minutes after cold start the after-treatment devices have not reached their operating temperature. Figure 2.4 eloquently illustrates this for CO and HC emissions of a Euro 4 passenger car.

The same testing procedure is employed for CO_2 emissions. The EU does not directly set fuel consumption standards but regulates CO_2 emissions, from the late 90s following a voluntary agreement with car manufacturers, and from 2009 on a mandatory basis, also including penalty payments in case of exceedingly high fleet-averaged CO_2. Fuel consumption is also measured during the NEDC; urban (Part 1) and extra-urban (Part 2) values are calculated and reported too, without applying any weighting factors. Emissions are sampled during the whole 1180 s duration of the cycle according to the constant volume sampling technique detailed in Sect. 6.5. For the low-temperature (Type VI) test of spark-ignition engined

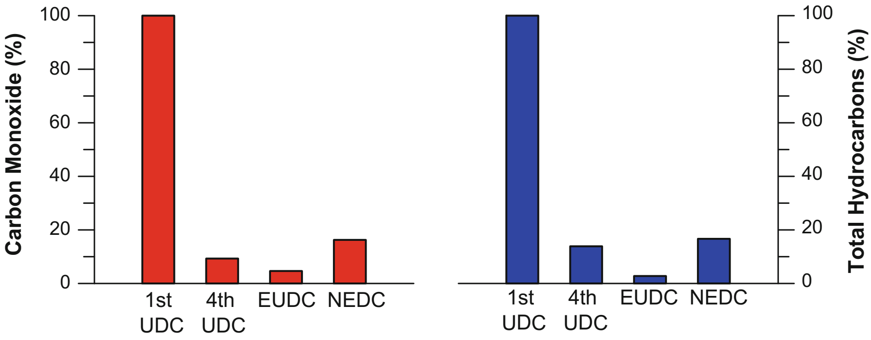

Fig. 2.4 Comparison of the relative CO and HC engine-out emissions during the NEDC for a Euro 4 diesel passenger car; the first UDC segment is the base (=100). During the fourth UDC, CO emissions are less than 10 % of those during the cold-started first UDC run (data from [9])

vehicles at −7 °C, however, initially legislated in Directive 98/69/EC to be valid from the Euro 3 standard, only the urban ECE part applies.[4]

Table 2.4 summarizes the driving cycles valid in the EU over the years, and Table 2.5 provides some of their important technical specifications. More detailed data is provided in the Appendix. Furthermore, Fig. 2.5 illustrates the frequency distribution for the speeds and accelerations encountered during the NEDC, where an increased density at zero acceleration is evident owing to the high percentage of time spent idling and cruising throughout the cycle. Figure 2.6 expands on the previous figure by highlighting the different speed/acceleration ranges between the urban and motorway segments of the NEDC.

Representative results during the NEDC are illustrated in Fig. 2.7 for a large passenger car. A strong influence between vehicle speed and traction force can be established from this figure. Aerodynamic resistance force follows closely the vehicle speed pattern; during the urban part of the cycle (0–780 s), where the vehicle speeds are maintained overall low, the rolling resistance term (not shown) generally prevails over the aerodynamic one. During motorway driving (781–1180 s) on the other hand, the aerodynamic force assumes much higher values. The points in the cycle where accelerations occur, lead to instantaneous sharp increases in CO_2 emissions, which are also indicative of the fueling rate.

Apart from the NEDC, Directive 91/441/EEC and Regulation 692/2008/EC defined special purpose cycles, namely the AMA and the SRC/SBC respectively, to be used for vehicle full useful life (durability) testing. These will be discussed in Sect. 2.2.7 as they also form part of the U.S. regulation.

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[4]*For the type approval in the EU, the tests conducted are: Type I (tailpipe emissions after a cold start), Type II (CO emission at idling speed—gasoline, LPG and natural gas PI engines), Type III (emission of crankcase gases—PI engines only), Type IV (evaporative emissions—gasoline PI engines only), Type V (durability of anti-pollution control devices), Type VI (low temperature CO and HC tailpipe emissions after a cold start—gasoline PI engines only).*

Table 2.4 Driving cycles legislated in Europe (1970–2016)

Cycle	Cycle type	Traffic type	Procedure/Duration	EU Directive (UNECE Reg.)
ECE (4 identical elementary sub-cycles)	Modal	Urban	Cold starting + 40 s (idling) + 780 s (sampling)	70/220/EEC (UNECE R15/00) (‘Single ‘big’ bag sampling/PI-engined vehicles) 83/351/EEC (UNECE R15/04) (constant volume sampling)
ECE + EUDC	Modal	Urban + Motorway	Cold starting + 40 s (idling) + 1180 s (sampling)	91/441/EEC (R83/01) (passenger cars) 93/59/EEC (R83/02) (light-duty trucks)
NEDC	Modal	Urban + Motorway	1180 s (cold started)	98/69/EC (R83/05)
WLTC (Sect. 2.5)	*Transient*	*Urban + Motorway*	*Cold started*	*To be finalized (GTR No. 15)*

Table 2.5 Summary of technical specifications of the European driving cycle (1970–2016)

Cycle/Segment	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
ECE-15	780	4045	50	18.7	1.04	30.8	0.154
EUDC	400	6955	120	62.6	0.83	10.0	0.094
NEDC	1180	11,000	120	33.6	1.04	23.7	0.116
NEDC (low power)	1180	10,656	90	32.5	1.04	23.7	0.097

Discussion—Criticism

As is made obvious from the previous figures, the European regulatory test cycle is quite simplistic, with long constant-speed phases. This is entirely unrealistic of real driving, where changes in the throttle position are practically continuous even when cruising, a fact that affects both the air-fuel ratio and the emissions from the vehicle. Moreover, constant accelerations are established throughout the cycle. The maximum speed (120 km/h) might be considered low by the standards of current European cars and drivers, although it is higher compared to other legislated test cycles that will be discussed in the next sections. What is undeniably low is the maximum acceleration, being only 1.04 m/s^2 or 3.74 km/h/s, i.e., much lower than would be expected during daily driving. In other words, and based on the cycle's specifications, almost 27 s are needed to reach 100 km/h from standstill. This acceleration lasts for 4 s during the first brief peak at the beginning of each UDC. Similarly unrealistic are the values of the accelerations throughout the beginning of the EUDC. Consequently, the NEDC is run with the vehicle actually operating at

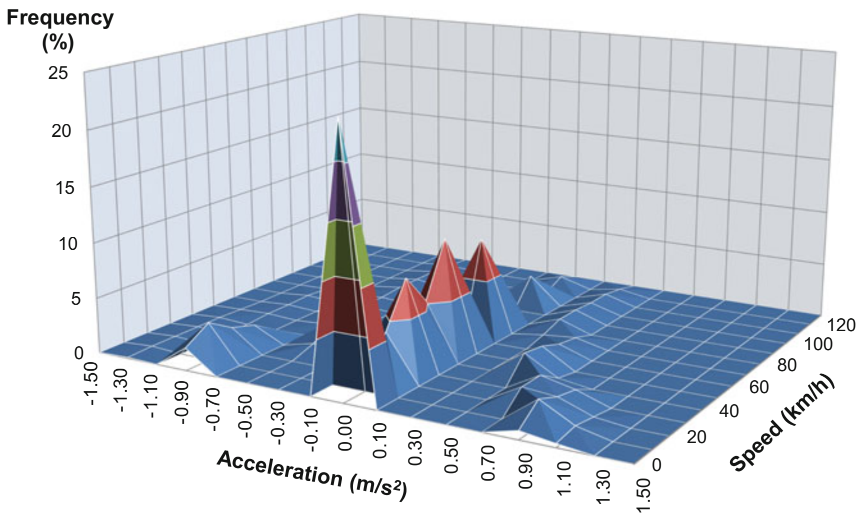


Fig. 2.5 3D speed/acceleration frequency distribution of the NEDC; notice the high density at zero acceleration, and the absence of penetration in many speed/acceleration combinations

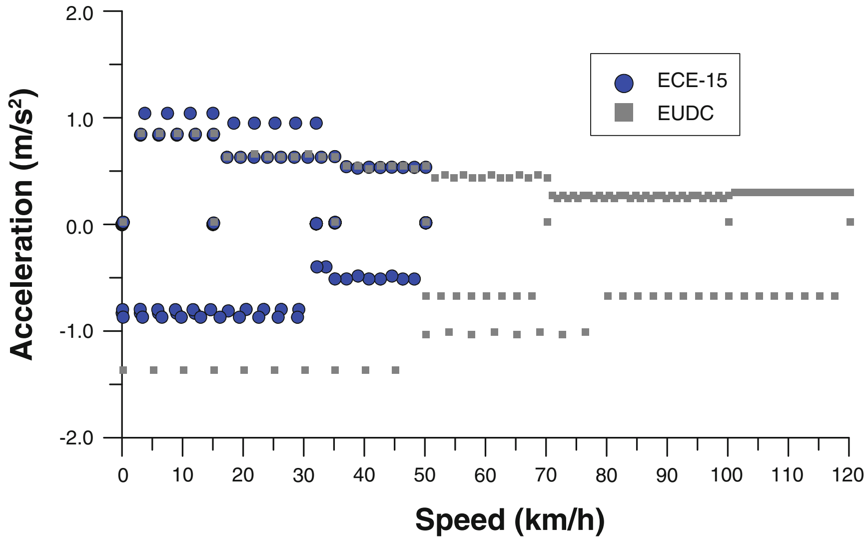


Fig. 2.6 Speed/acceleration distribution of the ECE-15 and EUDC segments of the European NEDC; the modal profile of both sub-cycles is evident

relatively low engine loads (cf. Figs. 2.69 and 2.70 at the end of the chapter). It follows that it is not difficult for the manufacturers to calibrate the engine ECU so that operation outside the tested cycle points, that is medium to high speeds/loads, is

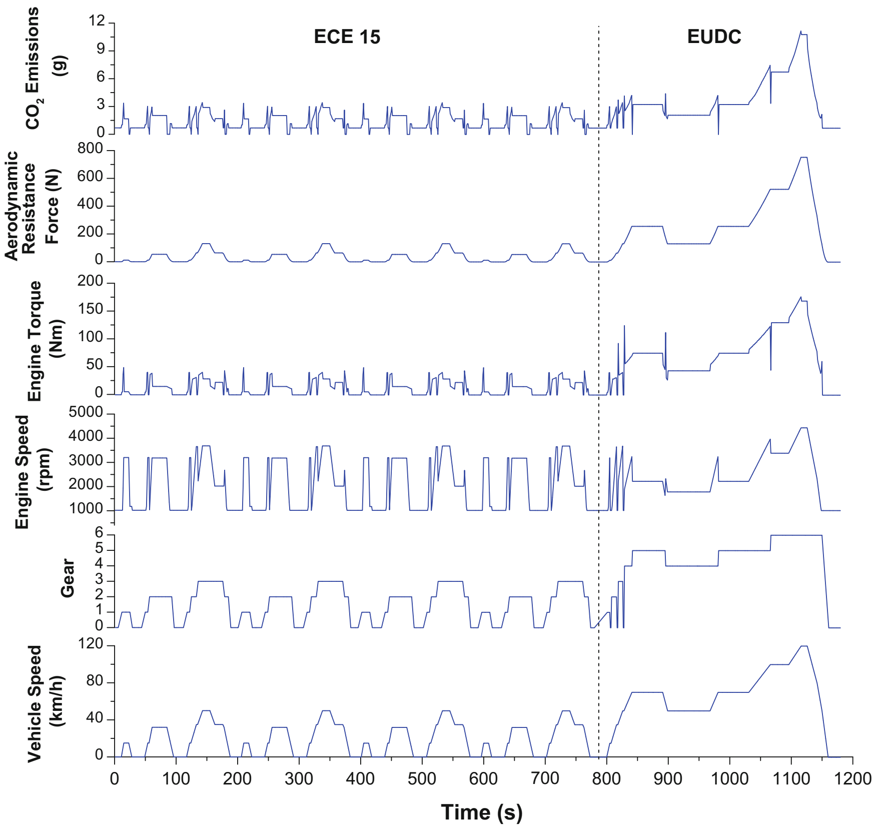


Fig. 2.7 Development of various engine and vehicle parameters during the European NEDC for a diesel-engined vehicle (reprinted from [10], copyright 2010, with permission from Elsevier)

strictly performance/fuel consumption oriented, with no concern for the emitted pollutants.

Further constraints/loopholes originate in the legislation itself (some of these loopholes exist in the U.S. and Japanese legislation too):

- The exactly defined profile of the gear-shift schedule makes it easy for the manufacturers to implement 'cycle beating' techniques.
- No account is taken for the use of air-conditioning, which is nowadays fitted to almost every car (or any other accessory for that matter).
- The wide range, as well as the rather high ambient temperatures during the test (20–30 °C), is another cause for inconsistencies and unrepresentative results.
- There is a 2 % allowable margin between the achieved and target velocity profiles, which can be exploited to achieve better fuel economy.

- Particularly as regards CO_2 emissions, manufacturers can declare up to 4 % lower values compared to the measured results.
- Instead of using its actual weight, the vehicle is categorized for the test into a discrete inertia class; this made sense when mechanical dynamometers were used but nowadays seems unreasonable with electronic dynamometers being capable of simulating practically any weight. As a result, manufacturers design their vehicles so as they belong to the lower class.
- Certain flexibilities also exist with regard to the coast-down test that determines the resistances of the dynamometer, discussed in Sect. 6.4 [11].

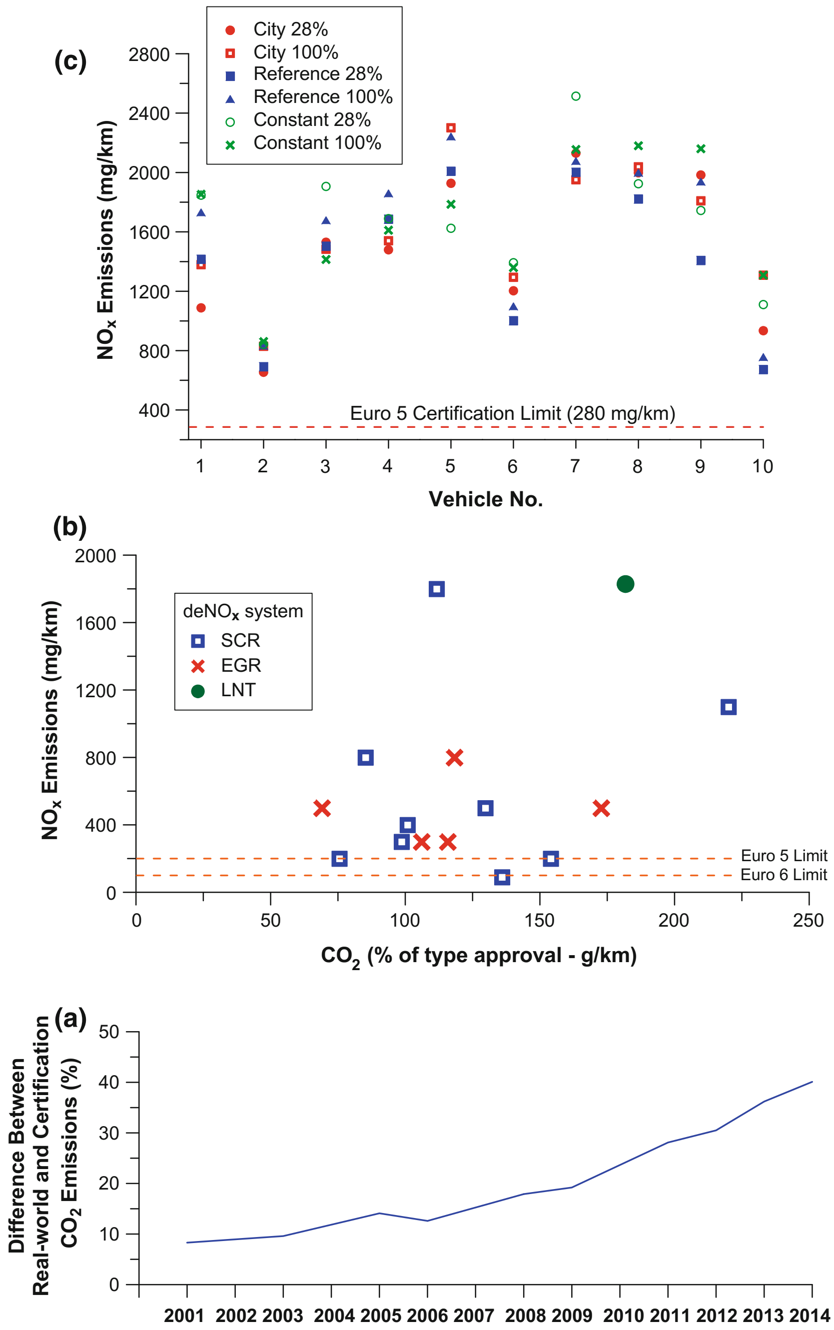
On the other hand, the test procedure only accounts for cold starting and disregards the fact that a typical daily driving schedule includes hot-started trips too. This fact, combined with the relatively short distance of the cycle, results in overestimation of cold-started emissions.

As a result of the above, much has been reported about the extent to which the NEDC fails to represent the real-world driving behavior of cars as regards both pollutant emissions and fuel consumption/CO_2 [12–23]; a few examples follow. Based upon analyses of more than 600,000 vehicles from eleven data sources and six countries, a study published by ICCT (International Council on Clean Transportation) revealed that the divergence, or 'gap', between real-world and certification CO_2 emissions increased from approximately 8 % in 2001 to 40 % in 2014, as the lower sub-diagram of Fig. 2.8 demonstrates [18]. Almost half of this gap is attributed to the non-realistic test cycle. Similar gaps were reported as regards fuel consumption measurements from 924 cars by Ntziachristos et al. [19].

For another research program, NO_x emissions from fifteen Euro 5 and 6 certified diesel passenger cars equipped with three different deNO_x technologies were measured using portable equipment on the road. It was found that, on average, about seven times higher NO_x was emitted than indicated by the official laboratory test results, as the middle sub-diagram of Fig. 2.8 indicates. Some individual vehicles performed significantly worse, although few exhibited an 'acceptable' and one a very good behavior [20].

A detailed study on ten Euro 5 certified light commercial N_1 Class III vehicles was conducted by TNO in 2015 regarding NO_x and CO_2 emissions. Tests were conducted on the road with the vehicles loaded at 28 and 100 %. For CO_2, a difference (increase) of the order of 7–52 % was measured between real-world and certification results. For NO_x, on the other hand, the results were much more impressive, as the upper sub-diagram of Fig. 2.8 illustrates, with on-road results found five to six times higher than the certification limit of 280 mg/km [21]. Interestingly, the same study concluded that driving behavior, vehicle payload and external circumstances caused less than 15 % variation in the obtained results.

Lastly, based on data collected from various passenger cars and vans in [22], it was found that for speeds up to 100 km/h, the NEDC covers only half the range of the accelerations of real-world driving. It follows that this leaves a wide area of operating conditions of daily driving conditions practically uncontrolled.


(c)
City 28%
City 100%
Reference 28%
Reference 100%
Constant 28%
Constant 100%
NO_x Emissions (mg/km)
2800
2400
2000
1600
1200
800
400
Euro 5 Certification Limit (280 mg/km)
1
2
3
4
5
6
7
8
9
10
Vehicle No.
(b)
deNO$_x$ system
SCR
EGR
LNT
NO_x Emissions (mg/km)
2000
1600
1200
800
400
0
Euro 5 Limit
Euro 6 Limit
0
50
100
150
200
250
CO_2 (% of type approval - g/km)
(a)
Difference Between Real-world and Certification CO_2 Emissions (%)
50
40
30
20
10
0
2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

◀ **Fig. 2.8** Discrepancies between certification and real-world emissions in Europe regarding: **a** CO_2 emissions from passenger cars (data from [18]); **b** NO_x emissions from fifteen Euro 5 and 6 certified passenger cars (data from [20]); and **c** NO_x emissions from ten Euro 5 certified N_1-class III commercial vehicles ['city' refers to exclusively urban route, 'reference' to an urban/rural/highway mix, and 'constant' to exclusively highway driving (data from [21])]

Prospect

Taking into serious consideration the above-mentioned emission discrepancies, and acknowledging (even with considerable delay[5]) the shortcomings of the NEDC, the EU authorities established in January 2011 a working group to address the severe inconsistency between real-world and certification emissions from passenger cars, and propose best new strategy. One component of the new approach is the adoption of a much more representative cycle, which will be the worldwide WLTC (Sect. 2.5), effective September 2017. Following the WLTC suite of cycles presentation in Sect. 2.5, a detailed comparison between the NEDC and the WLTC will be performed in Sect. 2.7.

In parallel, the introduction of the Real Driving Emission (RDE) test in the European legislation will take place. This means that, for the first time, driving of the car on the road under real and varying traffic conditions will form part of the certification process; measurements will be conducted using PEMS. It was decided that the RDE test should be introduced in two stages to allow manufacturers to gradually adapt. During a first transitional period, the procedure will only be applied for monitoring purposes. Afterwards, binding quantitative RDE requirements will be set. These will be in the form of conformity/multiplicative factors CF with respect to certification Euro 6 limits (Regulation 2016/646/EU). The not-to-exceed NTE limit during the RDE is

$$\text{NTE} = \text{CF} \times \text{Euro}\,6 \tag{2.1}$$

More specifically, for NO_x, which is the usually manipulated pollutant from diesel engines owing to its inverse relation with fuel consumption, the conformity factor will be temporarily set to 2.1, effective 1 September 2017 ('2nd RDE package'/standard Euro 6d-'Temp'). On January 1, 2020, the factor will drop to 1.0 plus a margin parameter to take into account measurement uncertainties (Euro 6d); the latter margin is initially set at 0.5, and will be reviewed annually, with the aim to be eliminated in the future, at the latest by 2023 (all the above-mentioned dates correspond to new car type approvals). The particle number conformity factor has not been determined yet; CO emissions will be recorded too.

Furthermore, Regulation 2016/427/EU describes the exact procedure for the RDE test. Specifically, the RDE trip, between 90 and 120 min duration, will consist

[5]Reportedly, the European Commission preferred in the mid 2000s to put forward the Euro 5/6 legislation and develop a new procedure at a later stage, over the alternative scenario of adopting at that time a more realistic test cycle and put the Euro 5/6 stricter levels on hold (European Parliament's Committee of Inquiry into Emission Measurements in the Automotive Sector-EMIS).

of approximately 34 % urban (speed up to 60 km/h), 33 % rural (between 60 and 90 km/h) and 33 % motorway (higher than 90 km/h) operation, following random acceleration and deceleration patterns. At least 16 km will be driven during each of the three phases. The average driving speed of the urban phase of the trip including stops, should be between 15 and 30 km/h. Stop periods, defined as vehicle speed of less than 1 km/h, will account for at least 10 % of the time duration of urban operation. Cold-start emissions, although monitored, will not be accounted for in the calculations. The speed range of the motorway segment will cover a range between 90 and at least 110 km/h; the vehicle's velocity should be above 100 km/h for at least 5 min. The regulation also defines that the air-conditioning and other auxiliary systems will be operated in a representative way during the test. It should be noted that the not-to-exceed limits in Eq. (2.1) should be met not only on the whole RDE trip but also its urban part.

The 3rd RDE package will define a procedure for the measurement of the particulates, and includes the effect of vehicle cold starts into the RDE testing. In addition, manufacturers will be obliged to publish the conformity factor of an individual vehicle in its certificate of conformity. In the 4th RDE package, the rules for independent real driving emissions testing of vehicles being in-service will be defined, including the regulatory consequences in case of non-conformity. In order to take into account the statistical and technical uncertainties of the measurement procedures on the road, it may be considered in the future to reflect in the RDE emission limits applicable to individual PEMS trips the characteristics of those trips, described by certain measurable parameters, e.g., related to the driving dynamics or workload.

Following the requirements of Regulation 2016/427/EU, the European Automobile Manufacturers Association (ACEA) has launched a web page providing access to the real driving emission results of new type-approved vehicles.[6]

It is expected that owing to the RDE test, manufacturers will be forced to apply emission optimization strategies over a much broader engine operating range, affecting the exhaust after-treatment strategy. For example, greater volume of exhaust after-treatment systems will be needed, deactivation of the EGR system at high altitudes will not be feasible anymore, most probably LNT will not be adequate for efficient NO_x control, whereas higher urea (AdBlue®) consumption will be required in the SCR-equipped vehicles. Several test cycles have been used by vehicle and component manufacturers to approximate the demands of the RDE test in the laboratory, such as the Artemis-project cycles discussed in the next section, the RTS-95, illustrated in Fig. 2.9, the TNO random cycle generator etc. [23].

Lastly, Fig. 2.10 provides a synopsis of the applicable test cycle, emission regulation, controlled pollutants and typical exhaust after-treatment over the years in Europe for both compression ignition and positive ignition engined passenger cars and light-duty vans.

[6]Accessible via http://www.acea.be/publications/article/access-to-euro-6-rde-monitoring-data.

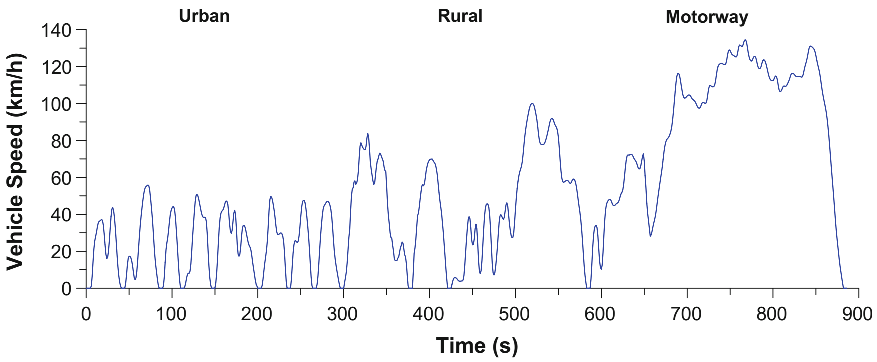


Fig. 2.9 Speed profile of the RTS-95 driving cycle employed for RDE simulation in the laboratory by many component and vehicle manufacturers in Europe (compared to the NEDC, this 886-s and almost 13-km long much harsher test schedule exhibits maximum acceleration of the order of 2.88 m/s^2 with an RPA value of 0.30); the cycle was developed based on driving activity incorporated in the WLTP database discussed in Sect. 2.5, and is actually a non-standardized cycle, therefore different versions might exist or be developed [24, 25]

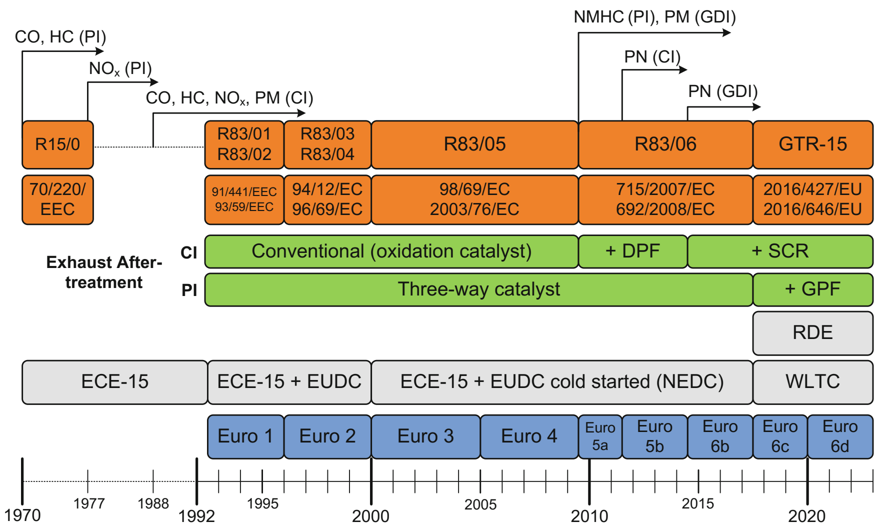


Fig. 2.10 Illustration of European emission standards, regulated pollutants, test cycles and corresponding directives/regulations over the years (adapted from [23]); dates correspond to new vehicle type approvals

2.1.2 Non-legislated Cycles

A much more realistic, although never legislated but frequently employed in research studies, approach to simulate real driving conditions in Europe has been the ARTEMIS cycles. These were developed within the frame of the European ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) research project funded by the EC within the 5th framework research program DG TREN [26]. Throughout a period of 5.5 years, data on actual driving conditions was collected in 1-s time intervals in four European countries in the frame of the DRIVE-MODEM[7] [27]) and HYZEM[8] [12] research projects. Specifically, 77 instrumented vehicles were monitored in France, the UK, Germany and Greece for 2000 days, 10,300 trips, 88,000 km and 2200 h of driving.

For the purpose of cycle development, elementary periods or kinematic segments with homogeneous sizes (distance varying from a few hundred meters at low speeds to a few kilometers at higher speeds) were defined within the trips. These kinematic segments were described by their idling duration and cross-distribution of the instantaneous speeds and accelerations. Correspondence analysis (based on chi-squared distance) and clustering tools were then used to classify the segments according to their speed/acceleration distribution. Eventually, three fundamental cycles were developed considering 12 different typical driving conditions, in effect forming sub-cycles within the cycle: an urban, a rural road and a motorway one; the latter was expressed in two variants, one with 130 and one with 150 km/h maximum vehicle speed [26]. The speed profiles of these three fundamental cycles are illustrated in Fig. 2.11.

Each cycle lasts approximately 1000 s, with increasing average, driving and maximum speed, and decreasing maximum acceleration and idling time from urban to rural to motorway parts. Three classes of congested urban driving (average speeds from 10 to 16 km/h) can be identified in Fig. 2.11. Free-flow urban driving is described in two classes (26 and 32 km/h). Three classes with speeds ranging from 44 to 64 km/h correspond to driving on secondary roads or in suburban areas, two classes correspond typically to driving on main roads, and two classes describe motorway driving (average speeds 115 and 124 km/h). Representative strategies of gearbox use were also computed, allowing the driving cycles to be monitored in terms of the vehicles' technical performance and reproducing actual driver behaviors [26].

Figure 2.12 demonstrates the complete version of the ARTEMIS cycle for the 150 km/h maximum vehicle speed case. This cycle lasts more than 50 min corresponding to a traveled distance of more than 50 km, making it one of the longest both in duration and traveled distance of the chassis-dynamometer cycles. Unlike the NEDC, this is a true transient cycle, having been composed of real driving data and not just specific driving modes.

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[7]MODeling of EMissions and fuel consumption in urban areas research project within the DRIVE initiative (Dedicated Road Infrastructure for Vehicle Safety in Europe), funded by the EC, DG XIII.

[8]European development of HYbrid vehicle technology approaching efficient Zero Emission Mobility research project of BRITE/EURAM 2, EC-DG XII.

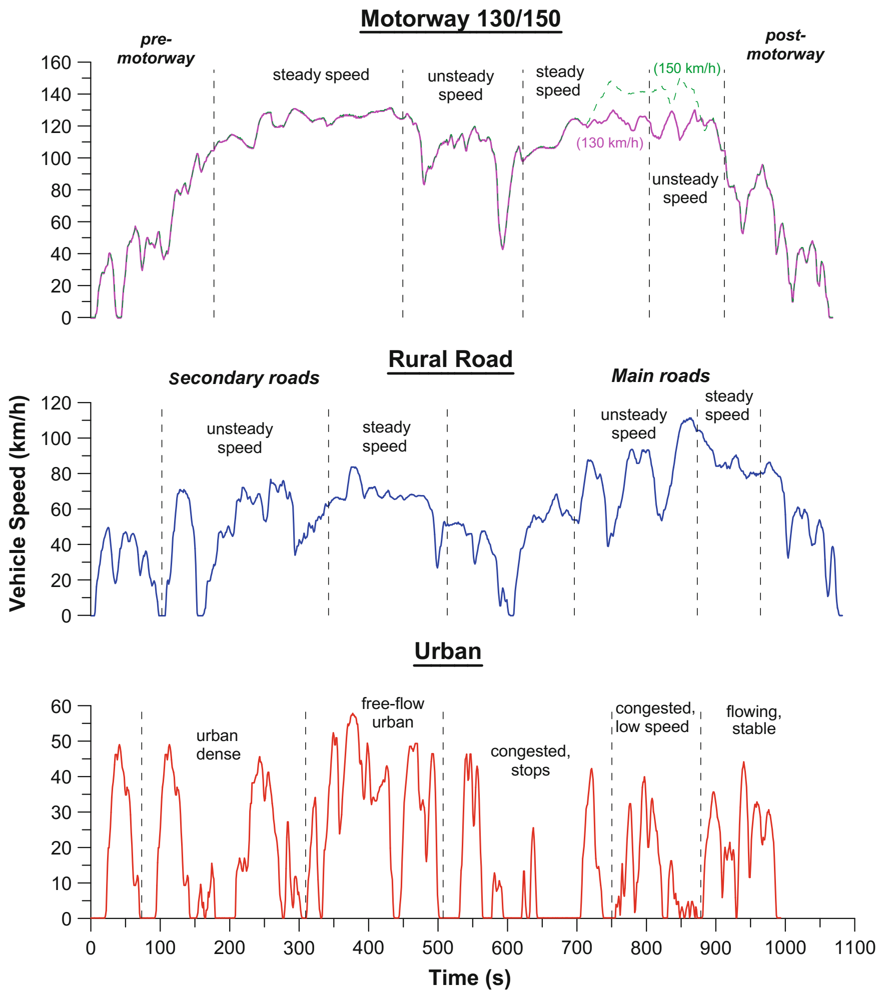

Fig. 2.11 Speed profiles of the ARTEMIS-project urban, rural road and motorway driving cycles with reference to their structure encompassing typical driving conditions (see Fig. 1.35 regarding the different driving conditions incorporated)

Some of the most important technical specifications of the ARTEMIS cycles are summarized in Table 2.6. Comparing this data with that of the NEDC from Table 2.5, it is clear that the ARTEMIS cycles are much harsher, with more frequent and steeper accelerations and higher vehicle speeds. A much more realistic speed profile with almost complete absence of steady-speed phases is also established from Fig. 2.11.

Figure 2.13 further supports these arguments by directly comparing the speed/acceleration distribution between the NEDC and the Artemis cycles; a much broader profile in both vehicle velocity and acceleration can be established for the

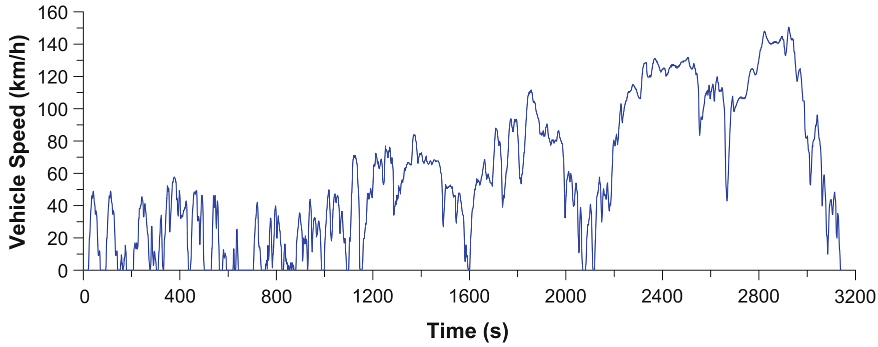

Fig. 2.12 Speed profile of the full version of the Artemis-project driving cycle

Table 2.6 Summary of technical specifications of the ARTEMIS-project cycles

(Sub)cycle	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
Urban	993	4870	57.7	17.7	2.86	26.2	0.342
Rural	1082	17,272	111.5	57.5	2.36	2.7	0.182
Motorw. 130	1068	28,736	131.8	96.9	1.92	1.3	0.137
Motorw. 150	1068	29,545	150.4	99.6	1.92	1.3	0.134
URM 150	3143	51,687	150.4	59.2	2.86	9.6	0.170

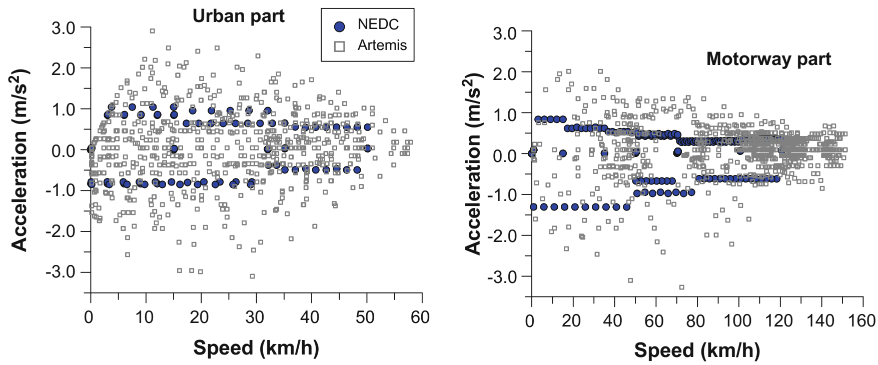

Fig. 2.13 Comparison of the vehicle speed/acceleration distribution between the NEDC and the ARTEMIS cycles (denser areas correspond to higher frequency of vehicle/acceleration points)

latter from this figure. This results in the Artemis cycles being more compatible with the daily driving behavior, and covering wider range of daily driving. Unsurprisingly, as many reports have shown, emission/fuel consumption results compared to the NEDC are much higher [28].

Many non-legislated cycles have been developed based on European driving conditions, with driving behavior data collected in various countries. These have been primarily used in research studies, and are summarized in Table 2.7. Speed traces together with detailed technical specifications for these cycles are provided in Reference No. 29.

Table 2.7 Various European non-legislated driving cycles [12, 29]

Project	Number of cycles	Description	Duration (s)	Average speed (km/h)
INRETS	10	5 urban, 3 rural and 2 motorway cycles derived from actual driving conditions around Lyon, France (Institut National de REcherche sur les Transports et leur Sécurité)	680–1067	3.8–94.5
INRETS	4	Urban and rural short cycles derived from the previous ones to measure cold-start effects	126–208	7.3–41.1
MODEM	14	Urban cycles derived from monitoring of 60 European cars in 6 cities, based on speed, acceleration and trip length parameters over significantly varying time periods	91–1027	5.1–42.5
MODEM-IM	4	Based on the same database as the MODEM ones; they include congested urban, free urban, rural and motorway driving; intended to be used for inspection and maintenance	355–712	14.4–101
MODEM-HYZEM	8	Driving cycles for evaluating hybrid cars	560–1868	18–92.2
EMPA	22	Developed by the Swiss EMPA Laboratory (ETH)	399–2290	3.2–130
Handbook	9	Nine driving cycles	1208–4820	17.2–108.2
Warren Spring Lab	12	Developed by the TRL (Transport Research Laboratory, UK) used for road tests	256–1207	6.7–112.1
OSCAR	10	Defined within the European 5th framework project OSCAR-cars (Optimized expert System for Conducting environmental Assessment of urban Road traffic)	350–455	7.8–35.8

A European cycle of special interest and use is the German ADAC or BAB130, illustrated in Fig. 2.14, being part of the ADAC EcoTest conducted since 2003. The test provides consumers with information on the eco-friendliness of cars (covering CO_2 and pollutant emissions incl. particle number). Since 2012, the EcoTest is performed over the NEDC cold started, the worldwide WLTC Class 3-2 hot-started with the air-condition on (at the moment, for CO_2 measurements only), and the BAB130, again with the air-condition on. Vehicles are tested at their actual weight, with daytime running lights or low beams on. Based on the results from all three tests, each car is assigned an EcoTest rating ranging from one to five stars. The EcoTest rating is calculated from the combined scores for pollutant emissions and CO_2. The pollutant score is indicated as an absolute value, regardless of vehicle size and fuel type. The consumption-dependent CO_2 emissions, on the other hand, are assessed individually for each vehicle class [30].

The BAB130 employed in the ADAC test is a highway cycle, as the EUDC, but with steeper and more frequent accelerations; it lasts 13 min. The cycle was developed in order to also test the vehicle in operating points outside the NEDC. It comprises three parts, a preconditioning segment, and phases 1 and 2. The two phases are identical, and testing the vehicle on both of them is made in order to identify possible actuation of the after-treatment regeneration system (in which case, the test is repeated). As the name suggests, maximum speed is 130 km/h maintained for a long period throughout the cycle; specifically, for approximately three quarters of the time the vehicle cruises. RPA is 0.122 for the 25 km traveled distance throughout the cycle. Notice in Fig. 2.14 the repeated hard accelerations during phases 1 and 2.

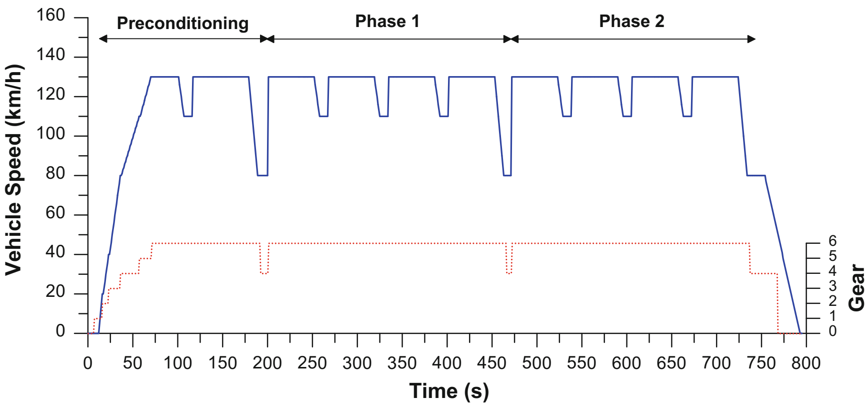

Fig. 2.14 Speed trace and gear schedule of the ADAC/BAB130 driving cycle. The cycle is run with the vehicle hot started, and measurements for the EcoTest rating are taken during phases 1 and 2, each of approximately 10 km length. A modified version of the cycle is employed for testing electric vehicles [30]

2.2 United States of America

In the United States, the research in the field of emissions from motor vehicles was initiated in the early 40s sparked by the Los Angeles photochemical smog. On July 14, 1955, the first federal legislation was signed dealing specifically with air pollution (the 'Federal Air Pollution Control Act'), with the Clean Air Act (CAA) of 1963 being the first federal legislation regarding air pollution control [2, 31]. The research was expanded considerably with the enactment of the Clean Air Act Amendments on December 31, 1970 (1970 CAAA). Following the 1970 CAAA, test cycles as well as the respective federal emission standards in the United States is the responsibility of the Environmental Protection Agency (EPA), created in December 1970. EPA issues regulations through a process in which regulated entities, and other interest groups, have the opportunity to comment on proposals, seek judicial review of the agency's procedures and compliance with the statutory framework created by the legislature, and seek action by the political branches to alter the agency's actions. In effect, the CAA requires EPA to act but also constrains how it may act [32]. The CAA was later amended in 1977 and 1990, introducing, among other things, evaporative emissions testing and on-board diagnostics [2]. Interestingly, California is the only State in the U.S. which has the right to adopt its own standards (CAA, Section 209); these are more stringent than the federal. The pertinent authority here is the California Air Resources Board (CARB), created in 1967. A comprehensive presentation of U.S. air pollution control laws is available in [31].

The first nationwide U.S. light-duty vehicle emission standards were implemented in 1966 for model year 1968 vehicles. Initially, new standards were referred to by the effective model year of the regulation. In order to meet the 1975 and subsequent limits, oxidation catalysts were required combined with unleaded gasoline. Federal legislation in 1981 established new emission standards, retroactively known as 'Tier 0' beginning in 1987. The CAAA of 1990 subsequently defined two new levels of standards for LDVs, namely Tier 1 (phased-in progressively between 1994 and 1997), and Tier 2 (phased-in between 2004 and 2009). These applied to vehicles up to 8500 lbs GVWR (3850 kg) and 'medium-duty' passenger cars (MDPV), i.e., larger SUVs and passenger vans, between 8500 and 10,000 lbs GVWR (3850–4530 kg) [3]. From 2017–18, Tier 3 standard comes into force to be phased-in from 2017 to 2025. The new standard also extends coverage to HDVs of Class 3 (10–14,000 lbs/4530–6350 kg GVWR). Gross Vehicle Weight Rating (GVWR) is defined by federal regulation in 40 CFR 86.082-2 as 'the value specified by the manufacturer as the maximum design loaded weight of a single vehicle'. It is the weight of the vehicle completely loaded with the maximum load that the manufacturer states the vehicle is capable of carrying. The controlled pollutants are mass emissions of non-methane organic gases (NMOG), CO, NO_x, PM, and formaldehyde (HCHO).

One marked difference between U.S. and European regulations is that U.S. emission limits are the same irrespective of fuel used. Moreover, each manufacturer in the United States can choose, among several emission ‘bins’, the one which best fits to his vehicles, provided that a certain NO_x (or NMOG+NO_x from Tier 3 standards) emission target is achieved for the whole fleet each model year. As will be discussed in the next paragraphs, U.S. test cycles are far more representative, encompassing substantial portion of real driving activity compared to the simplistic NEDC that has been in use in Europe from 1970 up to 2017.

Unlike other countries, where the ‘best cycle’ approach is employed, in the United States a multiple-certification cycle approach is followed. At the moment, four different cycles are used during each light-duty vehicle’s certification procedure (regarding tailpipe emissions), or five if we also take evaporative emissions testing under consideration; each one of these cycles covers a specific segment of a vehicle’s operation.

2.2.1 California 7-Mode

California was not only the first region in the world to establish motor vehicle emission standards but also legislated the first chassis-dynamometer driving cycle for emission certification, together with the relevant test procedure [2]. The first attempts to construct a drive cycle were made in the 50s by the Los Angeles (LA) County Air Pollution Control District Laboratory for emissions measurement of typical LA driving. As was also the case with Europe and Japan at that time, researchers characterized real-world driving (of gasoline-engined cars) on the proportion of time spent in specific engine speed/manifold pressure bins, which were then used to define databases of driving modes. In 1950, an initial survey was carried out in Los Angeles using a single vehicle along a single route, with stop-watches to time the various modes; the results obtained were: idle for 18 % of the time, acceleration 18 %, deceleration 18 % and cruise 46 % of the total time [6].

A more elaborate survey was conducted in 1956 by the (then called) Automobile Manufacturers Association, employing seven vehicles. From this survey (see also Table 1.4), a cycle was recommended, comprising eleven driving modes chosen to represent average urban vehicle usage. These were: idle, cruising at 20, 30, 40 and 50 mph, acceleration from 0 to 25, 0 to 60 and 15 to 30 mph, and deceleration from 50 to 20, 30 to 15 and 30 to 0 mph. Weighting factors were also assigned to these modes, with the 0–25 mph mode’s factor being 18.5 %, and that of the 15–30 mph mode 45.5 % [33]. Examination of these eleven modes reveals that it is impossible to combine them in a continuous cycle in the proper time proportions without inserting additional transition modes. Thus, in total 19 sequences were derived for the 11-mode cycle to become drivable. Based on these, the 7-mode cycle, the first certification drive cycle in the world, was subsequently formulated [34, 35]. To obtain the seven modes from the initial eleven, the cruise modes were reduced to two at 30 and 15 mph, the 0–25 acceleration was extended to 0–30 mph, and the 0–60 and 15–30 mph accelerations were replaced by a 15–50 mph acceleration; the 50–20 and 30–0 mph decelerations were combined. The modes were further weighted to represent typical driving based on frequency of mode of operation in urban traffic during a day, and exhaust volume produced in that mode, as detailed in Table 2.8 [6]. The cycle is graphically demonstrated in Fig. 2.15, identifying also the respective modes. The detailed requirements for emissions testing of passenger cars were approved by the recently (1960) created California Motor Vehicle Pollution Control Board on May 19, 1961, and the cycle was later modified in 1964. It was used to test emissions in California from 1966 to 1971 [2, 6, 34–37].

The 7-mode cycle lasts 137 s with a maximum speed of 80 km/h (50 mph) and an average driving speed of 41.8 km/h (25.9 mph). Unlike its European ECE-15 counterpart, which was more urban oriented, the idling phase is much smaller (14.6 % instead of 31 %) and so is cruising (21.9 % instead of 32 %). This results

Table 2.8 Description of modes and weighting factors of the California 7-mode cycle [34, 35]

Mode	Speed (mph)	Acceleration (mph/s)	Duration (s)	Weighting factor (%)
1	Idle	–	20	4.2
2	0–25	2.2	11.5	24.4
	25–30		2.5	Data not read
3	30	–	15	11.8
4	30–15	–1.4	11	6.2
5	15	–	15	5.0
6	15–30	1.2	12.5	45.5
	30–50		16.5	Data not read
7	50–20	–1.2	25	2.9
	20–0	–2.5	8	Data not read

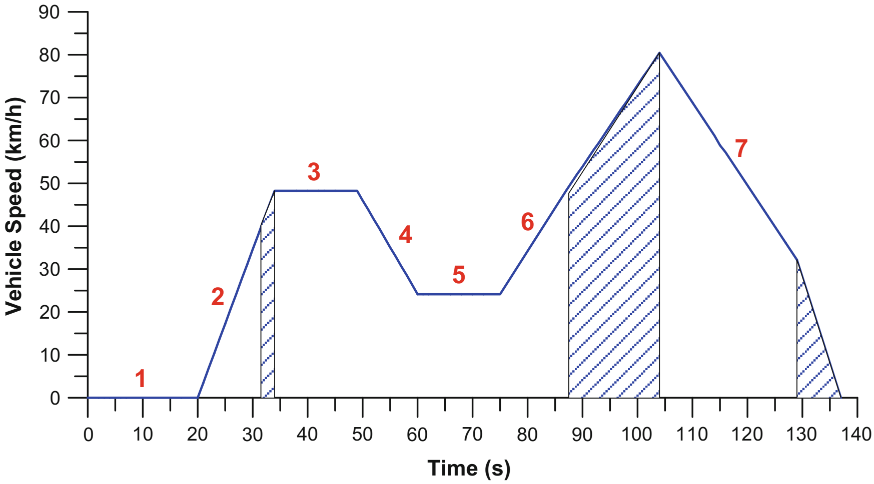

Fig. 2.15 Speed profile of the California 7-mode driving cycle according to Table 2.8 (*shaded areas* correspond to data not read during the test procedure)

in the cycle being much more transient and dynamic compared to the ECE-15; RPA is 0.24 for the California 7 mode in contrast to ‘only’ 0.15 for the ECE-15.

The California 7-mode cycle, with slight modifications, was adopted by the federal regulation as the 1968 U.S. FTP procedure for passenger cars and light-duty trucks (FR Vol. 31, No. 61, March 30, 1966). In application, the cycle was run 7 times, starting with a cold engine. The ‘cold’ runs (1–4) were weighted by 0.35 and the ‘hot’ runs (6 and 7) by 0.65, and the results summed; run 5 of the cycle was discarded. Effective model year 1970/71, the methodology changed to mass emission values; these were converted from the respective concentration measurements applying an empirically determined formula, which assumed the exhaust gas volume as a function of vehicle mass and transmission type for an average vehicle of the 4000 lbs inertia weight class [2]. A truly CVS system was introduced as of model year 1972 together with the FTP-72 cycle (next section).

Even before the cycle was used to certify MY 1966 vehicles in California, some of its serious shortcomings were recognized. For example, since the operating modes included were rather few, the cycle practically encouraged manufacturers to design control systems that would function on the 7 mode but not under other common driving conditions. It was further recognized that the cycle did not represent driving under the morning rush-hour traffic conditions, which were believed to be the most polluting, as the cycle had been designed to represent 24-h average conditions. Another significant drawback was the simplistic form of the schedule being not compatible with the real-life driving habits [36].

2.2.2 FTP-72 and FTP-75

Similar to the European (and Japanese) approaches in the 60s, the initial cycle employed in the United States for testing the compliance of motor vehicles with the emission standards was modal/‘stylized’, with constant accelerations and a repetitive form. Unlike the European and the Japanese regulations however, the federal legislation soon moved from simple/modal to much more realistic transient cycles (modal cycles were still employed in the United States during the 70s and 80s for special purposes, such as the FSC discussed later in the text).

In 1965 (that is, before the 7-mode cycle was employed for certification purposes in California), work began on the development of a new drive cycle, with the purpose to represent typical morning (home-to-work) driving in Los Angeles in rush-hour traffic. Among other things, the methodology focused on finding a specific road route that produced the same average mode distribution (based again on inlet manifold vacuum and speed ranges) with a variety of drivers using the same test vehicle. A single car driven by various employees of the California Emissions Laboratory was used to develop this street route. The research eventually led to the short-lived, and never legislated, XC-15 cycle. This was a synthetic cycle comprising 18 operating modes, with 22.7 mph average speed and 4 min duration [36]. During this research, a 12-mile commute route, called the LA4, beginning and ending at the California Emissions Laboratory was established. This route met the pre-defined criteria of being representative of typical driving in central LA during morning peak-hour traffic, and was used in a subsequent research effort, this time with the participation of the EPA [36, 38].

With the aim to develop an improved federal test procedure (based on speed/time distributions instead of manifold pressure/rpm ranges, and applying advanced vehicle instrumentation techniques), six different drivers from EPA's West Coast Laboratory drove a specific vehicle over the LA4 route. The six traces were analyzed for idle time, average and maximum speed, and number of stops; total time required ranged from 35 to 40 min One of the six traces demonstrated much harder acceleration rates than the other five and was discarded. The remaining five traces were surprisingly similar. Of those five, the trace with the actual time closest to the average was selected as the most representative speed/time trace. This trace contained 28 micro-trips and had an average speed of 31 km/h.

Subsequently, EPA—based on a 1969 report on driving patterns in Los Angeles [39]—shortened the LA4 from 12 to 7.5 miles (12 km) to represent the average commute length in Los Angeles at that time; this was denoted the LA4-S3. An attempt was made to preserve the proportionate time in each operating mode, so that average speed, proportion of idle time etc. remained unaltered. This paring process removed much of the low-speed driving iterations to compensate for the freeway driving reductions. Further, EPA adapted the cycle for use in the laboratory on a chassis dynamometer by cutting back the accelerations and decelerations to 3.3 mph/s (equivalent to 1.48 m/s^2), which was the maximum design rate of a belt-driven dynamometer at that time to avoid tire slip. Comparison of mass emission tests between the shortened cycle and the full cycle showed very high correlation. This, shortened and modified, final version of the drive cycle is known as the Urban Dynamometer Driving Schedule—UDDS, and is shown in Fig. 2.16. It is also referred to as the LA4-S4, or simply LA4; it was originally published in the U.S. FR Vol. 35, No. 219, November 10, 1970.

The UDDS/LA4 became the standard driving cycle for the certification of passenger vehicles and light-duty trucks in the United States, starting with the 1972 model year, for this reason known as FTP-72. The FTP-72 was the first cycle to employ the CVS sampling method and, as of model year 1973, the test was expanded to also include NO_x emission measurement via the chemiluminescence method [2]. At the time of its implementation, light-duty vehicles were defined as 'any motor vehicle either designed primarily for transportation of property and rated at 6000 lbs GVW or less or designed primarily for transportation of persons and having a capacity of 12 persons or less'.

The much more realistic compared to the California 7 mode, in terms of daily driving conditions, FTP-72 cycle simulates urban/suburban routes. It is a true transient cycle with 74 % of the time spent with the vehicle accelerating or decelerating. The cycle lasts 1372 s (approx. 23 min), and is divided into two segments: a cold-started 'transient' phase after overnight parking, and a second 'stabilization' (in terms of the engine having reached its fully warmed-up condition) phase with frequent accelerations and stops. Table 2.9 details some technical

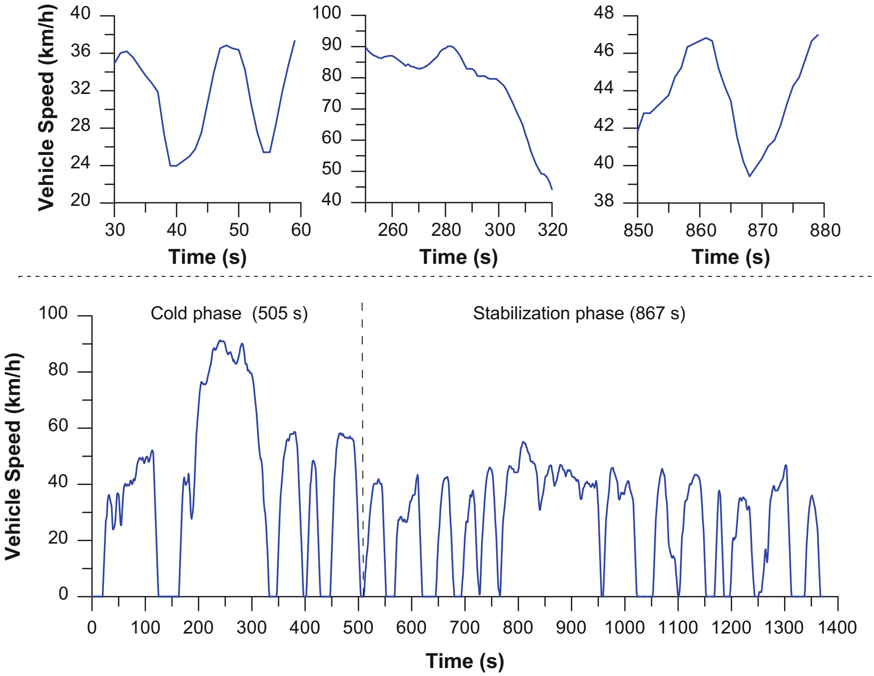

Fig. 2.16 Speed profile of the U.S. FTP-72 (the UNECE Reg. No. 53 refers to the cycle as the 'Test equivalent to Type I test (verifying emissions after a cold start)'; the upper three sub-diagrams illustrate in more detail specific segments of the cycle (40 CFR 86, App. I)

Table 2.9 Specifications of the FTP-72 cycle (max. acceleration for all phases is 1.48 m/s^2)

FTP-72	Duration (s)	Distance (m)	Maximum speed (km/h)	Average driving speed (kmh/h)	Idling phase (%)	RPA (m/s^2)
Phase 1	505	5779	91.2	50.6	18.6	0.181
Phase 2	867	6211	55.2	31.2	17.3	0.190
Whole cycle	1372	11,990	91.2	38.3	17.8	0.185

specifications of the two segments and of the whole cycle. Ambient temperature range is 68–86 °F (20–30 °C) and absolute humidity 75 grains of water per pound of dry air; the vehicle is allowed to soak for at least 12 h before the test.

Overall, maximum speed during the cycle reaches 91.2 km/h, total traveled distance is 12 km with 17.8 % of the time spent idling. Interestingly, the highest speeds in the cycle are experienced during the first minutes after cold start, a fact that influences decisively the warming-up of the catalyst, and is certainly not representative of other areas/cities or routes. Figure 2.17 highlights the speed/acceleration distribution of the cycle.

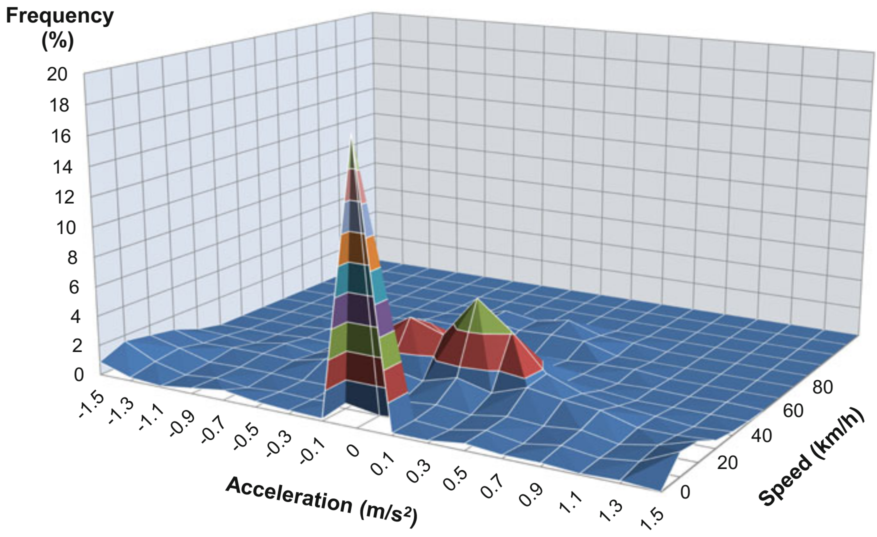

Fig. 2.17 3D speed/acceleration frequency distribution of the FTP-72 driving cycle

The FTP-72 is the applicable cycle for battery electric vehicles testing according to the SAE J1634 standard. Following the standard, the battery is fully charged, the vehicle is parked overnight, and then the following day it is driven over successive UDDS cycles until the battery becomes discharged (and the vehicle can no longer follow the cycle). After that, the battery is recharged from a normal AC source and the 'city' energy consumption of the vehicle is determined (in kW-h/mile or kW-h/100 miles) by dividing the kW-h of energy to recharge the battery by the miles traveled by the vehicle [40].

A subsequent 'variation' of the FTP-72 cycle was the FTP-75 (also known as EPA75), which is based on the FTP-72 adding a third 'transient' phase of 505 s exactly as the first (cold-started) one, but this time hot started; this extended version is demonstrated in Fig. 2.18.

The FTP-75 has been the 'primary' cycle used in the U.S. for testing the compliance of passenger cars and light-duty trucks with the emission standards, beginning with the 1975 model year. Diesel-engined vehicles were included as of model year 1975 for passenger cars and 1976 for LD trucks, with particulates measured from 1982 [2, 36]. It is important to note that during the FTP-75, the third phase starts after the engine has stopped for 10 min. This intends to simulate parking a car and then returning to it after a short period. Thus, emissions are collected during the cycle not only after a cold start (as was the case with the FTP-72 and the European NEDC) but also after a hot one. By so doing, the test provides a more accurate reflection of typical driving experience than running just

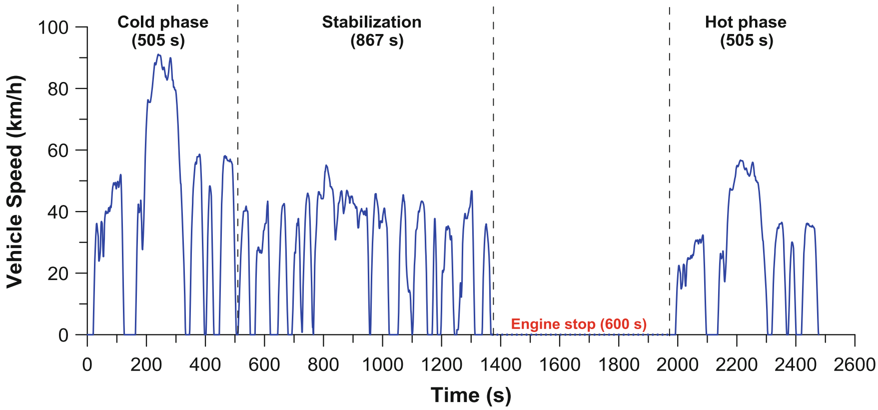

Fig. 2.18 Speed profile of the U.S. FTP-75 driving cycle

one 12-km cycle from a cold start [41]. The emissions from each phase are collected in a separate Teflon bag, analyzed and expressed in g/mile, with weighting factors 0.43 for the cold-started phase, 1.0 for the 'stabilization' and 0.57 for the hot-started one.[9] According to 40 CFR 86.544-90, the final reported 'weighted' distance-related emission result E_{wi} of pollutant i (gaseous or PM, and CO_2), is calculated as follows

$$E_{wi} = 0.43\left(\frac{E_{i-ct} + E_{i-s}}{S_{ct} + S_s}\right) + 0.57\left(\frac{E_{i-s} + E_{i-ht}}{S_s + S_{ht}}\right) \tag{2.2}$$

where E_{i-ct}, E_{i-s} and E_{i-ht} the emission of pollutant i during the cold transient phase, stabilization phase and hot transient phase respectively (Sect. 6.5) in grams per test phase, and S_{ct}, S_s and S_{ht} the respective distances ($S_{ht} = S_{ct}$).

For hybrid vehicles, the stabilization phase is run again after the hot phase, for a total duration of 2744 s. For the cold CO testing, adopted in 1992 for gasoline vehicles, the FTP-75 is also run at 20 °F (approximately −7 °C).

Table 2.10 summarizes some characteristics of the cycle phases.

Among the problems noted in the FTP cycle (besides the relatively high speeds at the beginning of the test, which accelerate the catalyst warming), the underestimation of acceleration and cruise activities between 64 and 80 km/h and above 96 km/h, the underestimation of the time spent in cold transient mode and thus the

[9]During work performed in the late 60s within the APRAC (Air Pollution Research Advisory Committee) project CAPE-10 of the Coordinating Research Council (CRC), it was found that vehicles in Los Angeles were used on average for 4.7 trips per day. From these, two were cold-started (one in the morning) and the rest hot-started. Hence, the cold weighting factor resulted as 2:4.7 = 0.43, and the hot one 2.7:4.7 = 0.53. These factors became part of the test procedure as of model year 1975 [2].

Table 2.10 Specifications of the FTP-75 phases

FTP-75	Duration (s)	Description	Distance (m)	Maximum speed (km/h)	Weighting factor
Phase 1	505	Cold start	5779	91.2	0.43
Phase 2	867	Stabilized	6211	55.2	1.00
Engine stop (600 s)					
Phase 3	505	Hot start	5779	91.2	0.57

emissions, and the overestimation of the time at stop and at cruise between 40 and 56 km/h have been identified [42]. Since the cycle was based on vehicle tests from the late 60s, and following the limited capabilities of the dynamometers at the time, maximum acceleration (and the level of accelerations in general) cannot be considered representative of modern real-world driving.

2.2.3 Highway Fuel Economy Test—HFET

In the 70s, EPA began to publish city fuel economy values based on the FTP cycle (the official fuel economy labeling program began in 1975). This was largely initiated by the 1973 disruption of U.S. oil imports caused by an oil embargo of the OPEC members. The need for a highway cycle became evident at some point, as some manufacturers, complaining about the lack of non-urban fuel economy reports, began advertising 'highway' fuel economy figures based on their own tests.

This new highway cycle was designed with the aim to [43, 44]:

- reflect driving on a variety of non-urban roads;
- be self-weighting (i.e., have the correct proportion of travel on each road type);
- be of a length equal to the average trip in a non-urban area;
- be appropriately transient; and
- have an average speed and number of stops per mile equal to that experienced in non-urban driving.

Unlike with the development of the LA4, which was a minimally shortened version of one particular trip, the developed highway cycle was a composite one; it comprised four different road types, namely locals, collectors, minor and principal arterials. These were selected from different trips made by three drivers of a single vehicle following other cars but also 'flowing along' with traffic over 1700 km of non-urban roads. The data was collected in southern Michigan (Ann Arbor), northern Ohio, and Indiana. In particular, the principal arterial data was collected in the Ohio area only, which had a strictly enforced 55 mph speed limit (drafted in response to oil supply disruptions and price spikes during the 1973 oil crisis). The routes traveled during the development of the cycle did not contain the target mix of operation. Thus, when the shortened version of the cycle was constructed, the length of the speed/time trace from each type of road was selected in such a way to achieve the target mix. Additionally, each segment of the speed/time trace was selected to match the average characteristics of all operation on the same road type in terms of average speed, major and minor speed deviation and stops per km [36, 43, 44]. The resulting drive cycle is the Highway Fuel Economy Test (HFET, also known as HWFET or FET), developed in 1974 and demonstrated in Fig. 2.19; in this figure, the segments corresponding to each of the four road types are also

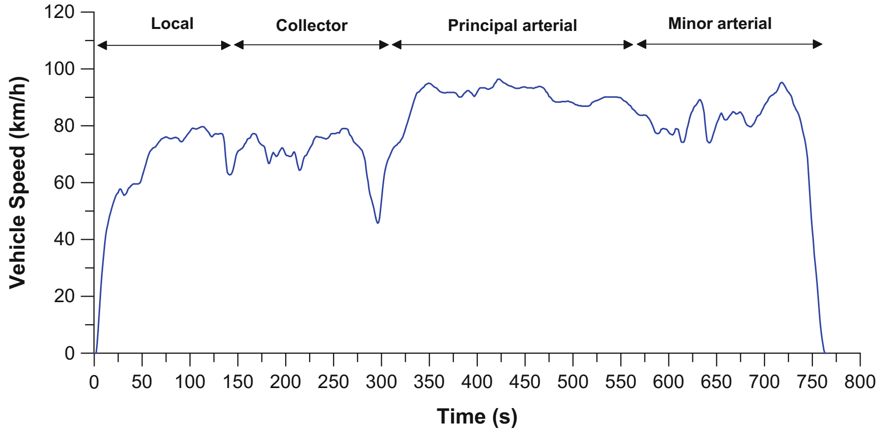

Fig. 2.19 Speed profile of the U.S. HFET cycle (40 CFR 600, App. I)

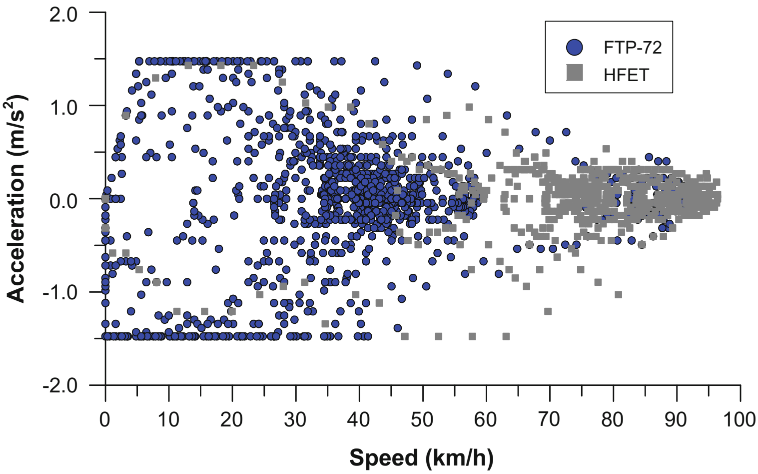

Fig. 2.20 Speed/acceleration distribution of the urban FTP-72 and highway HFET driving cycles (notice the strictly defined maximum acceleration and deceleration values at ± 1.48 m/s^2 (=3.3 mph/s) imposed by the capabilities of the Clayton dynamometers at the time)

identified. Further, Fig. 2.20 compares the speed/acceleration distribution between the FTP-72 and the HFET.

Overall, HFET simulates interstate highway and rural driving conditions, with the purpose of a highway fuel economy test (urban fuel consumption is calculated during the FTP-75). The cycle lasts 765 s (approx. 13 min) for a total traveled distance of 16.5 km, with maximum speed 96 km/h (60 mph). There is a steep acceleration at the beginning (indicative of the vehicle entering a highway), and after that speed is almost constantly maintained at values higher than 70 km/h, hence the 78 km/h average driving speed. The initial version of the cycle had accelerations up to 2.2 m/s^2 (4.9 mph/s), which caused tire slip on dynamometers with belt-driven inertia weights. Consequently, the first 10 and the last 20 s of the cycle were modified so as to limit the acceleration and deceleration to lower than 1.48 m/s^2 (3.3 mph/s), as was also the case with the LA4. Although hard acceleration events are well known to significantly affect emissions and fuel consumption, EPA contended that owing to their very small duration, these segments did not affect the total fuel economy results during the cycle. Furthermore, two seconds of idle were added at the beginning and the end to account for the portion of idle operation the analysis indicated would be experienced in this length of non-urban driving (idle time less than 1 %) [44].

The cycle is run twice, with the first run serving to warm-up the engine, so as sampling takes place during the second run with hot engine; a break of 15 s is allowed between the two runs. Alternatively, it is run once immediately after the FTP-75 (40 CFR 1066.840). Although the cycle is named 'highway', nowadays, with the introduction of a true high-speed cycle (the SFTP US06—Sect. 2.2.4), HFET practically represents in the U.S. EPA fuel economy program, driving on lower-speed highways as well as rural and suburban driving.

Interestingly, although EPA developed the HFET, it was the California ARB that initially implemented it in an attempt to investigate whether manufacturers employed control systems that would fail to limit NO_x emissions during extended high-speed operation, outside the range of the FTP-72 [36].

As already mentioned, the primary objective of the HFET is for fuel economy purposes (miles per gallon—mpg, in effect, the inverse of fuel consumption). Up to MY 2007, fuel economy was estimated from FTP-75 and HFET values weighted 55 and 45 % respectively. Equation (2.3) provides the initial (up to 1984) formula

$$\text{EPA combined mpg}_{\text{until 1984}} = \frac{1}{\frac{0.55}{\text{FTP mpg}} + \frac{0.45}{\text{HFET mpg}}} \tag{2.3}$$

Since the late 70s, this fuel economy value has been indicated on a window sticker on the vehicle. Further, it was used for the manufacturers' corporate average fuel economy (CAFE), a program managed by NHTSA (National Highway Traffic Safety Administration). The CAFE achieved by a given fleet of vehicles in a given model year is the production-weighted harmonic mean fuel economy. CAFE was established following the Energy Policy and Conservation Act of 1975, and became effective as of model year 1978 (FR Vol. 42, No. 176, September 12, 1977).

From 1985, adjustment factors of the order of 90 % to the FTP and 78 % to the HFET values were adopted (only for the window sticker—not for CAFE purposes) to account for real-world driving effects such as road, vehicle condition, tire pressure, weather etc. [45]

$$\text{EPA combined mpg}_{1985-2007} = \frac{1}{\frac{0.55}{0.90 \times \text{FTP mpg}} + \frac{0.45}{0.78 \times \text{HFET mpg}}} \tag{2.4}$$

Beginning with model year 2008, a new formula for fuel economy has been adopted, based now on a 5-cycle procedure, that will be discussed in the next section. Formulas for calculation of the FTP and HFET mpg values will be provided in Sect. 6.5.

Apart from fuel economy purposes, and beginning with the Tier 3 standard, the HFET is also used for emission testing. Specifically, the new standard requires that NMOG+NO_x emission limits should be met on the HFET as well apart from the FTP-75 [46].

The HFET cycle, together with the UDDS, are the applicable cycles for battery electric vehicles testing according to the SAE J1634 standard. The procedure described earlier for the UDDS test is applied with the vehicle running on the HFET to calculate highway energy consumption [40].

Figure 2.21 illustrates the development of some characteristic engine and vehicle parameters during the HFET for a turbocharged, diesel-engined large vehicle. Owing to the exclusively motorway pattern, the engine in Fig. 2.21 is kept at relatively high loads, as indicated by driver demand or 'fuel rack' varying between roughly 0.6 and 1.0 during most of the cycle. Consequently, engine speed is also relatively high; it is close to 2000 rpm during the first 300 s of the cycle, while during the high-speed part of the cycle it fluctuates between roughly 2300 and 2400 rpm (2400 being the rated-power engine speed). The upper sub-diagram of Fig. 2.21 shows that turbocharger speed follows these trends, hence during high speed driving, the rotor speed approaches 100,000 rpm. The most critical transient, besides the one at launch, occurs at t = 295 s, when the high speed of the cycle is initiated, and this is expected to produce the highest amount of engine-out soot/PM [47].

2.2.4 Supplemental FTP US06 and SC03

Section 206(h) of the Clean Air Act, as amended in 1990, requires that EPA consider actual driving conditions under which motor vehicles are used, including conditions relating to four areas: fuel, temperature, altitude, and acceleration. To this end, on October 22, 1996, the final rule on 'Motor Vehicle Emissions Federal

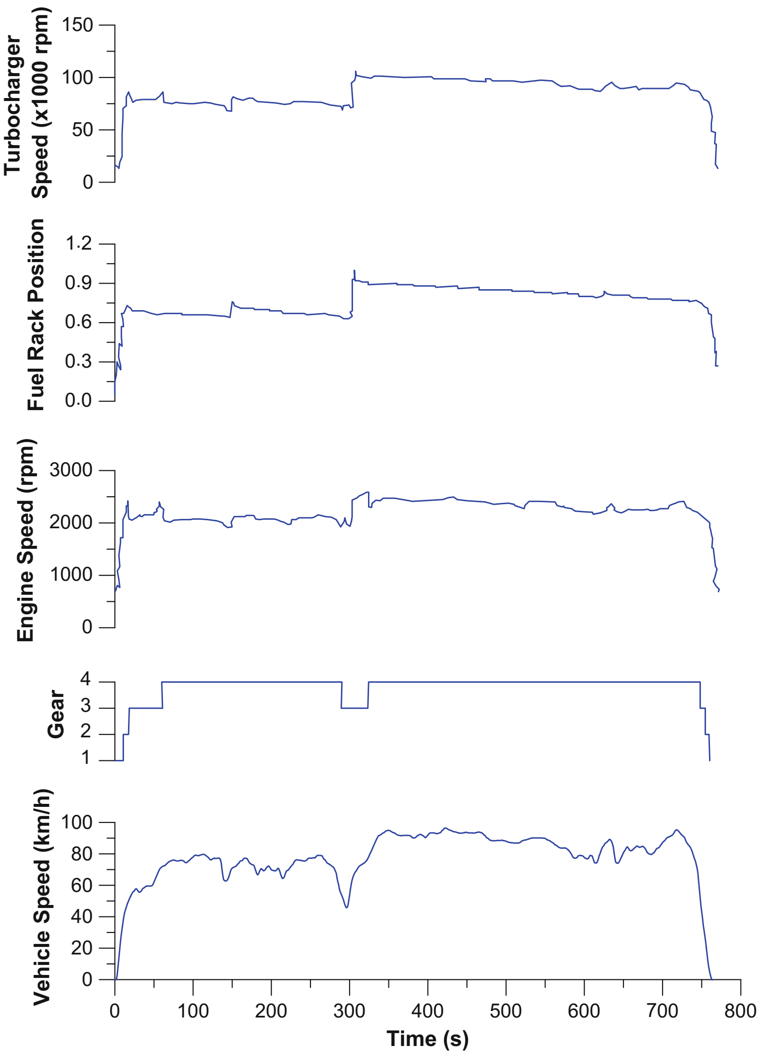

Fig. 2.21 Development of engine and vehicle parameters during the U.S. HFET driving cycle (adapted from [47])

Test Procedure; Final Regulations' was published in the Federal Register [48]. The primary new element of the rulemaking was a Supplemental Federal Test Procedure (SFTP) designed to address shortcomings with the FTP-75 cycle, some of which were mentioned in Sect. 2.2.2. The basis for the SFTP rulemaking was two studies of real-world driving conducted during the early 90s. From the studies, two new driving cycles were legislated, the US06 and the SC03. These cycles were not meant to replace the FTP-75 procedure but rather expand it to also include engine speed/load conditions not covered during the testing of vehicles but experienced by drivers on the road. It is important to note that by the time the SFTP cycles were legislated, dynamometer technology had improved, and higher acceleration rates were possible. Thus, these new drive cycles were not limited to acceleration rates of 1.48 m/s^2 as was the case with the LA4 in the early 70s.

The first study was conducted (initially) in two U.S. cities, Baltimore, MD and Spokane, WA, using a combination of instrumented vehicles and chase cars [41]. Baltimore was chosen to represent a northeast, medium-sized, ozone non-attainment area. Spokane was selected being typical of a CO non-attainment area (a suitable mid-west city could not be found). Overall, 215 vehicles in Baltimore and Spokane were instrumented with three-parameter data logger packages that recorded second-by-second engine speed, vehicle speed and inlet manifold vacuum; 79 more vehicles were equipped with six-parameter data loggers, also recording coolant temperature, throttle position and air-fuel ratio downstream of the catalyst. These 294 instrumented vehicles were observed for a period of one week. On the whole, approximately 1700 h of data was collected. The final count of vehicles for which the data was good was eventually reduced to 217 (168 three-parameter and 59 six-parameter vehicles). A separate chase-car study collected similar speed data in the two cities using a laser device mounted on a patrol car that tracked in-use target vehicles. This produced relatively short sequences of data but on a much larger sample of vehicles (the number of targets from both cities was 1641, and, in total, approximately 40 h of target time was collected). In addition to Baltimore and Spokane, two other cities had already been selected for related studies, namely Atlanta, GA (101 instrumented vehicles) and the South Coast Air Basin around Los Angeles, CA (chase-car work performed on 102 routes) [41]. It should be noted that both studies were conducted prior to the 1995 repeal of the federal 55 mph freeway speed limit.

From the collected data in Baltimore, it was found that driving was characterized by (much) higher speeds and steeper accelerations than the FTP and the HFET. More specifically [41]:

- About 8.5 % of all speeds exceeded the FTP maximum (only in part attributed to newer, higher-powered cars).
- 2.5 % of all driving in Baltimore exceeded the FTP maximum acceleration of 1.48 m/s^2.
- Whereas the proportion of time spent in the four fundamental operating modes (idle, acceleration, constant speed and deceleration) only slightly differed from the FTP-75, the average trip length was found shorter than the 12 km of the LA4, on average 7.9 km. This means that much higher proportion of the overall driving was actually performed with the engine during the warming phase, i.e., before the after-treatment devices reach their normal operating temperature.
- The soak periods (time between the end of a trip and the beginning of the next), were much different too. The LA4 soak periods are 12–36 h before the test and 10 min before the beginning of the third phase. In contrast, almost 40 % of all soak periods in Baltimore were between 10 min and 2 h, which is the most critical period concerning catalyst cool-down. This poses another potential

emission concern as catalysts cool off much faster than engines, and most are completely cold in approximately 1 h. Hence, the implicit assumption of the FTP that 57 % of all starts occur with the catalyst hot was not confirmed (30 % was the new figure found). The other implicit assumption of the FTP that 43 % of the starts are cold was not confirmed too but this time the new figure was found lower (around 25 %) (in any case, it is possible that these two counter-effecting properties might cancel themselves out).

All in all, a significant (18 %) part of driving in Baltimore was found to occur outside the speed/acceleration distribution of the FTP drive schedule, highlighting the fact that the LA4 doesn't (any more) realistically account for the emission effects of real-world aggressive driving behavior and high acceleration rates, all of which contribute significantly to vehicle emissions. Subsequent analysis on the larger 3-city (Baltimore, Spokane, Atlanta) instrumented vehicle database showed the results to be consistent with the Baltimore ones; the 3-city analysis showed that nearly 13 % of vehicle operation time occurred at combinations of speed and acceleration that fell outside the matrix of those found on the LA4 [49].[10]

Following the data collection from these driving surveys, three cycles were initially developed by the EPA, based on selection of actual segments of in-use driving which best matched the joint distribution of speed and acceleration (primarily from the Baltimore database): the start driving (ST01) cycle, the aggressive driving REP05 and the Remnant cycle REM01. The ST01 cycle represented driving immediately following engine start-up; REP05 represented high speed and aggressive driving; the REM01 cycle represented all other driving [49].

For the Start cycle (Fig. 2.22), three target surfaces were developed from the database, representing three successive 80-s segments of in-use driving immediately following the initial idle. The combinations of speed and acceleration found in these distributions could largely be found in the FTP-72, but in a different sequence and with different percentages. The micro-trips that produced the best fit to these surfaces, together with an initial idle period that best matched in-use initial idles, generated a start cycle that was 258 s long [49].

The REP05, on the other hand (illustrated in Fig. 2.22, with basic parameters provided in Table 2.11), targeted speeds and accelerations, as well as micro-transient effects, not covered by the LA4. Thus, the in-use data points used in developing the REP05 target surface were those with combinations of speed and acceleration that were not represented on the LA4 cycle ('non-LA4') and, in addition, were not part of the ST01 target surfaces. These points tended to be either high-speed or high-acceleration, or both. By assembling the cycle from actual idle-to-idle driving segments, however, the cycle necessarily included some

[10]Results from a later (2004–2005) survey conducted by the EPA in Kansas City confirmed these findings. Based on instrumented vehicle studies in Kansas City and chase car in California, it was found that 28 % of driving (vehicle miles traveled) is at speeds greater than 60 mph. About 33 % of real-world driving was found outside of the FTP/HFET speed and acceleration activity region [49, 50].

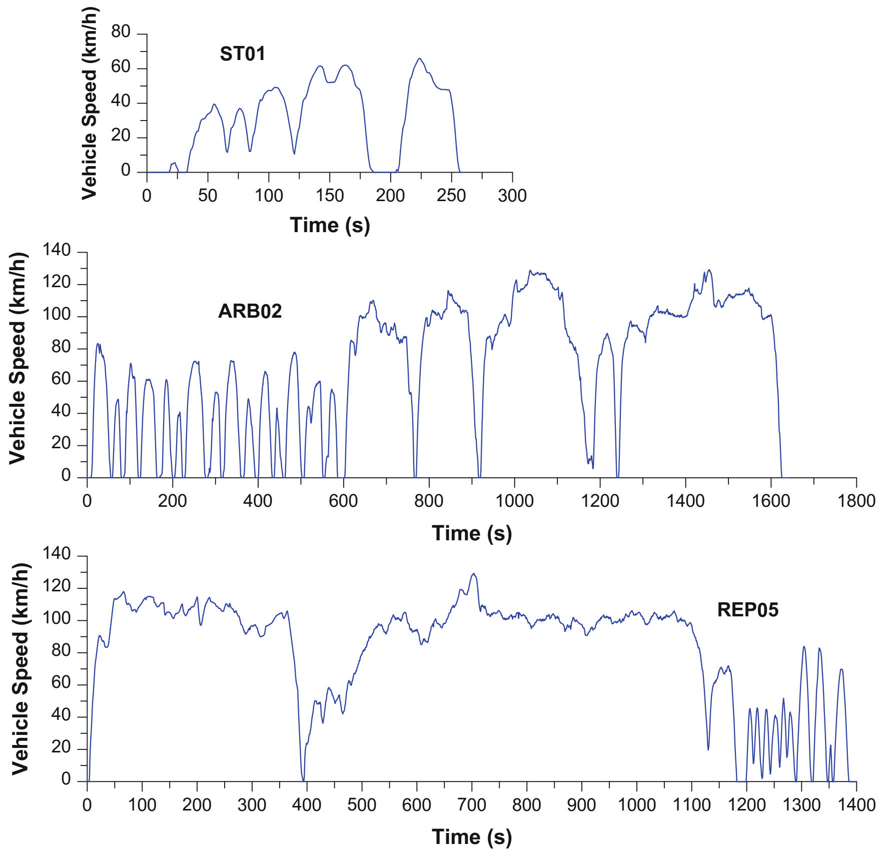

Fig. 2.22 EPA cycles REP05 and ST01, and California ARB02 from the SFTP research

Table 2.11 Summary of technical specifications of the ST01, REP05 and ARB02 cycles

Cycle	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
ST01	258	2234	66.0	31.2	2.28	16.7	0.263
REP05	1400	32,065	129.2	82.9	3.79	2.8	0.160
ARB02	1640	31,900	129.2	70.0	3.53	6.5	0.216

speed/acceleration combinations that were represented on the LA4, amounting to about 30 % of the cycle's 1400 s [49].

The Remnant/REM01 cycle was intended to represent the balance of in-use driving not already covered by ST01 or REP05 (hence, the combination of ST01, REP05 and REM01 should cover the full range of in-use driving activity). Thus, the Remnant target surface was obtained by using the remaining speed/acceleration distribution after subtracting that found in the REP05 and ST01 cycles [49].

Additionally, the ARB02 cycle was developed by the California ARB based on data from their Los Angeles chase-car study (illustrated in Fig. 2.22 too, with basic parameters given in Table 2.11). The purpose of this cycle was, again, to test vehicles over in-use operation outside the boundary of the LA4, including extreme in-use driving events. Additionally, the HL07 engineered cycle was developed by EPA in coordination with auto manufacturers. The purpose of this cycle was to test vehicles on a series of acceleration events over a range of speeds, so severe that most vehicles will go into WOT operation [49].

In order to address the vital shortcoming of the LA4, most importantly the absence of aggressive driving, the US06 cycle was the cycle that was eventually developed, illustrated in Fig. 2.23. The cycle was constructed from parts taken from the REP05 and ARB02. The US06 targets specific high emission non-FTP operation, and at the same time is based on actual segments of in-use driving. The cycle encompasses the range of non-FTP driving operation with all the most severe accelerations, incorporating also high speed cruise operation. Further to the above, the severe driving events contained in the US06 also provide for some control over the emission impact of road grade [49].

Overall, the supplemental FTP US06 addresses the need for aggressive, high-speed and/or high-acceleration driving behavior, rapid speed fluctuations and driving behavior following startup. Maximum speed is 129.2 km/h (compared to 91.2 for the LA4), whereas maximum acceleration reaches 3.75 m/s^2 or 13.5 km/h/s (1.48 m/s^2 for the LA4, and only 1.04 m/s^2 for the European NEDC). The cycle lasts 10 min and the vehicle covers a distance of 12.9 km. The structure of the cycle is as follows:

- The first two micro-trips in Fig. 2.23 (t = 0–130 s) correspond to the first 'city' part;

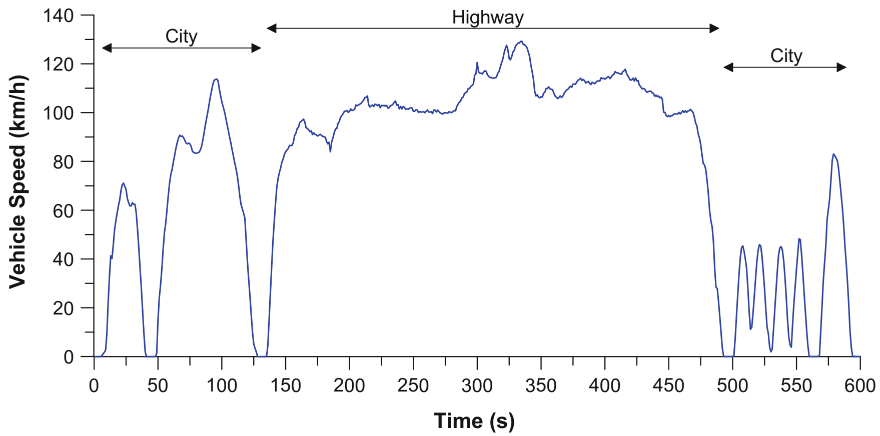

Fig. 2.23 Speed profile of the supplemental US06 (40 CFR, Pt. 86 App. I); the rule includes adjustments for low-performance vehicles

- The third micro-trip (approx. 6 min duration from t = 131–495 s) to the 'highway' part (taken from the ARB02 cycle as evidenced from Fig. 2.22); and
- The last micro-trips (t = 496–600 s) form the second 'city' part.

The US06 is run with the vehicle in the hot stabilized condition (engine and catalytic converter have reached typical operating temperatures by some type of preconditioning, e.g., running the LA4 cycle). The US06 exhaust emissions test procedure is described in 40 CFR 86.159 and 40 CFR 1066.831. Initially, exhaust sampling was a single-bag process but this changed later, as will be discussed in the next paragraphs. Indicative of the harshness of the cycle is Fig. 2.24, which compares the acceleration profiles between the FTP, HFET and the US06 during the first 300 s. Further, Fig. 2.25 supports the much broader profile of the US06 compared to the FTP by demonstrating the speed/acceleration distribution of the two cycles.

During the SFTP research, a second study was commissioned, this time focusing on the effects of the air-conditioning system on emitted pollutants. The air conditioner does not run during the FTP; instead, dynamometer load is increased by 10 % to simulate the average nationwide, year-around air-conditioning effects. Apparently, manufacturers did not optimize for low emissions with the air conditioner on, since they knew that the vehicle will not be tested in that condition. For the survey performed by an EPA contractor in Phoenix, Arizona in 1994, 20 vehicles were instrumented with data loggers for periods of 1–2 weeks, and data was collected on several air conditioner and trip parameters; data was recorded for more than 1000 trips [48]. It was concluded that engine-out NO_x emissions almost doubled with the use of air conditioners (further, fuel consumption increased by 20 %) [51].

Following the findings from this study, two cycles were considered at some point to be used as a supplemental air-condition test, namely the 568-s SC01 and

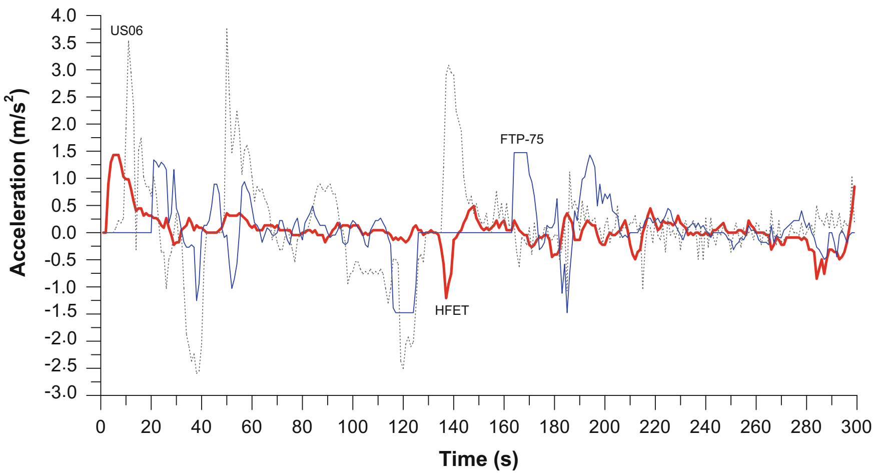

Fig. 2.24 Comparison of the acceleration profiles between the FTP, HFET and US06 cycles

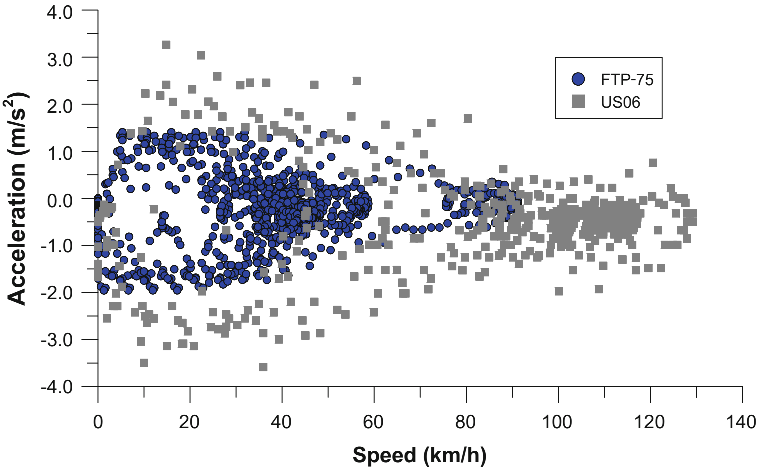

Fig. 2.25 Comparison of the speed/acceleration distribution between the FTP and the US06 (the FTP shows denser distribution at low speeds since it primarily focuses on urban driving)

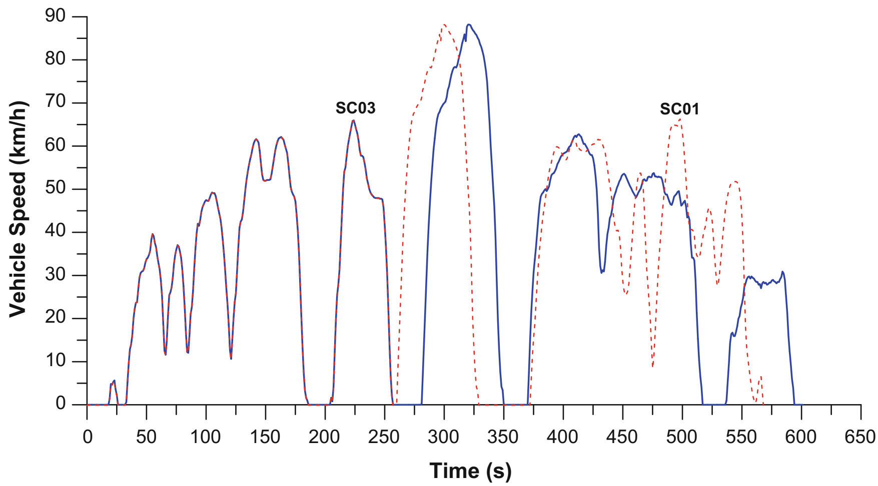

Fig. 2.26 Supplemental SC03 cycle (discontinuous line demonstrates the SC01 cycle, which was initially considered); the first 258 s of the SC0 cycles is the ST01 cycle (Fig. 2.22)

the AC866; the latter being essentially the stabilization phase (bag 2) of the LA4. In the end, the SC03 was the cycle developed to address the need to also test the engine load and emissions associated with the use of the air-conditioning system; the cycle is illustrated in Fig. 2.26.

As with the US06, the SC03 lasts 10 min, with the traveled distance 5760 m; maximum speed is 88.2 km/h (average driving speed is 42.3 km/h), while 18.3 %

of the time is spent idling. The cycle is run at 35 °C (95 °F) ambient temperature under high sun-load and high humidity. The first 258 s of the SC03 cycle is taken from the ST01 discussed previously (Fig. 2.22). The rest of the cycle was developed in such a way that the overall speed/acceleration distribution of the SC03 matched the remnant speed/acceleration distribution as closely as possible. The SC03 exhaust emissions test procedure is described in 40 CFR 86.160 and 40 CFR 1066.835. The two SFTP cycles can be run consecutively to save on preconditioning and setup time; however, separate runs of the cycles are permitted with the appropriate soak or preconditioning steps appended.

The US06 and the SC03, forming the supplemental FTP, concern all passenger cars and light-duty trucks (GVWR lower than 8500 lbs) beginning with model year 2000 and fully phased in by 2004. Beginning with the Tier 3 standard, MDPVs of Class 2b (GVWR between 8500 and 10,000 lbs), such as large SUVs, which are chassis certified, will also be tested on the US06 and the SC03, or, if their PMR is lower than 0.025 HP/lb (40 kW/t), the highway segment of the US06 and the SC03 [46]. The emission value for certification of pollutants is calculated as a weighted composite value of emissions on the FTP-75 and the two SFTPs, namely

$$0.35 \times \text{FTP-75} + 0.28 \times \text{US06} + 0.37 \times \text{SC03} \qquad (2.5)$$

For the case a vehicle is not equipped with an air-condition system, the SC03 results in the above formula are substituted with the FTP-75 ones. Tier 3 standard has also legislated separate PM limit to be met on the US06 [46].

Since model year 2008, the US06 and the SC03 are also used for the determination of EPA's on-road fuel economy ratings using the 5-cycle method [replacing the 2-cycle results from Eq. (2.4)]. The 5 cycles are the FTP-75, HFET, US06, SC03 and the FTP-75 'cold' run at −7 °C. By so doing, a large spectrum of driving conditions is included in the fuel economy determination, in contrast to the single test employed for many years in the EU on the simplistic NEDC. More specifically, the city parts of the US06 contribute to the 'city' fuel economy value together with the 'hot' FTP-75 results from bags 2 and 3. The highway part of the US06, along with the HFET, contribute to the 'highway' fuel economy value (therefore, collection of the exhaust sample during the US06 is now a two-bag process). The SC03 results are accounted for by increasing the previous results. Separate values are obtained from the cold-started FTP-75 phase and the 'cold' FTP-75 at −7 °C. Weighting factors are used for the contribution of each cycle or each part of the cycle. Values obtained from the calculation are further modified to account for road roughness and grade, wind, tire pressure etc. through a 9.5 % downward adjustment [52]. Details about the exact calculation algorithm are available in 40 CFR 600.114. The results are published on the window sticker of new vehicles sold in the United States, as illustrated in Fig. 2.27. Obviously, fuel economy values, although not fully compatible with the daily driving experience, are much more cohesive compared to the ones calculated in Europe, and by extension, the respective gap between real world and certification values much smaller [16].

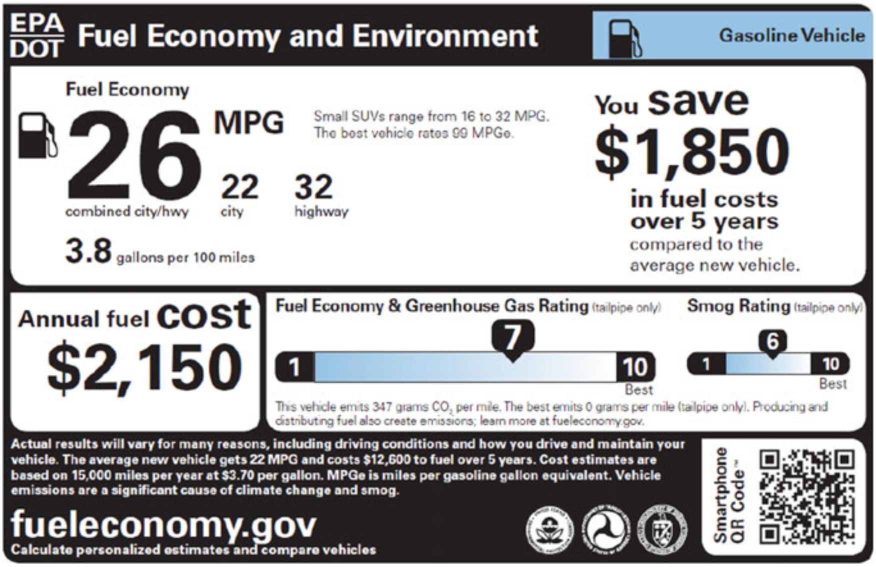

Fig. 2.27 U.S. EPA fuel economy window sticker for gasoline vehicles [53]

The decision to include US06 and SC03 (and 'cold' FTP-75) results on the fuel economy estimates was substantiated by studies which revealed that on average: (a) air condition operation at 35 °C reduced fuel economy by about 21 %, (b) fuel economy over the US06 cycle was almost 30 % lower than over the composite FTP and HFET, and c) fuel economy over the cold FTP-75 was about 12 % lower than over the standard FTP [52].

Tables 2.12 and 2.13 summarize some important technical specifications of the U.S. certification cycles.

It is without doubt that the suite of cycles employed for tailpipe emission and fuel economy testing in the United States, namely the FTP-75, HFET, US06 and SC03, encompass a considerable amount of real driving activity, much broader compared with the European NEDC (or the Japanese cycles, which will be

Table 2.12 Specifications of U.S. certification drive cycles

Cycle	Data collection		Engine temp.	Laboratory temp. (°C)	A/C
	Method	Year			
FTP-72/75	Instrumented vehicle on a specific route	1969	Cold	20–30	Off
HFET	Chase car	Early 70s	Hot	20–30	Off
SC03	Instrumented vehicles	1992	Hot	35	On
US06	Instrumented vehicles and chase car	1992	Hot	20–30	Off

Table 2.13 Summary of technical specifications of U.S. light-duty vehicles cycles (all are transient except for the modal California 7 mode)

Cycle	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
Cal. 7 Mode	137	1358	80.5	35.7	0.98	14.6	0.241
FTP-72	1372	11,990	91.2	31.5	1.48	17.8	0.185
HFET	765	16,507	96.4	77.7	1.43	0.5	0.071
NYCC	600	1898	44.6	11.4	2.68	32.2	0.345
SC03	600	5761	88.2	34.6	2.28	18.3	0.218
US06	600	12,888	129.2	77.3	3.76	6.5	0.222
Cal. LA-92	1735	17,706	108.1	36.7	3.08	17.5	0.250

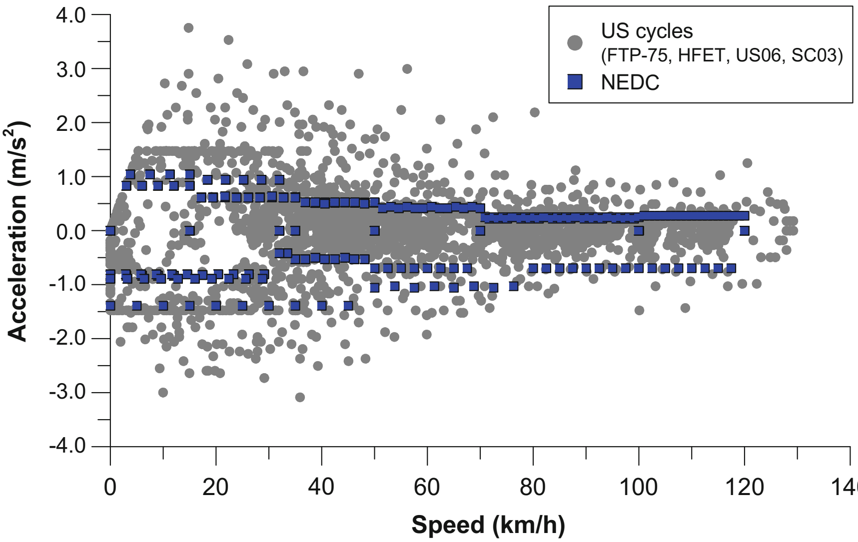

Fig. 2.28 Comparison of the speed/acceleration distribution between the U.S. and European (NEDC) cycles employed for emission certification testing of new light-duty vehicles; obviously, with the adoption of the WLTC cycle in Europe from 2017, the differences will be much smaller

presented later); Fig. 2.28 characteristically illustrates this. Although the U.S. test procedure is more costly and time lengthy, as many cycles need to be run, it is much more compatible with the daily driving activity, which is the single most important virtue a certification procedure must possess.

2.2.5 New York City Cycle—NYCC

Although the LA4 has been the primary cycle for vehicle certification in the U.S., it was acknowledged from the beginning, based on relevant observations, that it would not represent the worst-case scenario for sulfate emissions from catalyst-equipped vehicles. Under certain operating conditions, exhaust catalysts are capable of storing sulfur oxides as aluminum sulfate, which they release later on. It is therefore necessary to stabilize the vehicle and condition of the catalyst prior to emission measurement [36] (obviously, the continuous desulfurization of fuels has significantly diminished this risk). To deal with this, EPA developed in the 70s specialized chassis-dynamometer cycles.

One was the congested freeway driving schedule (CFDS), also known as sulfate emission test (SET) No. 7 or CUE (crowded urban expressway). The, now abandoned, highly transient cycle, is schematically represented in the upper sub-diagram of Fig. 2.29. It has 1398 s duration, covering a distance of 21.7 km, with 56 km/h average speed; as with the FTP cycles, maximum acceleration is 1.48 m/s^2 [54].

Another schedule was the New York City Cycle (NYCC). Oddly, very little is public knowledge regarding the construction of the NYCC. Apparently, the cycle

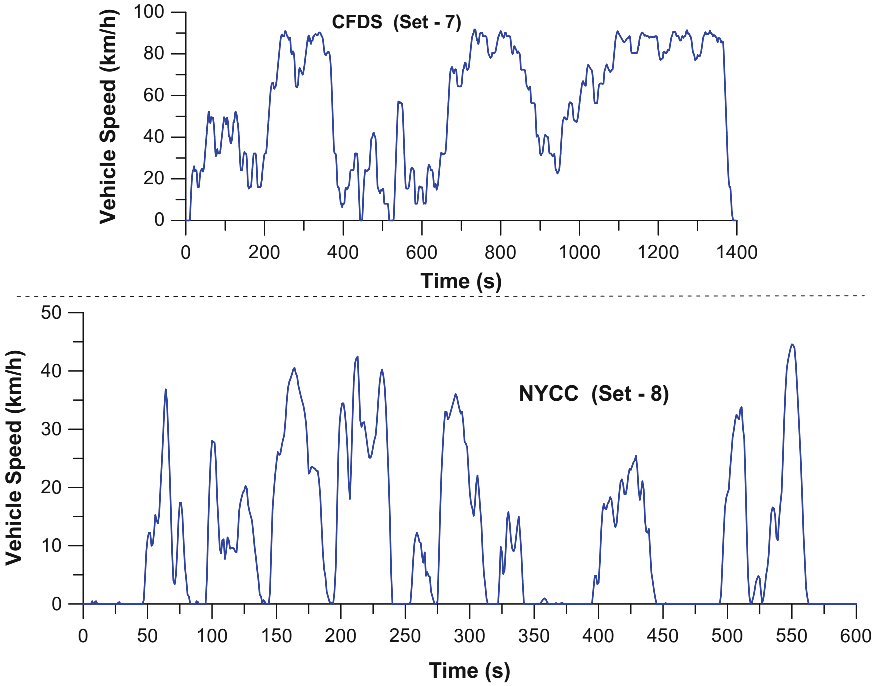

Fig. 2.29 Speed profile of the New York City cycle (40 CFR 86, App. I), also known as SET-8; the SET-7 congested freeway driving schedule—CFDS is depicted in the upper sub-diagram

was originally developed in 1975 by two employees of the New York City Department of Environmental Protection (DEP), with the aim to represent driving in highly congested urban traffic, typical of the city of New York, i.e., with frequent stops and idling. Speed/time data from midtown Manhattan was used in a stochastic model to generate speed/time tables for testing purposes. Vehicle acceleration and deceleration halves of the velocity/acceleration plane were treated separately to reflect vehicle differences implied by these mathematically inverse, but operational distinct, modes [55]. The cycle was often referred to in the 70s and 80s as SET No. 8, and is illustrated in the lower sub-diagram of Fig. 2.29. Duration of the New York City cycle is 598 s, with the traveled distance a little less than 2 km (1898 m). Maximum speed is 44.6 km/h but the average driving speed is only 16.8 km/h. If the extended (32 % of the total time[11]) idling period is accounted for, the average vehicle speed drops to 11.4 km/h. Owing to frequent and steep accelerations commencing from low speeds, this cycle exhibits a very high relative positive acceleration value of 0.345, indicative of its dynamic profile. Maximum acceleration is almost double than that of the FTP, at 2.68 m/s^2 (9.65 km/h/s).

As mentioned earlier, the New York City cycle was initially employed for (sulfate) emission testing in various research projects. Following the Clean Air Act Amendments of 1990, Section 202(k), the cycle formed an element of the HC evaporative emissions running losses test (FR Vol. 58, No. 55, March 24, 1993). Evaporative emissions, being fundamentally different from exhaust emissions, are tested:

- when the vehicle is stationary, after heating the fuel tank to simulate heating by the sun (the diurnal test);
- after the car has been driven and parked with a hot engine (the so-called hot-soak test);
- when the vehicle is driven, the so called running losses.

All these tests apply to gasoline or methanol-engined vehicles (not gaseous-fueled ones), with the whole test procedure requiring five days to be completed. For the running losses test, conducted at 35 °C, the New York City cycle is employed together with the UDDS/LA4 in the following sequence (Fig. 2.30): UDDS—2-min idle—NYCC—NYCC—2-min idle—UDDS—2-min idle. Initially, three UDDS cycle runs were considered (as proposed by General Motors and adopted by CARB [56]), but EPA decided to replace the second UDDS with two NYCCs to provide for a broader range of driving patterns, that is, more low-speed and idle operation. The test began with model year 1996 and was fully phased-in with model year 1999 [56]. The exact procedure employed nowadays is described in 40 CFR 86.134-96.

[11] 32 % of the total time is spent with the vehicle at zero velocity and acceleration; for 41 % of the time during the NYCC, vehicle speed is lower than 1 km/h.

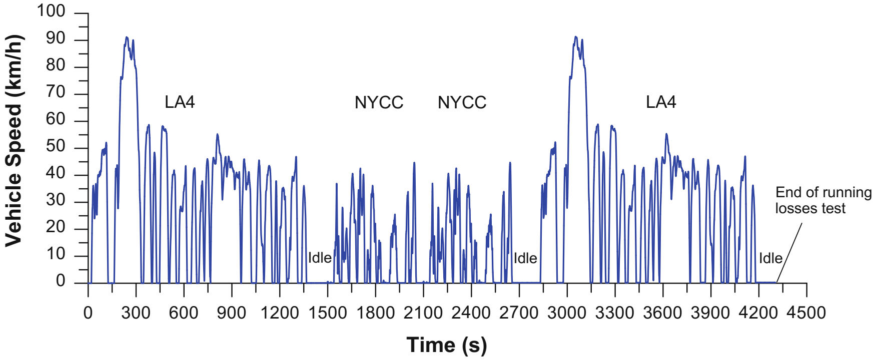

Fig. 2.30 Dynamometer schedule for HC evaporative emissions running losses measurement (40 CFR 86.134-96)

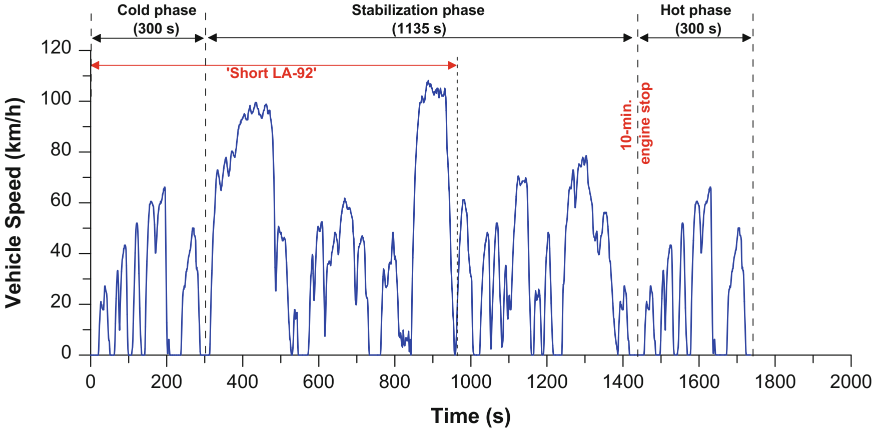

Fig. 2.31 Speed profile of the California LA-92 driving cycle (40 CFR 86, App. I)

2.2.6 California LA-92

The California Unified cycle, also known as Unified Cycle Driving Schedule (UCDS) or, simply, LA-92, Fig. 2.31, is a chassis-dynamometer driving schedule for light-duty vehicles developed by the California Air Resources Board (CARB) in 1992. Its construction was based on driving data—102 runs and 28 h of route-based second-by-second speed traces—recorded while following randomly selected vehicles operating on a mix of routes from the Greater Metropolitan Los Angeles area between April and May of 1992 using a refined chase car protocol [36, 42]. 'Composite' driving data, i.e., mix of chase and target vehicle data, was both used to generate the speed/acceleration frequency distribution plot and the driving cycle.

47 % of the data came from the chase car and 53 % from the target vehicle. To construct the cycle, the sample data were first divided into micro-trips. Although chase car data only accounted for about half of the sample data, it was used to generate the set of micro-trips and the target vehicle data was ultimately ignored. A total of 833 micro-trips resulted from the sampling of the 102 different routes.

For the cycle construction, a 'quasi-random' approach for micro-trip selection was utilized as discussed in Sect. 1.4.2. Firstly, 'seed' micro-trips were selected, entirely at random, to complete a seeding period forming the first 120-s start phase. Subsequent micro-trips were randomly selected in such a way that they improved the match to the sample's SAFD. Each time a micro-trip was selected, it was removed from the micro-trip set. The remaining micro-trips were scanned and subsequent micro-trips were again selected such that they improved the match of the cycle's speed/acceleration frequency distribution to the sample's SAFD. At the end of the process, 18,000 cycles had been created by repeatedly combining a subset of the micro-trips such that each cycle was approximately 20 min long. The final driving cycle, i.e., the Unified Cycle, best matched the speed/acceleration frequency distribution of the entire data set within 22 % of the sum of differences [36, 42].

The LA-92 test has a similar three-phase structure as the FTP-75. The first cold-started phase lasts 300 s, the second phase 1135 s, and the third is identical to the first but with the vehicle hot-started after a 10-min engine shutdown. The cycle was intentionally made more aggressive than the FTP-75 (maximum acceleration is 3.08 m/s^2) to account for more realistic simulation of true driving habits (cf. the supplemental driving cycle SFTP US06, which was based on driving data from the same period).

Not surprisingly, it has been found that CO and NO_x emissions during the LA-92 are higher than those produced during the FTP-75 [57]. The cycle is also characterized by higher speeds and fewer stops as well as less idle time than the FTP-75. It lasts 1735 s (phases 1, 2 and 3) for a traveled distance of 17.70 km. Maximum vehicle speed is 108.1 km/h and the average driving speed is 44.5 km/h; 17.5 % of the time is spent idling. A shorter version also exists that is limited to the first 969 s. Cycle emissions are calculated in the same manner as the weighted, overall FTP-75 formula from Eq. (2.2).

The LA-92 cycle was initially developed as a tool for future emissions inventory improvement efforts [36, 57]; for California's mobile emissions model EMFAC, emission rates are defined by testing a vehicle on the LA-92 for the base emission rate. Beginning with the Tier 3 standard, the 1735-s version of the LA-92 is the supplemental test cycle for Class 3 HDVs (GVWR 10–14,000 lbs) that are chassis tested [46].

Having concluded the discussion of the federal EPA and California CARB driving cycles employed for certification purposes in the United States, concerning passenger cars and light-duty vans, Table 2.13 (earlier in the text) summarizes some of their major technical specifications. More detailed and specialized vehicular data is available in the Appendix.

2.2.7 *Special Purpose Cycles*

Inspection and Maintenance—IM240

Various short cycles have been developed over the years in the U.S. for road-side vehicle testing. The aim of such tests is to ensure that the after-treatment devices function properly, so vehicles retain their low emission profiles in actual use. Originally, some of these tests were carried out with the vehicle idling, or on a dynamometer but the vehicle operating at one or two speeds. For example, the Federal 3-mode test was developed in the 70s as a possible short procedure for evaluating emissions from gasoline-engined cars in inspection and maintenance (I/M) programs. The car was placed on a dynamometer without a flywheel. The test involved two different speeds at 48 and 80 km/h (30 and 50 mph) with load points according to the vehicle's inertia weight. The applied dynamometer load simulated the average power which occurred at the respective speed of the UDDS. A low idle (unloaded) point was tested too. The Clayton Key Mode was another test, similar in logic to the Federal 3 mode. Obviously, such tests were only acceptable for older-technology vehicles with no electronic control.

The IM240 cycle, schematically represented in Fig. 2.32, is the current short-cycle employed in the United States to ensure that vehicles retain their low pollution profiles in actual use (purge flow test of the evaporative canister as well as pressure test of the evaporative system are two other tests applied in this regard). The abbreviation IM corresponds to Inspection and Maintenance, whereas 240 designates the (maximum) duration of the cycle in seconds. The cycle was developed in the early 90s following the 1990 CAAA. Maximum traveled distance is 3.15 km at an average driving speed of 49.1 km//h. Maximum speed is 91.2 km/h (as is the case

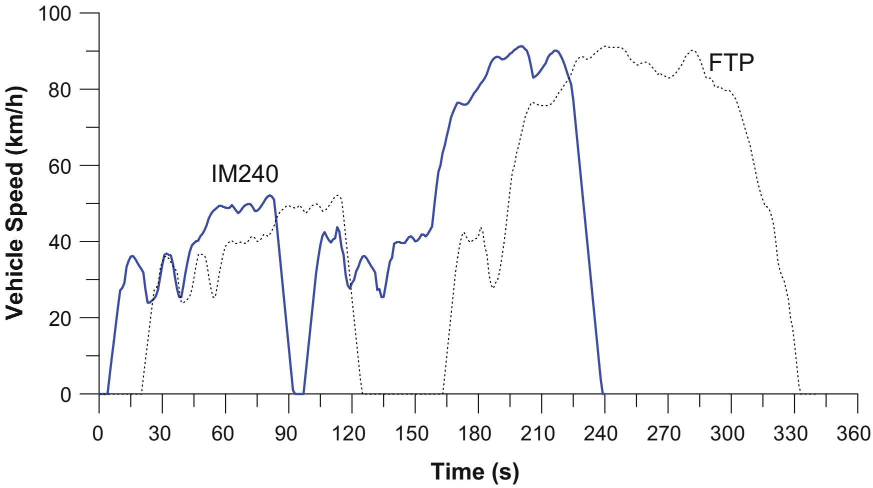

Fig. 2.32 Speed profile of the U.S. Inspection and Maintenance IM240 driving cycle (*dotted line* corresponds to the first 340 s of the FTP cycle)

with the LA4); on the other hand, only 3.8 % of the time is spent idling. Apart from CO and HC, the IM240 included from the beginning nitrogen oxides testing, and employed the CVS system, providing the emissions on a mass basis.

As is obvious from Fig. 2.32, the IM240 was patterned closely on the first two micro-trips of the FTP-72, using actual segments of this cycle. Testing over the entire range of speeds was considered important to detect malfunctioning vehicles given the discontinuous operating characteristics of electronically-controlled vehicles. It was considered important to utilize actual parts of the FTP-72 to help improve correlation and minimize errors of commission (when vehicles fail an I/M test but pass the FTP) and errors of omission (when vehicles pass the I/M test but fail the FTP). The two large decelerations from short-trips 1 and 2 are the only segments that were not taken directly from the FTP-72. The deceleration rate for both micro-trips was set at 1.56 m/s^2, whereas the maximum deceleration rate from the FTP is 1.48 m/s^2. The higher deceleration rate prevents the IM240 from exceeding 4 min, which was taken somewhat arbitrarily to be a measurable upper limit for a test time that would allow an adequate rate of vehicle processing. The 1.56 m/s^2 rate also allows time for an idle and an additional transient portion on the second short-trip (between 140 and 158 s). The IM240 test is run in two segments. The shorter segment is 93 s in duration, which is an informed guess as to the minimum amount of time needed to realize significant improvements in FTP correlation. Exhaust sampling begins simultaneously with the start of the driving schedule [58].

To determine emission levels, second-by-second instantaneous emission measurements are taken and integrated by a computer. The computer uses pass/fail algorithms to identify exceptionally clean or dirty vehicles. As soon as the emission rates indicate that a car is exceptionally clean or dirty, the computer automatically notifies the inspector to stop testing (e.g., after only 30 s). For vehicles that are close to maximum allowable emission levels, the test may continue for the full 240 s. Thus, while the complete driving cycle is 240 s long, the average test time is usually shorter. The existing fast-pass procedure is based on a specific algorithm and a large (3718 tests) database derived from an Arizona IM240 data set [59]. The principal advantage of fast-pass (and fast-fail) is that their use can substantially reduce both the time motorists spend waiting in testing queues as well as the costs of vehicle emission testing itself [60].

Alternative versions of the IM240 also exist such as the IM93 (first 93 s), or the IM147 (second part of the IM240), employed in various U.S. states. Some states use the BAR31, where the vehicle accelerates sharply and then decelerates through the 31 s of the test. For both the BAR31 and the IM147, each vehicle is given up to three chances to pass the test [61, 62].

Standard Road Cycle—SRC

An important feature of the antipollution devices is their ability to maintain their effectiveness throughout the vehicle's useful life, as this is defined in the regulations. Unfortunately, the after-treatment effectiveness is expected to deteriorate over time owing to various reasons such as poisoning, engine mechanical wear, carbon deposits, and, most importantly, thermal ageing.

In order to prove full useful life of vehicles and emission components durability in the United States, a special cycle is employed, applicable in the EU too, the standard road cycle—SRC. The SRC, as well as the similar-logic SBC (standard bench cycle—next paragraph), were introduced by the EPA in 2005 under the Compliance Assurance Program—CAP 2000; the final rulemaking was published on January 17, 2006, applicable to all 2008 and later model-year vehicles [63].

Prior to CAP 2000, EPA's regulations (40 CFR 86), as well as European ones (Directive 91/441/EEC) specified a different method to demonstrate a vehicle's emission durability, namely a whole vehicle mileage accumulation cycle,

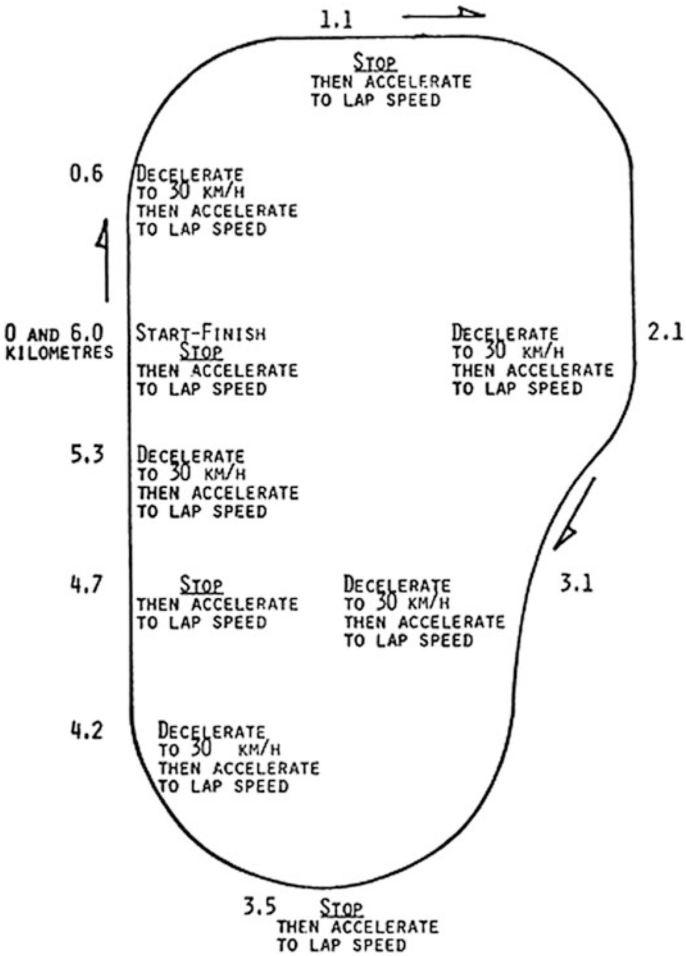

Fig. 2.33 Approved Mileage Accumulation cycle (AMA) (40 CFR 86, App. IV)

commonly referred to as the Approved Mileage Accumulation (AMA) cycle, illustrated in Fig. 2.33. This required manufacturers to accumulate mileage on a preproduction vehicle by driving it over the prescribed AMA driving cycle for the full useful life mileage. The cycle was originally defined in FR Vol. 35, No. 219, November 10, 1970.

During the AMA mileage accumulation, the car was tested in a laboratory for emissions at periodic intervals, and a linear regression of the test data was performed to calculate a multiplicative deterioration factor (DF) for each exhaust pollutant. Then, low mileage vehicles, more representative of those intended to go into production were emission-tested. The emission results from these tests were multiplied by the DFs to project the emission levels at full useful life ('certification levels'). The certification levels had to be at or below the applicable emission standards in order to obtain a certificate of conformity. EPA, however, had concerns that the AMA did not represent modern driving patterns and did not appropriately age modern-design vehicles for various reasons. First, the AMA cycle was developed (in the late 60s) before vehicles were equipped with catalytic converters. Second, the cycle contained a significant portion of low-speed driving, designed to address concerns about engine deposits. While engine deposits were a major source of emissions deterioration in pre-catalyst vehicles, the advent of catalytic converters, better fuel control, and the use of unleaded fuel shifted the causes of

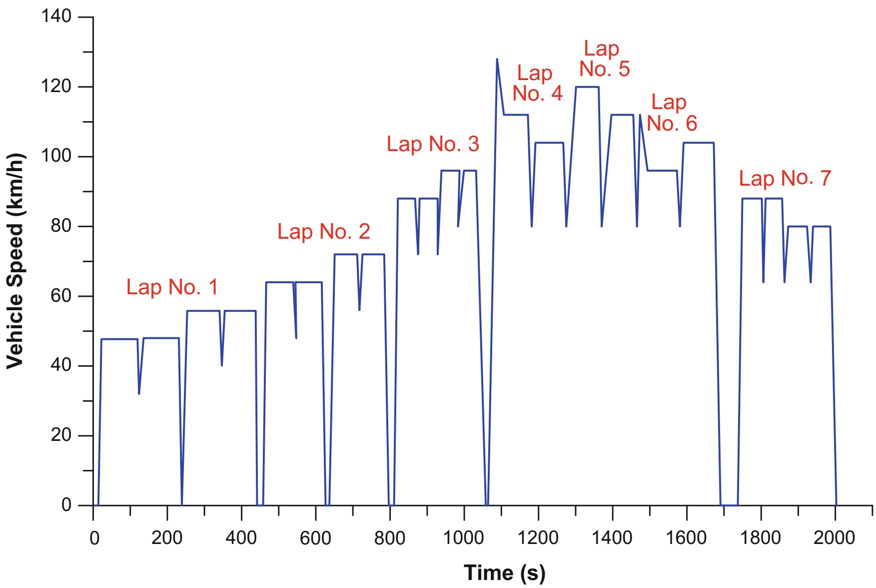

Fig. 2.34 Standard road cycle (SRC) for emission durability purposes; 40 CFR 86, App. V and European Commission Regulation 692/2008/EC provide the exact description of sequences for each lap; the cycle exhibits higher speeds and loads, being more appropriate to realistically age the antipollution devices compared to the AMA, also requiring shorter duration to be accomplished

deterioration from low-speed driving to driving modes which include higher speed/load regimes that cause elevated catalyst temperatures. In addition, manufacturers had long identified the durability process based on mileage accumulation using the AMA cycle as very costly and requiring extensive lead time for completion [63].

The new cycle developed in the 2000s for testing the durability of emission systems is the SRC, being practically a whole-vehicle aging cycle, Fig. 2.34. Manufacturers can demonstrate the emission levels of new vehicles at the end of their useful life period by running a vehicle on the SRC for the full useful life mileage of the vehicle, e.g., 120,000 miles for Tier 2 light-duty vehicles in the United States or 160,000 km in the EU (Euro 5/6 standard). The cycle, as demonstrated in Fig. 2.34, consists of seven laps of 5.95 km (3.7 miles) each [64]. As an example, lap No. 3 contains the following sequences: idle (10 s); hard acceleration to 88 km/h (1.79 m/s^2); cruise at 88 km/h for 1/4 lap; moderate deceleration to 72 km/h (−2.23 m/s^2); moderate acceleration to 88 km/h (0.89 m/s^2); cruise at 88 km/h for 1/4 lap; moderate deceleration to 72 km/h (−2.23 m/s^2); moderate acceleration to 97 km/h (0.89 m/s^2); cruise at 97 km/h for 1/4 lap; moderate deceleration to 80 km/h (−2.23 m/s^2); moderate acceleration to 97 km/h (0.89 m/s^2); cruise at 97 km/h for 1/4 lap; moderate deceleration to stop (−1.79 m/s^2).

Average speed on the SRC is 74 km/h (46.3 mph), maximum cruise speed is 120 km/h (75 mph), and the acceleration rates range from light to hard; most accelerations are moderate with no WOT ones. The SRC contains 24 fuel-cut

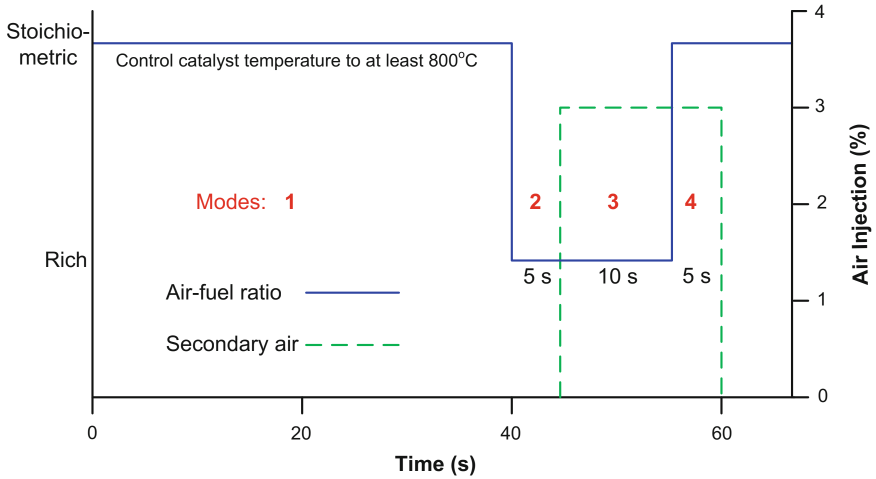

Fig. 2.35 Standard bench cycle (SBC) for catalyst aging in the U.S. and the EU (used to rapidly age emission components, primarily the catalytic converter and oxygen sensors, to the equivalent of the useful life period); 40 CFR 86, App. VII and European Commission Regulation 692/2008/EC provide details on the test sequence (for the rich operation during modes 2 and 3, catalyst temperature should be 890, or 90 °C higher than the low-control temperature)

decelerations; the deceleration rates range from coast-down (no brake force applied) to moderate [63]. Manufacturers in the United States may, with prior EPA approval, apply their own cycle or customize the SRC (or SBC) to their needs to mimic the aging of emission control components over their useful life.

Standard Bench Cycle—SBC

The standard bench cycle—SBC, Fig. 2.35, is a 60-s cycle intended for gasoline engines only, focusing on the catalyst aging, applying stoichiometric and rich operating phases. The cycle is composed of four modes, namely 40 s stoichiometric operation (mode 1), 5 s rich operation (mode 2), 10 s rich operation and air injection (mode 3), and 5 s lean operation (mode 4).

Overall, 108 days are needed to cover the 120,000 miles established in the U.S. legislation running the SRC cycle, compared to only 5–20 for the SBC, where only the engine is tested. EPA has developed a 'Bench Aging Time' (BAT) calculator that outputs the bench aging hours and temperature necessary on the SBC to replicate aging and deterioration that would occur on a road cycle (either the SRC or a manufacturer's alternative cycle). EPA's standard bench procedure specifies that the SRC be used to generate the catalyst temperature histogram needed to determine bench aging time. Specifically, catalyst temperature data is measured at a minimum rate of 1 Hz during at least two runs of the SRC. The temperatures are tabulated into a histogram with temperature bins of no larger than 25 °C [63].

Although requested by some manufacturers, a similar ageing bench cycle for diesel engines has not been defined by EPA. In Europe on the other hand, Regulation 692/2008/EC describes a standard diesel bench cycle (SDBC), which 'reproduces the engine speed and load conditions encountered in the SRC as appropriate to the period for which durability is to be determined. In order to accelerate the process of ageing, the engine settings on the test bench may be modified to reduce the system loading times. For example, the fuel injection timing or EGR strategy may be modified'. The SDBC requires use of an ageing bench with an engine as the source of feed gas for the system.

Facility Cycles

Historically, EPA has employed the MOBILE (initially) and MOVES (from 2009) simulation tools for emission inventory purposes. These models have been primarily based on testing on the FTP certification cycle. Correction factors for various conditions (e.g., average speed, temperature, fuels) are then applied to emissions measured at the FTP 'standard' conditions. The speed correction factors are based on test results for vehicles tested on both the FTP driving cycle but also on several other cycles, each having a different average speed. Specifically, driving patterns in the instrumented vehicle studies have shown that some types of facility (i.e., roadway)-specific driving contain more frequent and more extreme acceleration and deceleration than others, which reach a similar speed but remain at a steady cruise. As a result, it is important to quantify the emission differences for facility-specific speed-related traffic control measures in inventory modeling [65].

A number of specialized cycles has therefore been developed over the years to be employed in the EPA emission inventory simulation tools [66, 67]. The first set of 12 cycles (11 facility specific and one non-freeway area-wide) was developed in 1997 based on the SFTP instrumented vehicle and chase-car database from Baltimore, Spokane and Los Angeles. Sierra Research constructed the facility-specific cycles using randomly selected micro-trips to match the SAFD of all vehicle operation occurring under the conditions of interest (e.g., a particular facility type and congestion level). Moreover, a separate assessment of the highest load points (i.e., the highest combined speed/acceleration points) was conducted, to make sure the cycles had a representative sample of the high-load points. Another criterion for developing the cycles was to match the total proportion of specific power values in two groupings: between 200 and 299 mph^2/s (moderate high-load points) and higher than 300 mph^2/s (extremely high-load points). Since short-trips begin and end at idle, a modification to this methodology was required to develop cycles representative of uncongested freeway operation. More specifically, appropriate trip segments (in lieu of micro-trips) were used that were driven under the target levels of congestion on freeways [65, 66]. The main specifications of the developed cycles are provided in Table 2.14 according to roadway type and LoS (traffic amount; 'A' corresponding to uncongested conditions). As evidenced, most of the cycles have a short duration between 6 and 10 min.

Table 2.14 Summary of technical specifications of the U.S. facility cycles used in the MOBILE6 emissions inventory model (1997) [65, 66]

Cycle	Duration (s)	Distance (km)	Maximum speed (km/h)	Average speed (km/h)	Maximum acceleration (m/s^2)
Freeway, high speed	610	17.15	119.52	101.12	1.20
Freeway, LoS A–C	516	13.68	116.96	95.52	1.51
Freeway, LoS D	406	9.54	112.96	84.64	1.02
Freeway, LoS E	456	6.18	100.80	48.80	2.36
Freeway, LoS F	442	3.66	79.84	29.76	3.07
Freeway, LoS G	390	2.27	57.12	20.96	1.69
Freeway ramps	266	4.10	96.32	55.36	2.53
Arterials/Collectors LoS A, B	737	8.11	94.24	39.68	2.22
Arterials/Collectors LoS C, D	629	5.38	79.20	30.72	2.53
Arterials/Collectors LoS E, F	504	2.59	63.84	18.56	2.58
Local roadways	525	2.99	61.28	20.64	1.64
Non-freeway area-wide urban travel	1348	11.60	83.68	31.04	2.84

Since the Clean Air Act requires EPA to regularly update its mobile source emission model, EPA introduced in 2009 the successor to the MOBILE6.2, which was the MOVES2010. The newer version, which also focuses on micro-scale emission applications (e.g., from an arterial roadway corridor), is based on a set of new facility cycles [67]. Overall, 15 new cycles are incorporated in the model being specific to road types, velocity bins and traffic congestion levels.

For the cycles development, Sierra Research, which was again the subcontractor, reviewed and analyzed past driving datasets (incl. the SFTP one from 1992 used for the previous facility cycles), ultimately employing two, namely the Caltrans/CARB 2000 California route-based driving, and the CARB/Sierra 2004 Sacramento ramp driving. A total of 47 distinct link-level cycles were developed (again, on a second-by-second basis) best matching the statistical characterizations developed for each driving group. 39 cycles were constructed for individual roadway type and congestion level combinations, and 8 were specific to freeway on-ramps [67].

Initially, the speed measurements in the driving database were grouped into separate functional and LoS classes, representing the ranges of operation within each discrete driving data group for which individual cycles were to be constructed. Next, joint SAFD were generated from the data in each group; SAFD being the principal metric used to compare the speed and acceleration patterns in an individual cycle to those of the corresponding dataset. Target cycles in the range of 10–15 min were established (in contrast to 6–10 min for the MOBILE model). A computerized 'trial and error' method was used to select combinations of trip segments that best matched the population SAFD for each driving dataset for which cycles were constructed. Trip segments could be chained together only when the starting speed and acceleration of a candidate segment matched the ending speed and acceleration of the current segment within ±0.5 mph and ±0.5 mph/s respectively. The same hybrid random/best incremental cycle construction logic used for the MOBILE cycles was employed here (see Sect. 1.4.2 for more details) [67]. From the set of 47 cycles constructed, those that were ultimately incorporated in MOVES are detailed in Table 2.15.

It should be noted that apart from the above-mentioned facility cycles, MOVES incorporates 36 driving schedules for LD, medium-duty and HD vehicles, with their time length ranging from 253 to 4866 s, average speed between 2.9 and 125.2 km/h and maximum speed between 13.3 and 138.4 km/h.

Surveillance Driving Schedule—SDS

In 1971, the Surveillance Driving Schedule (SDS) was developed by the U.S. EPA to measure vehicle emissions over a variety of steady state and transient driving conditions, Fig. 2.36 [68].

The acceleration and deceleration phases represented in the SDS consist of all possible combinations of the following five speeds: 0, 15, 30, 45 and 60 mph. The average acceleration or deceleration rate observed for each mode in the Los Angeles Basin was used during the operation of 20 of the 26 transient modes. The remaining

Table 2.15 Summary of technical specifications of the 15 facility cycles used in the U.S. EPA MOVES emissions inventory software tool (2009) [67]

Cycle	Number of segments	Duration (s)	Distance (km)	Maximum speed (km/h)	Average speed (km/h)	Idling time (%)
FC01 LoS A–F	6	568	18.73	135.85	118.74	0.0
FC02 LoS D–F	7	680	14.92	117.55	78.95	5.0
FC11 LoS B	7	518	15.37	131.68	106.79	0.0
FC11 LoS C	13	904	26.02	125.81	103.64	0.0
FC11 LoS D	13	729	19.15	123.54	94.59	0.0
FC11 LoS E	13	972	20.03	115.04	74.21	0.1
FC11 LoS F	12	904	8.33	89.27	33.18	2.5
FC12 LoS C	10	886	25.21	127.74	102.45	0.0
FC12 LoS D	13	800	18.91	117.70	85.08	1.5
FC12 LoS E	12	912	17.63	114.03	69.64	0.0
FC14 LoS B	14	753	10.44	102.67	49.91	3.6
FC14 LoS C	12	512	5.81	85.42	40.85	8.0
FC14 LoS F	22	852	3.33	71.05	14.05	38.2
FC17 LoS D	18	708	5.89	80.98	29.93	16.1
FC19 LoS A–C	27	869	6.11	61.06	25.33	7.7

FC01 (interstate) and 02 (principal arterial) correspond to rural functional classes. All other FCs correspond to urban functional classes, namely *11* interstate; *12* other freeway/expressway; *14* principal arterial; *17* collector; and *19* local

6 transients were repeated using acceleration and deceleration rates higher or lower, in order to determine the effect of acceleration/deceleration rate on emissions. These were chosen to represent the full range of accelerations and decelerations observed in the CAPE-l0 project [6].

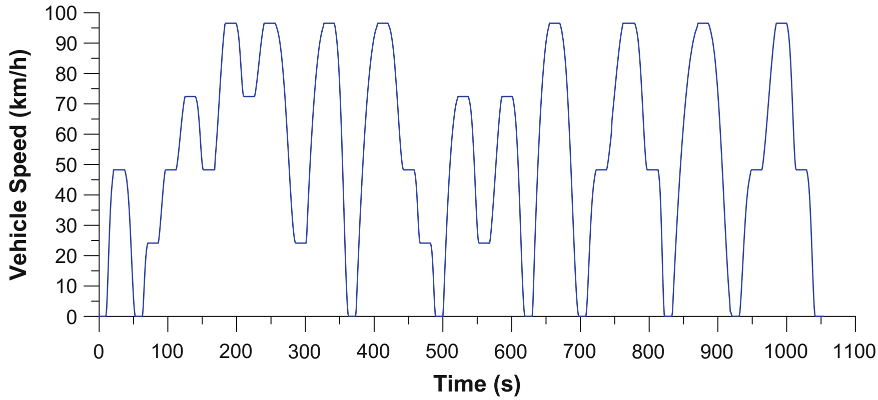

Fig. 2.36 EPA surveillance driving schedule SDS

Overall, 35 % of the total (1054 s) time during the cycle is spent cruising. However, owing to the increased frequency of accelerations, RPA is relatively high, namely 0.212 (30 % of the time is spent accelerating). Average speed is 54 km/h and, interestingly, the maximum acceleration reaches 2 m/s^2. It should be noted that the SDS is not a modal cycle, i.e., it is not described through a series of specific driving modes; instead, the cycle is defined as a vehicle speed versus time sequence on a 1-s basis [68]. Notice in Fig. 2.36 that, unlike modal cycles, the acceleration rate is not constant, but decreases as the demanded speed is approached.

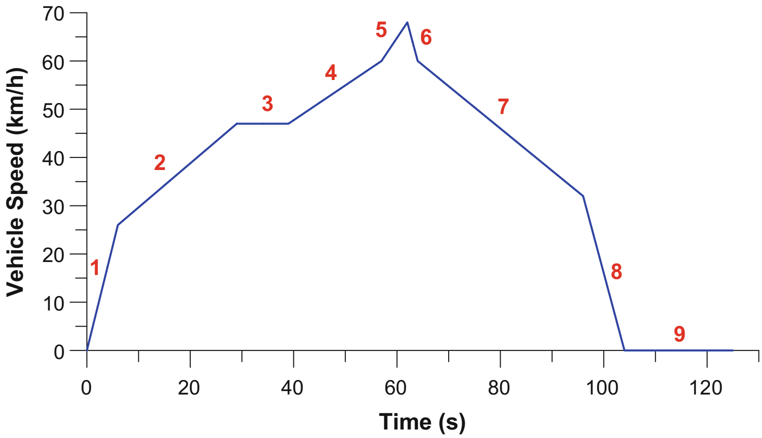

Fig. 2.37 Federal short cycle (FSC) for end-of-line testing (the 9 modes are: (*1*): acceleration from 0 to 26 km/h in 6 s; (*2*) acceleration from 26 to 47 km/h in 23 s; (*3*) cruise at 47 km/h for 10 s; (*4*) acceleration from 47 to 60 km/h in 18 s; (*5*) acceleration from 60 to 68 km/h in 4.5 s; (*6*) deceleration from 68 to 60 km/h in 2.5 s; (*7*) deceleration from 60 to 32 km/h in 32 s; (*8*) deceleration from 32 to 0 km/h in 7.5 s; and (*9*) idle for 21.5 s)

Federal Short Cycle—FSC

The FSC—federal short cycle—was developed by the EPA for fast analysis of vehicle emissions in the 70s. This was a highly transient 9-mode cycle based on the FTP-72 driving modes (specifically, the dynamometer loadings and transmission shift points follow the procedure as required for the FTP-72). Duration of the cycle was approximately 2 min (125 s), of which only 10 s spent cruising; distance traveled was 1.22 km, with 35 km/h average and 68 km/h maximum speed, for 0.151 RPA. Figure 2.37 provides a graphical illustration of the nine modes [69]. The cycle was used in various research projects during the 70s and 80s.

SAE J227a Driving Cycle for Electric Vehicles

In the 70s, SAE (Society of Automotive Engineers) developed the J227 cycle to be employed for the testing of electric vehicles (EVs) including two or three-wheelers, e.g., electric scooters. The cycle was designed to give approximately the same road-load energy demand as the FTP-72 but with lower peak road-load power. Since many EVs at the time were unable to follow the cycle, it was re-issued as J227a (now cancelled too) [70].

This is actually a suite of cycles, with four versions having different power and maximum speed requirements, named J227a-A, B, C, and D. Each version of the cycle has five phases: acceleration, cruise, coasting, braking and idle. Figure 2.38 shows the general speed profile of the J227a-C, which is the most commonly used variant.

As evidenced, the J227a is a typical modal/simplistic, short-duration and short-distance cycle, with increased cruising segment. Technical characteristics for each phase are summarized in Table 2.16 for all versions. The J227a procedure specifies only the cruise velocity and the transition time from one mode to another. The speed profile for the coasting segment (tractive force set to zero) is not

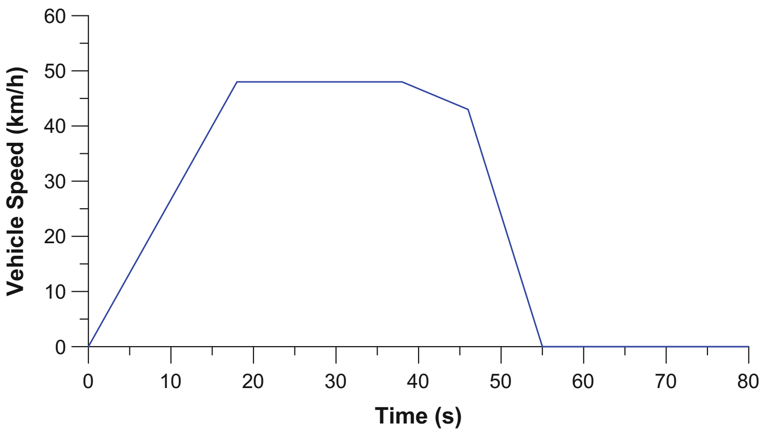

Fig. 2.38 SAE recommended J227a-C cycle for electric vehicles testing

Table 2.16 Specifications of the J227a suite of cycles [71, 72]

Cycle version	Maximum speed (km/h)	Acceleration time (s)	Cruising time (s)	Coasting time (s)	Braking time (s)	Idle time (s)	Total time (s)
A	16	4	0	2	3	30	39
B	32	19	19	4	5	25	72
C	48	18	20	8	9	25	80
D	72	28	50	10	9	25	122

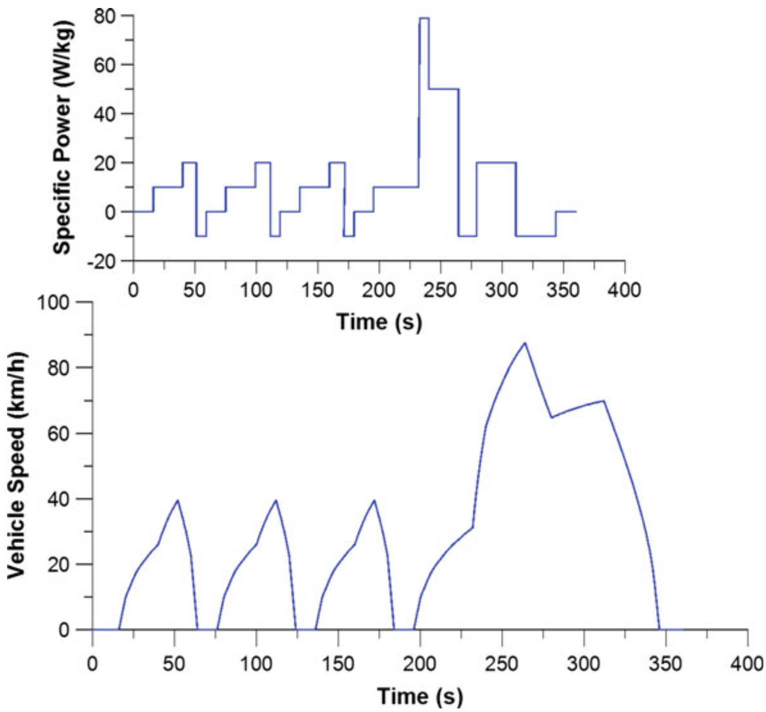

Fig. 2.39 Vehicle speed versus time schedule of the SFUDS (*lower sub-diagram*) and specific power versus time curve (*upper sub-diagram*)

explicitly defined, hence the traveled distance varies, depending on the acceleration capability of the vehicle under test [71, 72].

Simplified Federal Urban Driving Schedule—SFUDS

The prime consideration for electric vehicles is prescribing the power discharge profile of the battery and relating it to a particular vehicle design and driving cycle. Since the battery discharge profile for the FTP-72 (or FUDS) is very complex to simulate in the laboratory [73], a simplified version of the cycle, the SFUDS was developed by the U.S. Department of Energy in 1988. The cycle is illustrated in the

Table 2.17 Comparison of the technical specifications between the FTP-72 (FUDS) and the SFUDS cycle

Cycle	Duration (s)	Distance (m)	Average/Maximum speed (km/h)	Idle time (%)	Average/Maximum power (W/kg) [73]	Energy consumption (Wh/km) [73]	RPA (m/s^2)
FUDS	1372	11,990	31.5/91.2	17.8	10.1/79	225	0.185
SFUDS	360	3098	31.0/87.5	17.5	9.9/79	22.4	0.167

The specific energy (Wh/kg) of the battery primarily determines an EV's range; acceleration is determined by the battery's specific power (W/kg) upper sub-diagram of Fig. 2.39 in terms of W/kg versus time, for testing the battery following a variable power discharge schedule.

The test comprises 20 steps and six power levels; as evidenced, the cycle also includes regeneration phases. Even though the profile was derived for a specific vehicle, it has been widely applied to other battery/vehicle combinations, irrespective of the differences in battery weight fraction, road-load parameters etc. [74, 75]. The lower sub-diagram of Fig. 2.39 demonstrates the cycle in terms of vehicle speed versus time, with the intent to test the whole electric vehicle. A comparison between the FUDS and the SFUDS in Table 2.17 indicates they produce very similar results.

A more sophisticated version of the SFUDS, termed the generic SFUDS (GSFUDS), has been also developed, to provide a test that is not vehicle specific. The GSFUDS uses the concept of average power P_{ave}, which is calculated by dividing the net energy out of the battery by the time duration of the discharge [74].

2.3 Japan

In Japan, automobile emissions were first mentioned in the 'Air Pollution Control Law' of 1966, which replaced the 'Smoke and Soot Regulation Law' of 1962. The Law required that emission standards for vehicles be determined, including CO, HC, lead, and 'all other substances which might endanger public health' [2]. The pertinent authorities responsible for emission standards and test cycles/procedures have been the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and the Ministry of Economy, Trade and Industry (METI). Japan first established emission limits for gasoline-powered, light-duty vehicles in 1966 on a concentration basis [2, 76], and in 1973 with respect to mass emissions. Mass emission limits were set in 1986 for diesel-engined passenger cars and in 1988 for light-duty vans. Nowadays, the regulated pollutants are CO, NO_x, HC (NMHC for gasoline cars

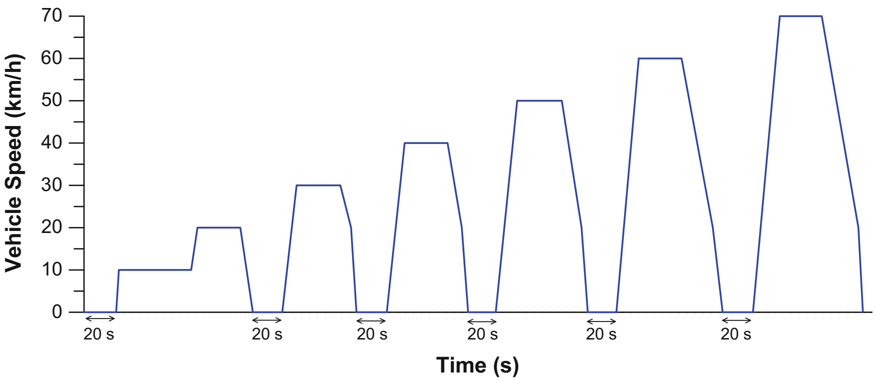

Fig. 2.40 Speed profile of the Japanese 4-mode (J4) driving cycle (only emissions during specific segments of the cycle were taken into account) [2]

from 1999) and PM. Standards apply to passenger cars and light-duty trucks with GVW lower than 3500 kg. Unlike the EU and the U.S., two types of exhaust emission standards are established, denoted as 'mean' and 'max'. The 'mean' standards are to be met as a production average and as a type approval limit. The 'max' standards are to be met generally as an individual limit in series production and as type approval limit if sales are less than 2000 per vehicle model per year [3]. In 1998, Japan joined the UNECE 1958 Agreement for mutual recognition of approvals for automotive equipment, as the first non-European country.

2.3.1 4-Mode—J4

A 4-mode cycle (J4) was initially employed in Japan, with the scope to limit the volumetric concentration of CO from gasoline and LPG fueled vehicles. The cycle, graphically illustrated in Fig. 2.40, was developed by the 'Traffic Safety and Nuisance Research Institute', after studying driving habits in Tokyo.

The cycle identifies four driving modes: idle, acceleration and deceleration at certain rates, and constant speed at specific values. On July 14, 1966, the J4 was officially adopted as the standard driving sequence in Japan, and was employed for seven years [2, 7]. As is evidenced in Fig. 2.40, the J4 consists of a simple sequence of acceleration, cruise, deceleration and idle, repeated seven times, with increasing cruise speed from 10 to 70 km/h at increments of 10 km/h. Idle time between the various sub-cycles is constant at 20 s. Since constant acceleration and deceleration rates are maintained throughout the cycle, the time length for each segment varies.

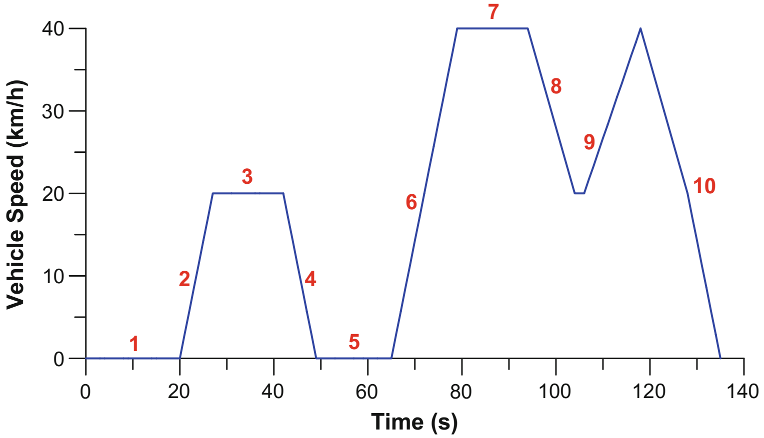

Fig. 2.41 Speed profile of the Japanese 10-mode (J10) driving cycle with identification of the various modes (see also Table 1.1 for a description of the ten modes)

2.3.2 10-Mode—J10

The 4-mode cycle was replaced by the 10 mode (J10), effective 1 April 1973. At the same time, the regulated pollutants were extended to HC and NO_x, and the test method changed from concentration measurement to the CVS technique. The J10, illustrated in Fig. 2.41 (its driving modes were detailed in Table 1.1), is similar in structure, simplicity and acceleration uniformity to the European ECE-15. It simulates urban traffic conditions in Tokyo, and was based on three earlier '8-mode' versions developed during the late 60s [2, 77, 78].

More than 25 % of the time during the J10 is spent idling compared to 31 % for the ECE-15, while the maximum vehicle speed throughout the 135 s of the cycle is limited to 40 km/h (50 km/h for the ECE-15); average driving speed is 24.1 km/h. Before sampling, there was a 15-min warm-up at 40 km/h, followed by one run of the cycle. After this warming phase, sampling commenced over five repetitions of the 10-mode cycle, i.e., for a period of 675 s [7]. As was the case with all test cycles at the time, the J10 was applicable to gasoline and LPG vehicles only. Diesel cars up to 1700 kg GVW were tested as of October 1, 1986 [2].

2.3.3 11-Mode—J11

In order to account for cold-started emissions, investigations about driving habits were conducted in 1973 that included early morning rush-hour traffic with

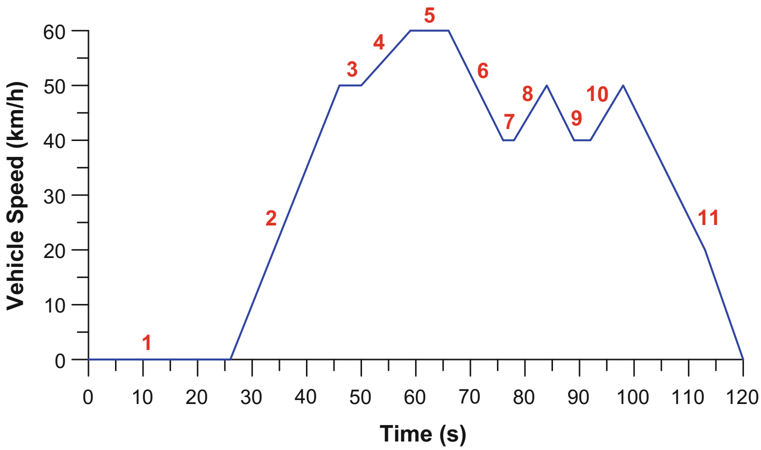

Fig. 2.42 Speed profile of the Japanese 11-mode (J11) cycle employed for emissions measurement under cold starting, with identification of the various modes

cold-started vehicles coming into Tokyo from outside the city area. The result was the development of a separate cycle, the suburban 11-mode test (J11), illustrated in Fig. 2.42.

The modal J11 lasts 120 s, with a 26-s initial idle period; it practically constitutes an expressway route after a cold start (cf. the first phase of the FTP-72) [78]. Maximum speed is 60 km/h, with the traveled distance a little over 1 km. As is evident from Fig. 2.42, the cycle is highly transient with limited constant-speed segments (only 13 %), unlike the much simpler J10; increased power demand is also established compared to the urban J10. As a result, the RPA value is rather high at 0.210.

During the certification procedure, the cycle was repeated four times, with measurements taken during all four runs [79]. Interestingly, the emission limits during the J11 were set in g/test and not g/km. The J11 came into effect as of April 1, 1975 for gasoline engined cars and was abandoned in 2008.

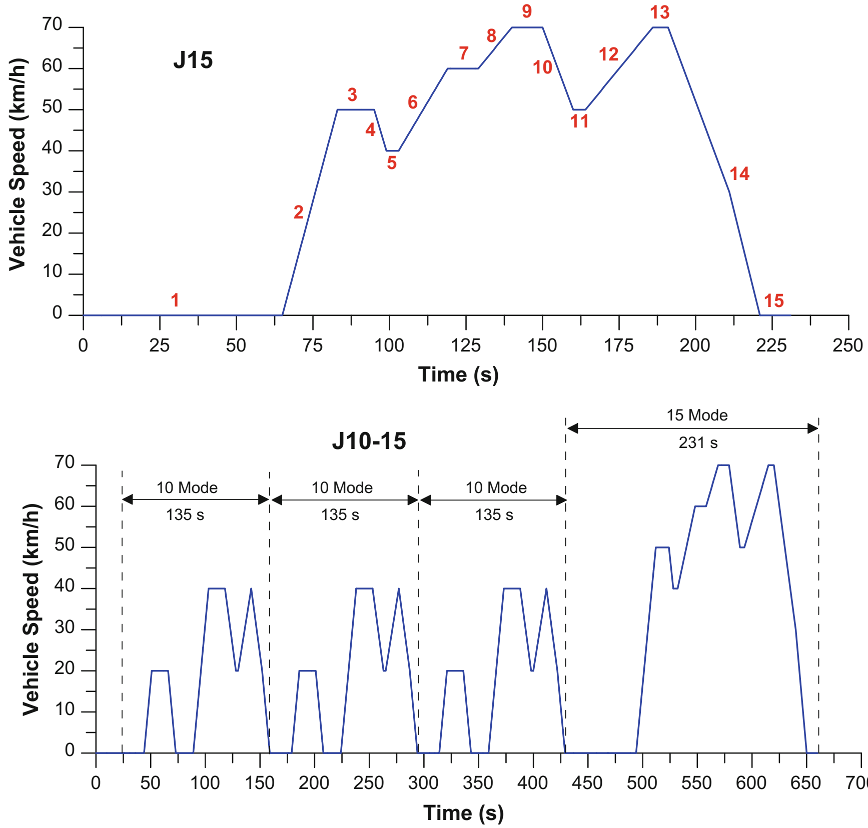

Fig. 2.43 Speed profile of the Japanese 15 mode (J15) and 10-15 mode (J10-15) driving cycles

2.3.4 10-15 Mode—J10-15

An extra-urban ('15-mode') segment was added from November 1991 (April 1993 for imported cars) to the J10 testing procedure to account for motorway driving at higher vehicle speeds [2]. The segment is illustrated in the upper sub-diagram of Fig. 2.43. Thus, the 10-15 mode (J10-15) cycle was formed comprising three repetitions of the J10 followed by one of the J15 (the latter denoted in the legislation as 'acceleration pattern'). The whole cycle is demonstrated in the lower sub-diagram of Fig. 2.43. It is specified in the Road Transport and Motor Vehicle Safety Standards (1951 Ministry of Transport Law 67), Article 31.2. It should be noted that an idling period of 24 s has been inserted prior to the first 10-mode run. The cycle reflects metropolitan driving conditions as well as highway ones, based on driving performance studies in major cities in Japan [80]. Notice the similarities between the 15-mode segment and the European EUDC in Fig. 2.2, as regards both structure and implementation date, as well as the overall similarity between the J10-15 and the European ECE+EUDC.

During the 231 s of the 15-mode segment, the maximum vehicle speed reaches 70 km/h, much lower compared to the 120 km/h of the EUDC, but fairly consistent with the driving habits of Japanese drivers at the time; average driving speed is 50.2 km/h for this motorway part. The whole 10-15 mode cycle lasts 660 s, with the traveled distance 4.16 km at an average driving speed of 33.1 km/h. As was the case with the J10, the vehicle was tested fully warmed-up; sampling was over one repetition of the whole cycle depicted in Fig. 2.43. The preconditioning included a sequence of a 15-min warm-up at 60 km/h, idle, 5-min warm-up at 60 km/h and one repetition of the 15-mode cycle [79]. Effective October 1993, the J10-15 cycle was also used for the certification of vans with GVW under 2500 kg. The cycle was used for fuel consumption measurements too, covering gasoline, LPG and diesel-engined vehicles, and for electric vehicles.

The extremely simplistic pattern of the J10 and J15 cycles is highlighted in Fig. 2.44 that demonstrates their speed/acceleration distribution.

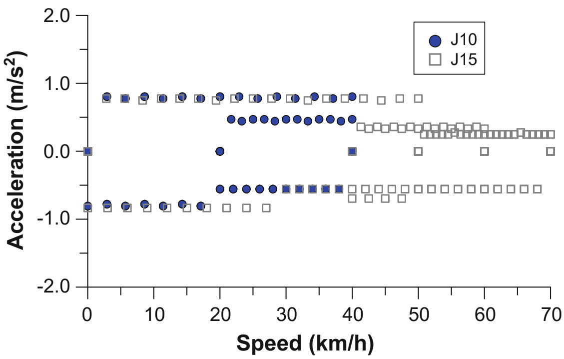

Fig. 2.44 Speed/acceleration distribution of the J10 and J15 cycles

2.3.5 JC08

An attempt to establish a driving cycle which would reflect real-world conditions and would deviate from the simplistic pattern of the J10/J11 cycles was made in 1976 by the 'Tokyo Metropolitan Research Institute for Environmental Protection' (TMRIEP). The developed cycle was composed based on 760 trips derived from Tokyo's ring artery road Meiji Dori, and took into account the frequency distribution of average vehicle speeds in relation to road characteristics and day time. Its speed versus time trace and duration (1466 s) resembled very much those of the U.S. LA4 cycle, however the average speed was only 22.5 km/h and its maximum one only 57.8 km/h. In any case, the cycle was never legislated [2].

Almost thirty years later, in 2005, the Japanese authorities finally introduced a realistic/transient test cycle, the JC08, for emission certification of passenger cars and light-duty trucks (GVW < 3500 kg). Graphical illustration of the JC08 is provided in Fig. 2.45. The cycle lasts 1204 s, with a covered distance of 8.16 km. Unlike its repetitive-type predecessors, the JC08 is highly transient with minimum cruising time; nonetheless, a long idling period (29 %), indicative of congested traffic in Japanese cities, is still maintained. Maximum speed is 81.6 km/h with an average driving speed of 34.2 km/h. The motorway segment is equal in duration

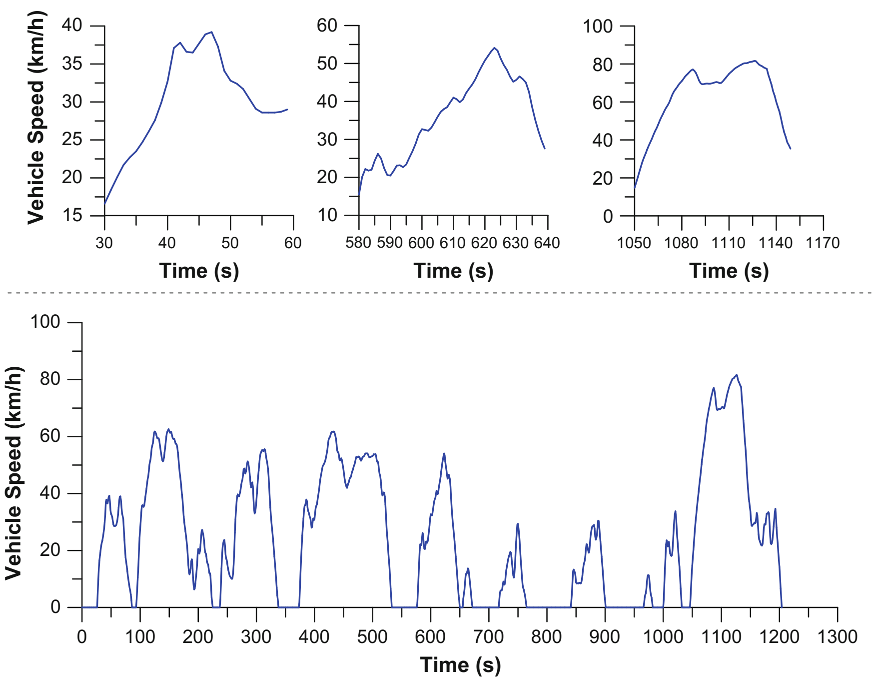

Fig. 2.45 Speed profile of the Japanese JC08 driving cycle (the *upper three sub-diagrams* illustrate specific parts of the cycle in more detail)

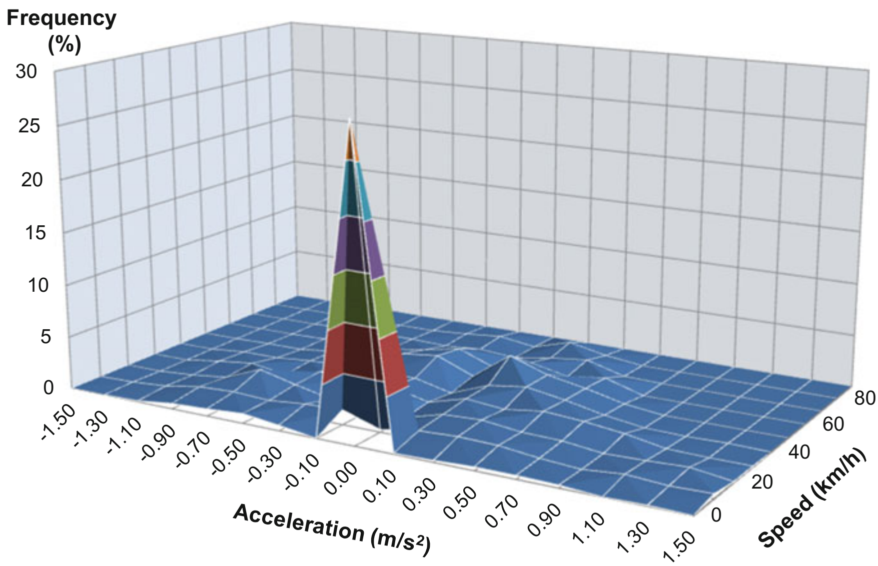

Fig. 2.46 3D speed/acceleration frequency distribution of the JC08 driving cycle (notice the high frequency at zero acceleration and speed, owing to increased idling period)

(short in any case) to the J15, with higher maximum speed (81.6 compared to 70 km/h for the J10-15). The 3D speed/acceleration frequency distribution for this cycle is provided in Fig. 2.46.

In November 2006, the 'Notice of the safety standard details for road trucking vehicles (Notice No. 619 of the Ministry of Land, Infrastructure and Transport, July 15, 2002)' was revised. For the purpose of evaluating exhaust emission performance more accurately, it was decided that driving modes of the new exhaust emission measurement method will be switched from the 11 mode to the JC08 cold started starting in fiscal year 2008, and from the 10-15 mode to the JC08 hot-started in 2011 [81], using the following weighting factors

- 2005: 12 % of J11 cold start/88 % of J10-15 hot start;
- 2008: 25 % of JC08 cold start/75 % of J10-15 hot start;
- 2011: 25 % of JC08 cold start/75 % of JC08 hot start.

The above dates were valid for domestic manufacturers. For imported vehicles, the transition phases began two years later.

For the cold-started JC08 test, the vehicle soaks for 6–36 h at 25 °C. The hot-started JC08 test commences after the vehicle is operated for at least 15 min at 60 km/h. The cycle is used for electric vehicles too; as is the case with the European NEDC, no allowance is made for the use of air-condition systems.

The much more realistic/transient pattern of the JC08 compared to the J10-15 is highlighted in Fig. 2.47 that illustrates the acceleration profiles of the two cycles during the first 300 s. Further, Fig. 2.48, comparing the speed/acceleration

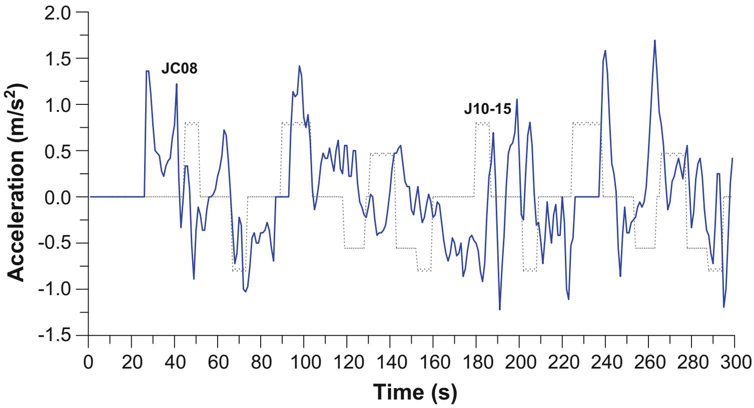

Fig. 2.47 Comparison of the acceleration profiles between the J10-15 and the JC08 driving cycles during the first 300 s (the JC08 exhibits higher, more frequent and non-steady accelerations)

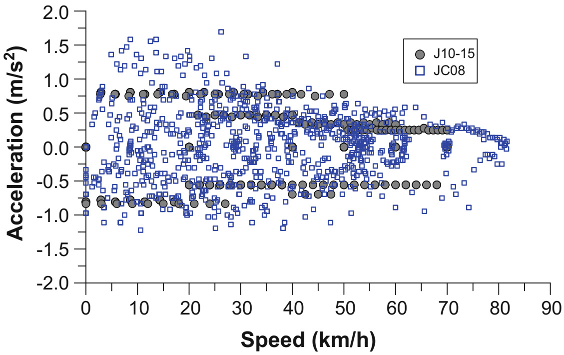

Fig. 2.48 Comparison of the speed/acceleration distribution between the J10-15 and the JC08

distribution between the J10-15 and the JC08, draws a more complete picture by shedding light into the latter's much broader driving activity.

For fuel economy purposes (km/L), the following formula is applicable, taking into account hot and cold JC08 results appropriately weighted (as is also the case with exhaust emissions)

$$\text{Fuel Economy} = \frac{1}{\frac{0.25}{\text{JC08C}} + \frac{0.75}{\text{JC08H}}} \quad (2.6)$$

Covered vehicles are gasoline or diesel-fueled passenger cars with a capacity of 10 passengers or less, passenger vehicles with a capacity of 11 or more passengers (GVW less than 3500 kg), and freight vehicles with GVW of less than 3500 kg that have received type designation under Article 75.1 of the Road Trucking Vehicle Law (1951, Law No. 185) [81]. Japan has expressed its intention to adopt the WLTC (Sect. 2.5), in the development of which it participated actively.

Table 2.18 Summary of technical specifications of Japanese passenger-car cycles (all are modal except for the JC08)

Cycle	Road category	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
J10	Urban	135	664	40.0	17.7	0.81	26.7	0.198
J11	Suburban	120	1021	60.0	30.6	0.69	21.7	0.210
J15	Motorway	231	2174	70.0	33.9	0.78	32.5	0.149
J10-15	Urban-motorway	660	4165	70.0	22.7	0.81	31.4	0.172
JC08	Urban-motorway	1204	8159	81.6	24.4	1.69	28.7	0.186

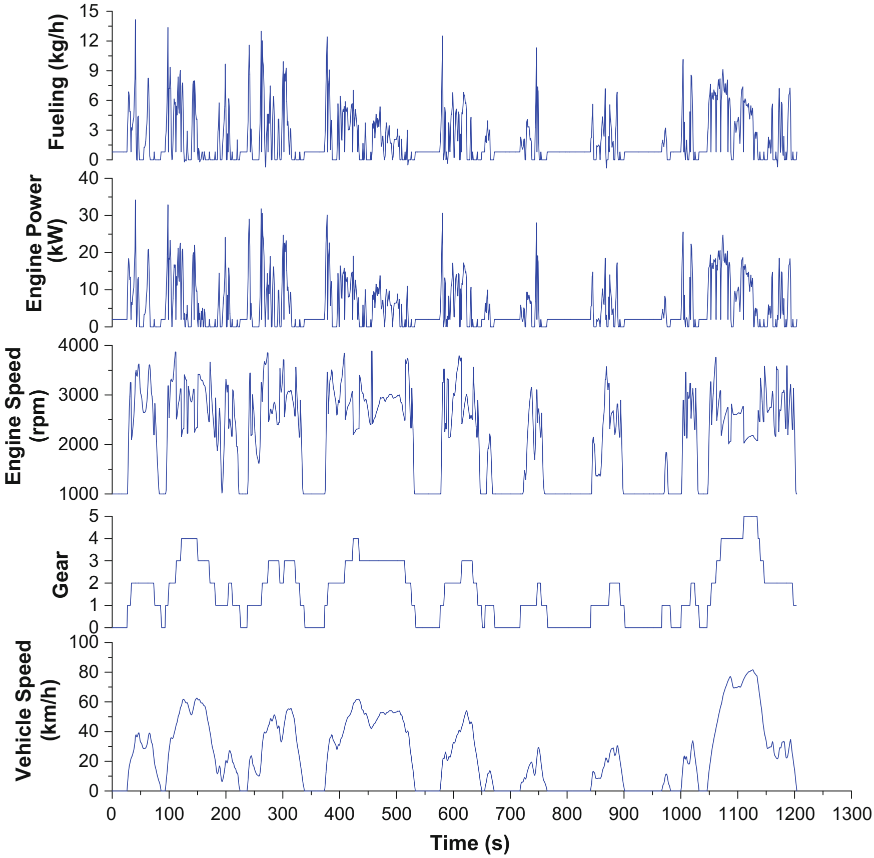

Fig. 2.49 Development of engine and vehicle properties during the JC08 for a SI-engined passenger car (notice the abrupt increase in fueling at each steep acceleration in the cycle)

Basic technical specifications of the legislated Japanese test cycles are summarized in Table 2.18. Increased idling period and rather low maximum vehicle speeds are common features in all the cycles.

Lastly, Fig. 2.49 illustrates engine and vehicle properties development during the JC08 for a gasoline passenger car.

2.4 Australia

In Australia, the Australian Design Rules (ADRs) apply, i.e., national standards for vehicle safety, anti-theft and emissions. The current (2016) standards, the third edition ADRs, are administered by the Australian Government under the Motor Vehicle Standards Act of 1989. Australia follows the European emission regulations and, from 2005, the NEDC is employed for the certification of light-duty vehicles. Nonetheless, a number of cycles have been developed in the 70s and 80s for research and inventory purposes, specifically the Sydney cycle [82], Melbourne cycle [83] and Perth cycle [84].

In the late 90s, a research project was undertaken with the goal to develop a national cycle for diesel-engined vehicles of various classes. The actual on-road driving patterns of 17 vehicles, ranging from off-road passenger to heavy-goods vehicles, were logged during normal use in Sydney in 1998. Using mathematical analytical tools, the data was analyzed according to the characteristics of micro-trips. For each vehicle, each micro-trip was allocated to a road flow category ('freeway/highway', 'arterial', 'residential/minor' or 'congested'). The most representative micro-trips in each road flow category were then combined to form an urban emissions drive cycle (UEDC) of approximately 60 min duration, for each vehicle/ADR category. The categories were:

- passenger cars (MA), forward passenger vehicles (MB) and off-road passenger vehicles (MC);
- light-goods vehicles (NA), and light buses (MD) below 3500 kg GVW;
- medium-goods vehicles (NB), and light buses (MD) above 3500 kg GVW;
- heavy buses (ME);
- heavy-goods vehicles (NC) below 25,000 kg GVW;
- heavy goods vehicles (NCH) greater than 25,000 kg GVW.

These UEDCs were recommended as 'reference' drive cycles. A CUEDC (composite UEDC) of approximately 30 min duration, and thus more suitable for test purposes, was then derived from each UEDC. The complex CUEDCs were recommended for in-service testing for inventory purposes. A 'straight line' 'simplified CUEDC' was also constructed from each CUEDC, in order to reduce the number and frequency of transients to allow greater ease of testing on less sophisticated (and less costly) chassis dynamometers [85]. Figure 2.50 illustrates the speed/time trace of the two LDV cycles and Table 2.19 provides some

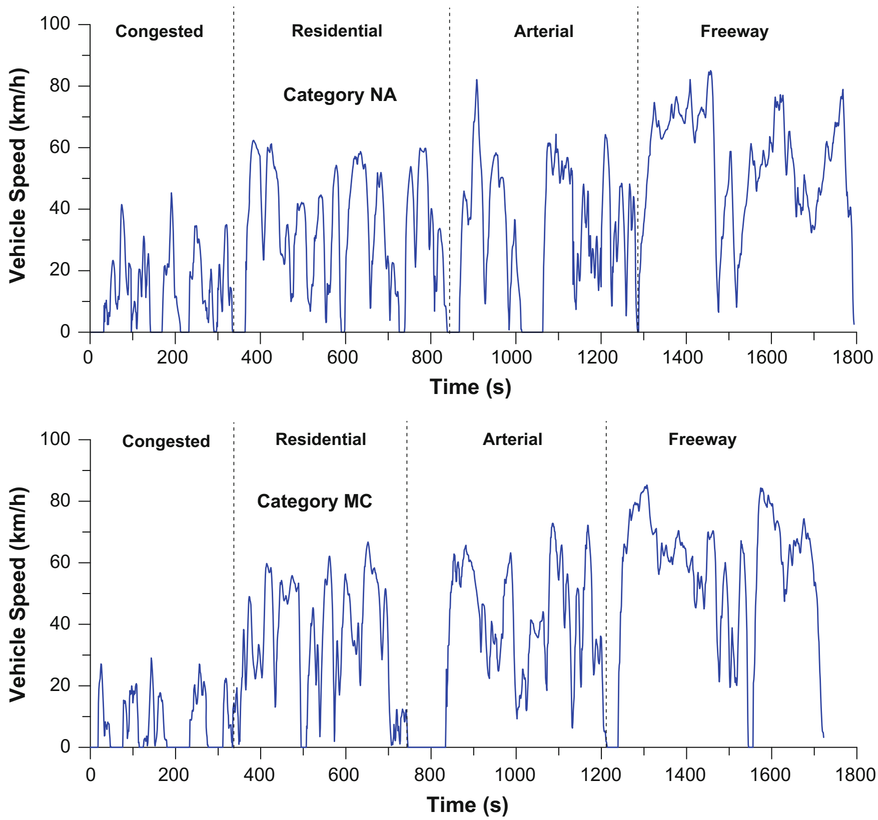

Fig. 2.50 Australian CUEDC cycles for diesel-engined light-duty vehicles [85] (see text for definition of MC and NA)

Table 2.19 Technical specifications of the Australian CUEDC cycle for LD vehicles

Cycle/Segment	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
Diesel—MC	1722	16,904	85.3	35.3	5.80	15.7	0.269
Diesel—NA	1794	17,477	85.0	35.1	5.22	11.4	0.281
Gasoline	1797	19,442	94.0	39.0	3.61	22.3	0.171
Gasoline cycle individual segments							
Residential	498	3839	58.0	27.8	3.06	21.1	–
Arterial	401	2793	67.0	25.1	3.61	13.9	–
Freeway	542	10,783	94.0	71.6	3.61	14.6	–
Congested	356	2027	59.0	20.5	2.50	28.2	–

important technical specifications. The four HDV schedules are demonstrated in Fig. 4.56.

For gasoline vehicles, a similar approach was followed in 2005 (NISE2) [86]. Sixty vehicles were monitored for a total of 431 h. Global positioning system (GPS) technology was used to collect driving data from the vehicles traveling AustRoads routes in each major Australian capital city (Sydney, Brisbane, Adelaide, Melbourne and Perth). As the AustRoads routes are arterial/freeway road types, data logging was initiated from trip origin (home/work) through to the final destination (work/home) so as to allow collection of residential road data at the start and end of each trip. Data was collected during three time periods of the day, namely AM peak, PM peak and inter-peak. Using specialized analysis techniques, each trip was broken down firstly into road flow category, and then into basic driving modes (idle, acceleration from idle, deceleration to idle, intermediate acceleration, etc.). These were then combined using VKT (vehicle kilometers traveled) weightings to account for state to state differences, to produce the average national drive profile for each road flow category.

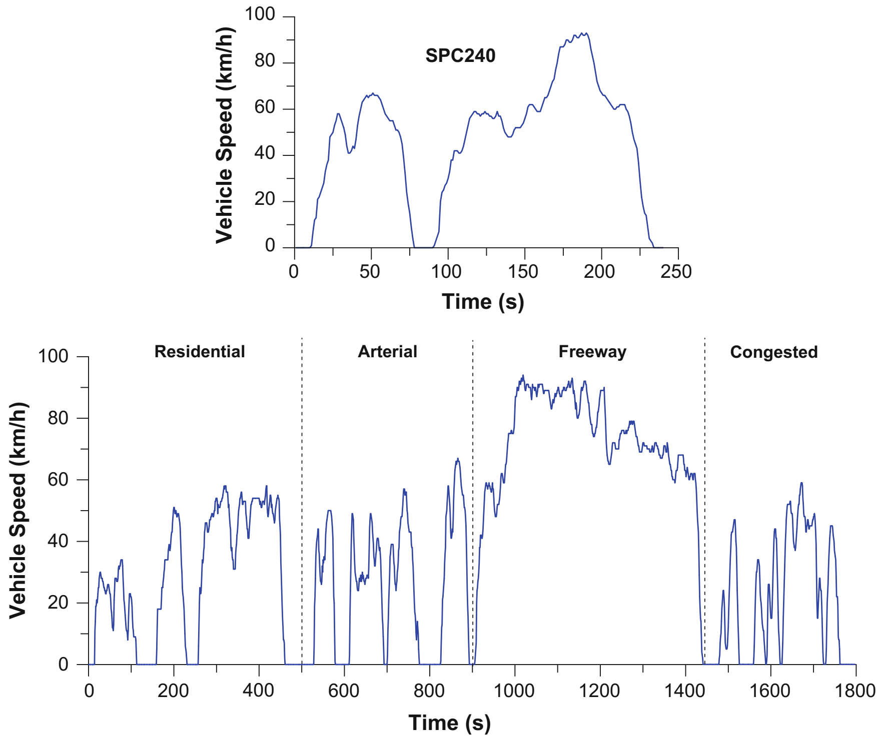

Fig. 2.51 The Australian CUEDC (composite urban emissions drive cycle), and inspection and maintenance SPC240 for gasoline vehicles

From the basic driving modes, 35 descriptive statistics were derived for each of the four road flow categories. Correlation analysis was conducted to identify individual 'trip segments', which had the highest correlation to the national average descriptive statistics for each road flow category. The corresponding composite cycle developed by the Transport Systems Centre of the University of South Australia is demonstrated in Fig. 2.51 [86].

Table 2.19 provides some technical specifications of the gasoline cycle and its intermediate phases. Notice in Table 2.19 the rather low maximum speed and the high maximum acceleration.

A shorter, 240-s version, titled SPC240 was also developed for inspection and maintenance purposes of gasoline cars, based on the last 2 min of the arterial phase and the first 2 min of the freeway phase (cf. the U.S. IM240 cycle in Sect. 2.2.7); this cycle is demonstrated in the upper sub-diagram of Fig. 2.51.

2.5 Worldwide—WLTC

Most manufacturers produce vehicles on a global scale or at least for several regions in the world. Nonetheless, since vehicle types and models tend to cater to local habits and living conditions, the vehicles produced worldwide are not identical. The compliance with different emission standards in each region, however, creates high burdens from an administrative and vehicle design point of view. Manufacturers, therefore, have a strong interest in harmonizing performance requirements and emission type approval procedures as much as possible on a global scale. Regulators have also an interest in global harmonization since it offers more efficient development and adaptation to technical progress, and facilitates the exchange of information between authorities. Harmonization doesn't necessarily mean having identical requirements/emission targets (as already mentioned, the needs of different countries vary, often by a lot). It does mean, however, that unnecessary differences can be eliminated, hence regulations can be brought closer. In this way, where possible and practical, a single vehicle specification can be built to satisfy all requirements instead of being country-specific. Common specifications of vehicle parts can reduce the cost of development and production and the retail price of vehicles. They can also make approving procedures easier, make the market larger, and give the consumers a wider range of choice. As a consequence, at its November 2007 session, the World Forum for Harmonization of Vehicle Regulations (WP.29) of the UNECE decided to set up an informal group under the working party on pollution and energy (GRPE) to prepare a road map for the development of the Worldwide harmonized Light vehicle Test Procedure (WLTP), with the aim to harmonize emission related test procedures for light-duty vehicles to the extent this was possible. The project was divided into 3 phases, as follows [87–89]:

- Phase 1 (2009–2014): Development of the worldwide harmonized light-duty driving cycle (WLTC) to reflect the actual driving conditions in real-world, as well as the associated test procedure for the measurement of pollutants, CO_2, fuel and energy consumption.

- Phase 2 (2014–2018): Low-temperature/high-altitude test procedure, durability, in-service conformity, technical requirements for on-board diagnostics (OBD), mobile air-conditioning system energy efficiency, off-cycle/real driving emissions.
- Phase 3 (2018–…): Emission limit values and OBD threshold limits, definition of reference fuels, comparison with regional requirements.

Work on the new cycle started in September 2009, the collection of driving data was launched in 2010, and the first version of the cycle was proposed by mid-2011; this was revised a number of times to take into consideration technical issues such as drivability and better representativeness of driving conditions after a first validation. The development of the WLTP was closely followed by various stakeholders (governments, industry, non-governmental organizations), as evidenced by the increased number of attendees to the UN GRPE's meetings [90]. In 2010, the U.S. EPA decided to withdraw its active participation in the WLTP, given the resource-intensive preparations for the 2012–2016 and 2017–2025 U.S. greenhouse gas standards. After the United States withdrew, the process was driven forward by the EU, South Korea, India and Japan [90].

For constructing the WLTC, driving data from all participating countries was collected and weighted according to the relative contribution of regions to the globally driven mileage and data collected for the WLTP purpose. The in-use data collected for the cycle development consisted of:

– 462,000 km from Europe (the involved countries were Belgium, France, Germany, Italy, Poland, Slovenia, Spain, Sweden, Switzerland and the UK);
– 56,000 km from India;
– 53,000 from Japan;
– 34,000 from South Korea; and
– 160,000 km from the U.S. (in total, 766,000 km).

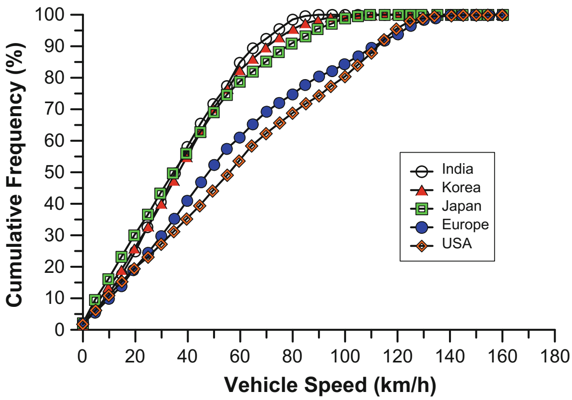

Fig. 2.52 Vehicle speed cumulative frequency distribution from the various regions in the WLTP database (data from [91])

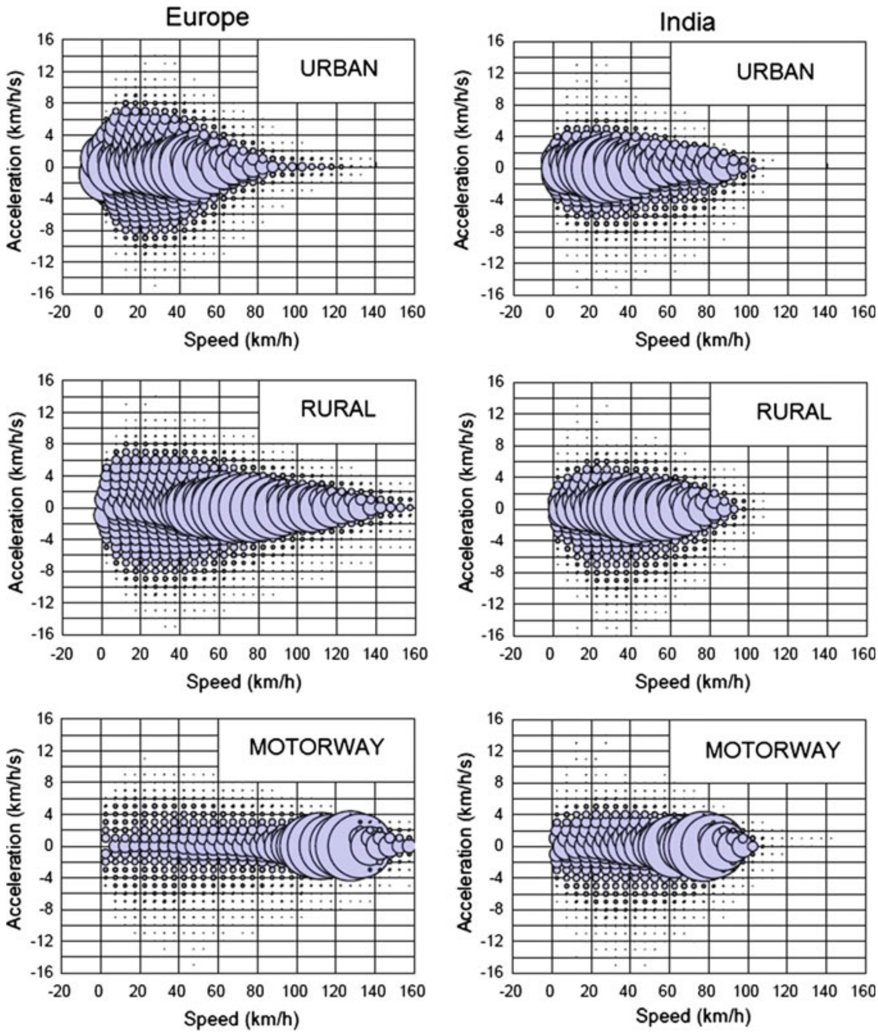

Fig. 2.53 Differences in the speed/acceleration distribution between the European (*left column*) and Indian (*right column*) data in the WLTP database [88]

394 vehicles of various engine capacities were used, with power to mass ratio ranging from 9 to127 kW/t, produced by a variety of manufacturers. The major part of this data corresponded to passenger car data but LD vans and mini-buses were represented in the database as well [88–90]. Data was collected from a combination of instrumented vehicles (Europe, India and the U.S.), 'instructed' drivers (Japan, Korea, India and the U.S.), and pure chase car (U.S. only).

Consistent with the common cycle construction practice, the data (after appropriately 'thinned' and smoothed) was separated into micro-trips and idling phases.

Unlike previous cycle development approaches, however, which were based on a road categorization, i.e., urban, rural and motorway, a different approach was followed during the WLTC development owing to the very different road categorization and speed limits existing throughout the world. The latter holds in particular true when comparing the European (or the U.S.) and Asian databases, as Figs. 2.52 and 2.53 confirm; the only exception being the urban road type, where a fairly good degree of similarity was found to exist worldwide. For the WLTC construction, the short-trips were binned according to their maximum speed, initially into three phases, i.e., low, medium and high. Subsequently, the high-speed phase was split into two segments: one high-speed phase with maximum speed representative of driving in Asia, and one extra high speed, more typical of motorway driving in Europe and the United States. These four speed-related phases are

- Low (up to 60 km/h), consisting of 97.1 % urban mileage;
- Medium or middle (between 60 and 80 km/h), consisting of 80.7 % urban and 19.2 % rural mileage;
- High (80–110 km/h), comprising 28.3 % urban and 71.5 % rural; and
- Extra high (>110 km/h), consisting of 55 % rural, 32.9 % motorway and 12 % urban mileage [87, 91, 92].

Table 2.20 Technical specifications of the regional databases [88]

	Japan	Europe	USA	S. Korea	India	Unified
Relative positive acceleration (m/s^2)						
Low	0.177	0.200	0.245	0.192	0.134	0.192
Medium	0.142	0.176	0.225	0.174	0.142	0.188
High	0.117	0.144	0.164	0.139	0.162	0.156
Extra high	0.086	0.114	0.103	0.155	–	0.108
Average speed (km/h)						
Low	19.8	20.0	18.8	17.2	21.1	19.8
Medium	40.1	39.9	37.0	34.1	39.5	38.4
High	62.9	55.6	59.7	53.9	56.1	58.0
Extra high	86.2	83.1	90.1	67.6	–	86.8
Average idle duration (s)						
Low	26.5	15.6	24.9	29.2	23.1	21.9
Medium	25.6	16.6	22.3	39.8	24.6	22.4
High	21.5	18.4	20.1	34.2	46.2	22.8
Extra high	15.5	17.1	12.2	22.1	–	14.5
Average short-trip duration (s)						
Low	66	68	63	64	148	84
Medium	161	221	125	201	642	238
High	458	473	284	691	1157	446
Extra high	1158	1082	601	1621	–	824

The disadvantage of this procedure (i.e., speed-related rather than road category-related segments) is that the phases consist of contributions from different road categories as detailed above. The threshold vehicle speeds between the various phases were chosen after comparative study of different candidate thresholds [88]. Table 2.20 presents data from the regional databases and the unified one regarding some important technical specifications for each speed segment considered.

The short-trips for the WLTC had to be selected from the unified database. The selection criteria were based on the concept that the selected short-trips must provide similar distributions of speed, acceleration, etc. to those of the unified database. Given the large number of different/possible short-trip combinations, several selection criteria (average vehicle speed, acceleration duration ratio, deceleration duration ratio) were applied. This selection was necessary to reduce the number of possible combinations and to keep computation time to a reasonable limit. The combination of the short-trips with the smallest chi-squared value was selected for the WLTC driving cycle construction [88].

The drivability of the WLTC was assessed extensively during the development process. In particular, specific cycle versions for certain vehicles with limited driving capabilities due to low power to mass ratio or limited maximum vehicle speed were introduced. As a result, three classes of the cycle were developed with respect to the vehicle power to (unladen) mass ratio PMR as follows (duration of each intermediate segment is fixed between the classes) [87, 88]:

- Within WLTC Class 3 (PMR > 34 kW/t), there are two versions of the cycle: version 3-1 (or 3a) for vehicles with maximum speed less than 120 km/h and version 3-2 (or 3b) applicable to vehicles with a maximum speed higher than 120 km/h. At the option of the country, the extra-high phase may be excluded, e.g., in India or China. Class 3-1 was developed in order to account for the special vehicle class of k-cars in Japan [91].
- WLTC Class 2 (22 kW/t < PMR $\leq$ 34 kW/t) is designed for lower powered vehicles; it has four speed phases like the WLTC Class 3 but with softer accelerations and top speeds in each phase. At the option of the country, the extra high phase may be excluded in this case too.
- WLTC Class 1 (PMR $\leq$ 22 kW/t) is to be applied to vehicles with the lowest PMR, and is designed to have only the low and medium-speed phases. The complete test cycle for type approval includes phases low, medium and again low.

For off-vehicle charging HEVs and pure electric vehicles (PEVs), the applicable cycle includes phases low and medium of Class 3 (‘WLTC city’).

Maximum duration of the cycle is 1800 s, similar to the earlier developed worldwide heavy-duty vehicles WTVC (Sect. 4.5.1) and motorcycles WMTC (Sect. 3.5). This cycle duration was believed to represent an acceptable compromise between statistical representativeness on the one hand and test feasibility in the laboratory on the other. The duration of each cycle segment was set in a way that reflected the mileage distribution among the phases, thus no weighting factors were

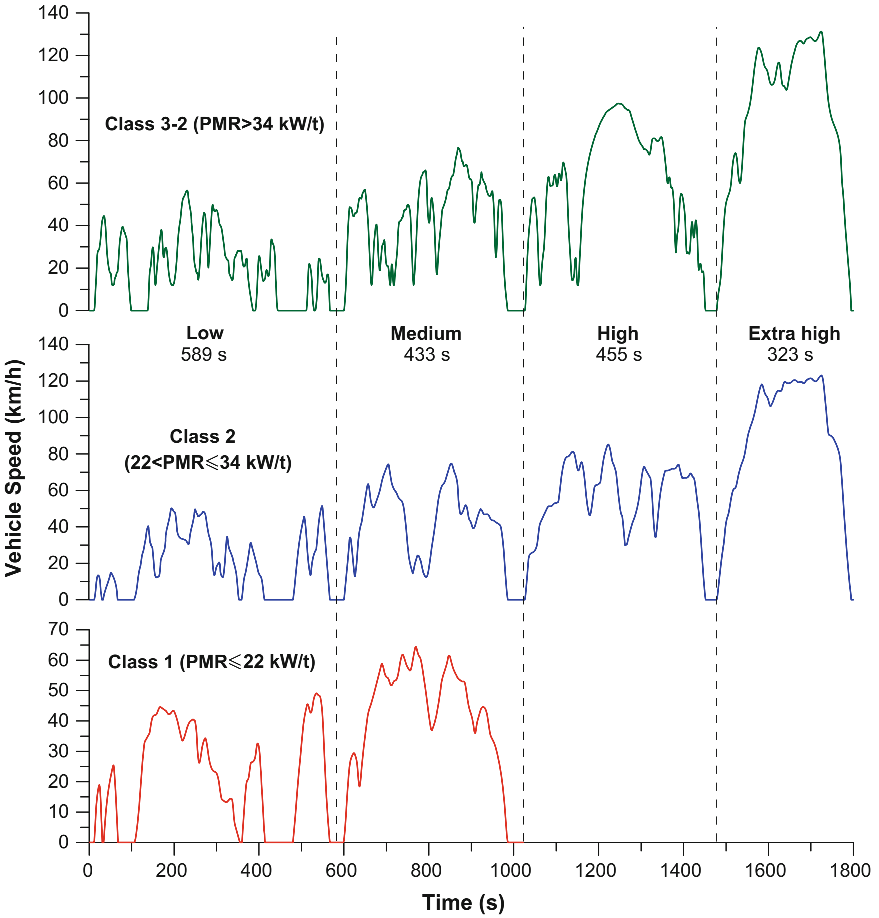

Fig. 2.54 Speed profile of the WLTC driving cycle; a downscaling procedure is applied to improve drivability for the cases of vehicles with PMR close to the borderlines between Class 2 and 3 or very low powered in Class 1, as detailed in [87]

necessary for the final result. Specifically, the low segment lasts 589 s (5 micro-trips and 6 stops), the medium 433 s (1 micro-trip, 2 stops), the high 455 s (1 micro-trip, 2 stops), and the extra high 323 s (1 micro-trip, 2 stops[12]). The final (2015) version of the WLTC suite of cycles is illustrated in Fig. 2.54, whereas Figs. 2.55 and 2.56 demonstrate the speed/acceleration distribution for Class 3-2.

Further, the corresponding UNECE Global Technical Regulation GTR No. 15 provides gear selection and shift point determination (the gear shift strategy

[12]The extra-high segment was developed based on a combination of different sub-segments, defined as take-off, cruise and slow-down.

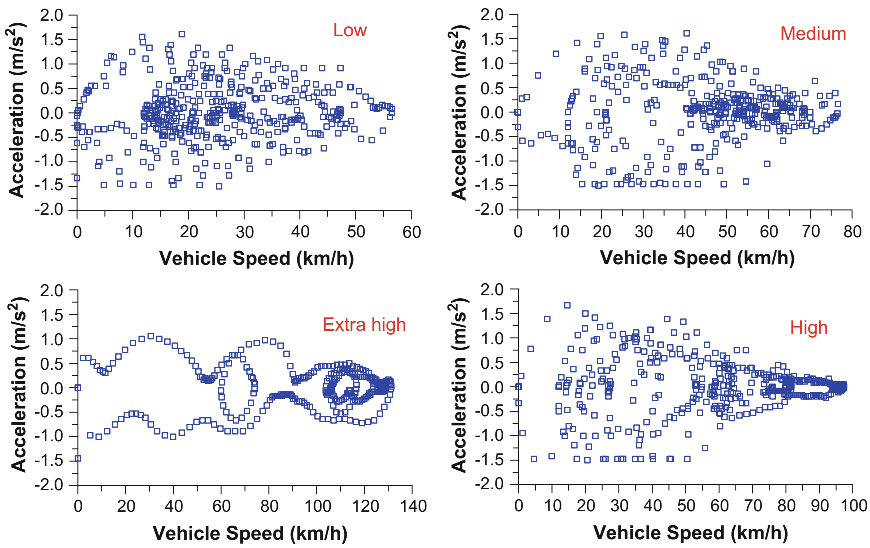

Fig. 2.55 Speed/acceleration distribution for the various segments of the WLTC Class 3-2

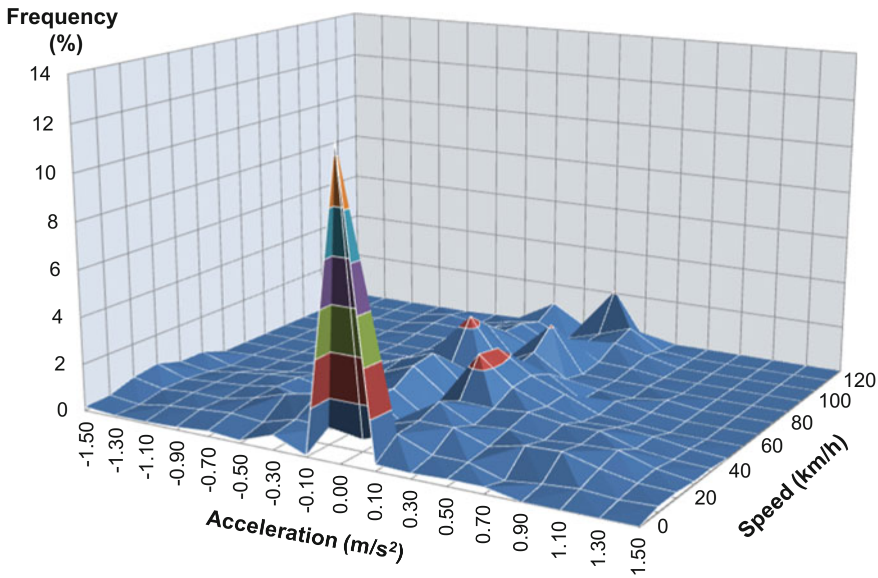

Fig. 2.56 3D speed/acceleration frequency distribution of the WLTC Class 3-2 cycle

being vehicle dependent and not fixed as is the case with the European NEDC), examples of reference fuels, road-load and dynamometer setting, test equipment such as analyzers and their calibrations, and test procedure and conditions to be

Table 2.21 Summary of technical specifications of the WLTC classes

Class	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
1	1022	8098	64.4	28.5	0.81	18.8	0.083
2	1800	22,649	123.1	45.3	0.97	12.8	0.119
3-1	1800	23,194	131.3	46.4	1.67	12.6	0.154
3-2	1800	23,266	131.3	46.5	1.67	12.6	0.159

Table 2.22 Summary of technical specifications of the WLTC Class 3-2

Segment	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
Low	589	3094	56.5	18.9	1.61	24.4	0.219
Medium	433	4756	76.6	39.5	1.61	10.9	0.206
High	455	7162	97.4	56.7	1.67	6.4	0.138
Extra high	323	8254	131.3	92.0	1.06	1.9	0.127

followed. These also cover vehicles with periodic regeneration, as well as hybrid-electric and pure electric vehicles [87].

Table 2.21 summarizes the main technical specifications of all WLTC classes, with Table 2.22 focusing on Class 3-2, providing data on all four segments

Lastly, development of various engine/vehicle properties, including CO_2 and engine-out NO_x during the WLTC is demonstrated in Fig. 2.57 for a gasoline-engined passenger car.

2.6 Other Countries

As mentioned earlier, the EU, the United States and Japan have been the pioneering regions in the world in developing emission standards and legislating the relevant test procedures for light (and heavy) duty vehicles. Not surprisingly, most of the other countries in the world follow either the European—owing to the close inter-relation with UNECE regulations—or the U.S. or Japanese legislation, often with a delay of some years. More specifically [3, 93–95]:

- Argentina follows the European emission regulations and test procedures;
- Brazil: the official emissions program 'PROCONVE' was published in May 1988. The U.S. FTP-75 cycle is employed (referred to as NBR6601);

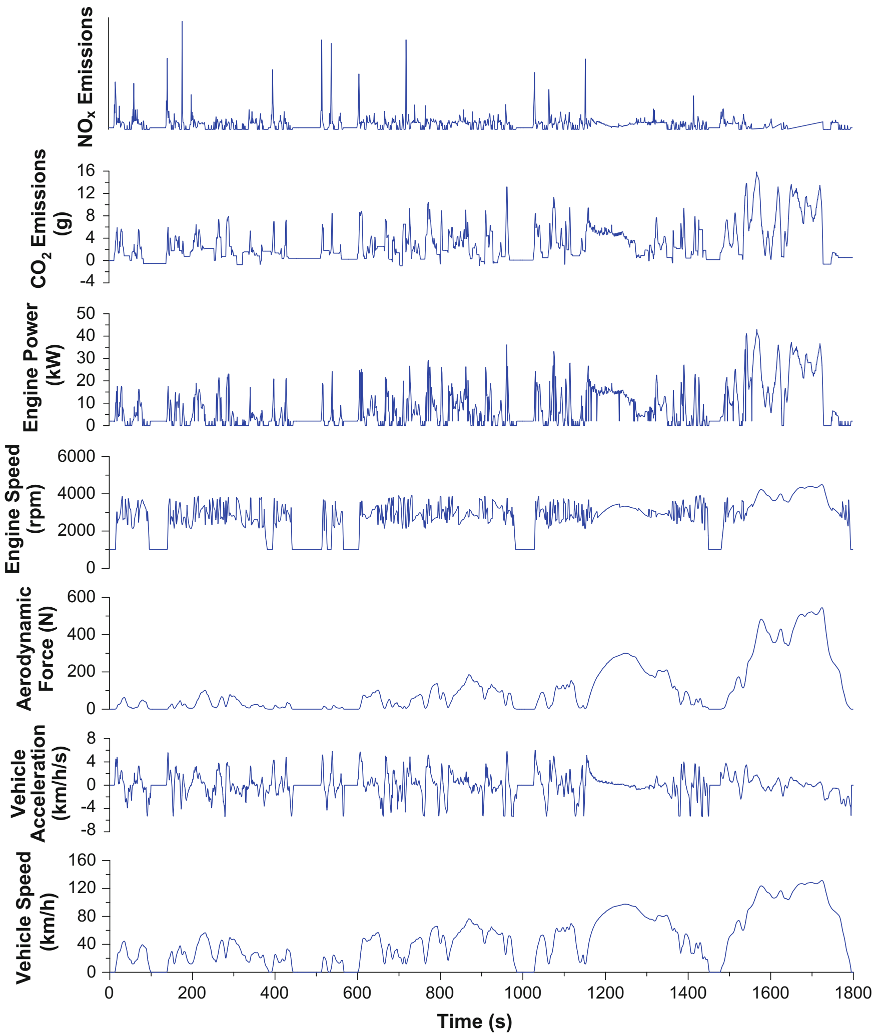

Fig. 2.57 Development of engine properties and emissions from a gasoline passenger car during the WLTC Class 3-2

- Canada: in January 2003, Environment Canada issued regulations for new on-road vehicle emissions, harmonizing its regulations with U.S. EPA standards from MY 2004 on;
- China follows the European regulations and cycles;
- Hong Kong: at the discretion of the manufacturer (EU, U.S. and Japanese tests are accepted);

- India follows the European regulations (the low-powered version of the NEDC was used for certification up to 2010 termed MIDC—modified Indian driving cycle [96]);
- Mexico: Standards that apply to model year 2004 and later are based on U.S. Tier 1 and Tier 2 standards and Euro 3 and Euro 4 limits;
- Russia has adopted the European standards;
- South Korea: the U.S. FTP-75 cycle has been in use for light-duty gasoline and diesel-powered vehicles; for small-sized diesel-engined vehicles, the ECE +EUDC has been in use since 2005;
- Taiwan: the U.S. FTP-75 cycle is employed for emissions certification; FTP-75 or NEDC for fuel consumption from 2011.
- Turkey follows the European legislation.

Apart from the schedules discussed in the previous sections, many more non-legislated cycles have been developed in many areas of the world (e.g., Australia and Asia), aiming at simulating local traffic conditions in specific cities, e.g., Melbourne, Perth and Sydney in Australia, Hong Kong, Pune (India), Bangkok etc., often for the purposes of emissions/fuel consumption modeling studies. For many of these cycles, a representative 'best' route was initially selected that was used for the collection of the driving data.

2.7 Comparative Data

Figure 2.58 summarizes the primary test cycles used for certification purposes in Europe, the United States and Japan over the years, whereas Fig. 2.59 illustrates the main modal cycles that have been at some point legislated or employed for the testing of passenger cars.

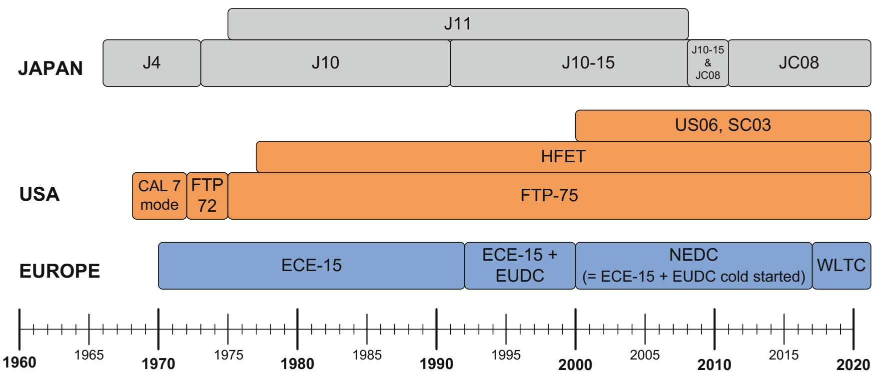

Fig. 2.58 Timeline of test cycles employed for (tailpipe) emission certification purposes in Europe, the U.S. (federal) and Japan

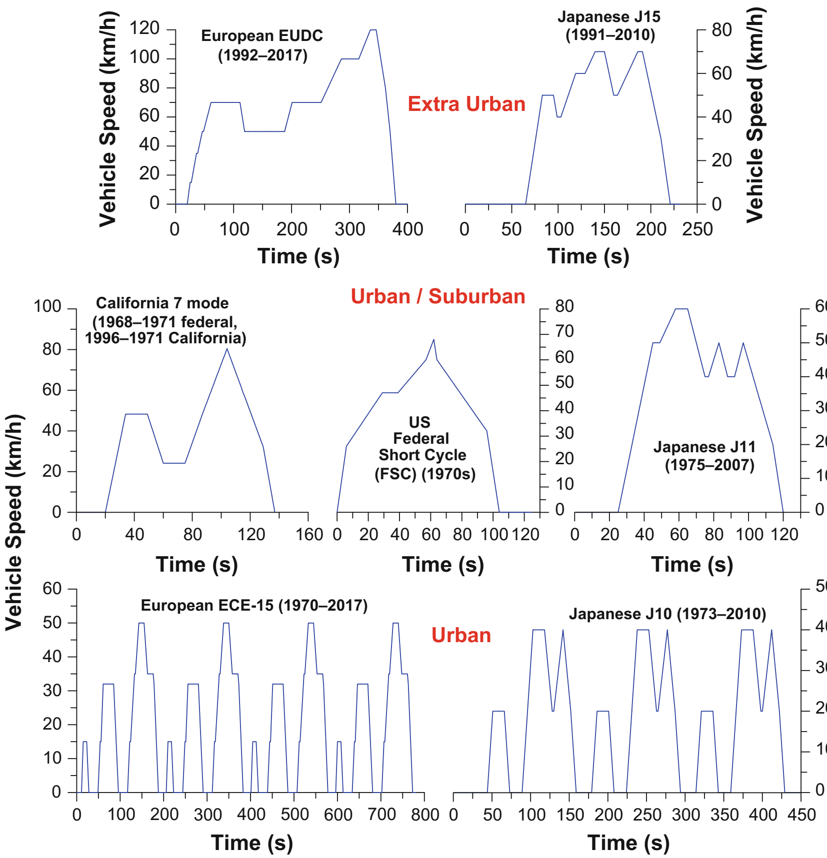

Fig. 2.59 Main modal cycles used for light-duty vehicles in the world together with application periods

The two-page Fig. 2.60 compares basic technical specifications of some of the most important (legislated) cycles mentioned previously. The following remarks can be made (although some of them on a purely statistical basis since not all the cycles depicted in Fig. 2.60 are directly comparable to each other):

– Both the U.S. FTP-75 and the WLTC Class 2 and 3 have the longest cycle duration (31 and 30 min respectively), followed by the California LA-92 (approx. 29 min for the whole, three-bag run). This also leads to these cycles exhibiting the longest distance traveled, over 16 km.
– On the other hand, the US06, being of special-supplemental to the FTP-75 purpose, as well as the NYCC, have the shortest duration (10 min). Owing to the much higher speeds involved and shorter idling period, the distance covered during the US06 is much longer than the urban NYCC.

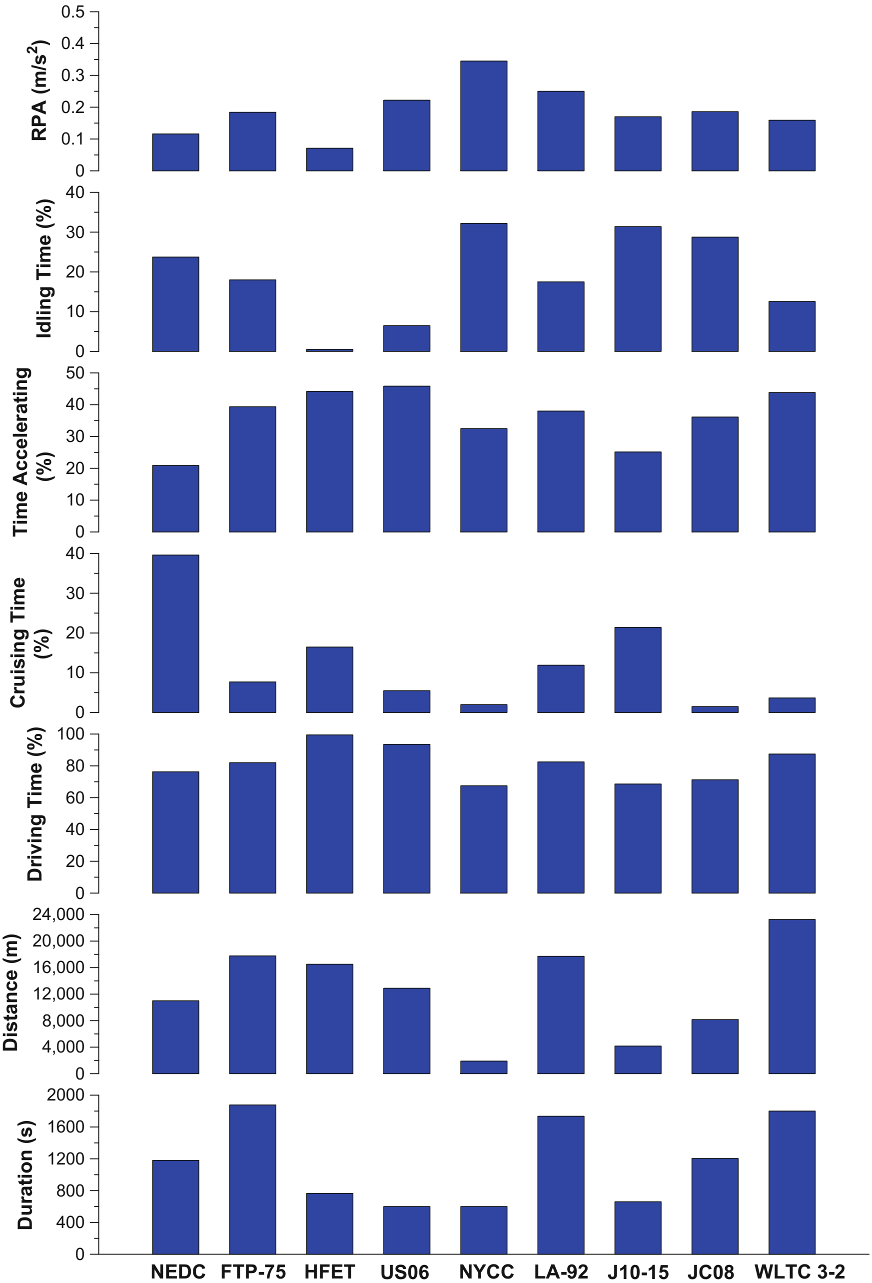

Fig. 2.60 Comparison of some important technical specifications between various light-duty chassis-dynamometer cycles

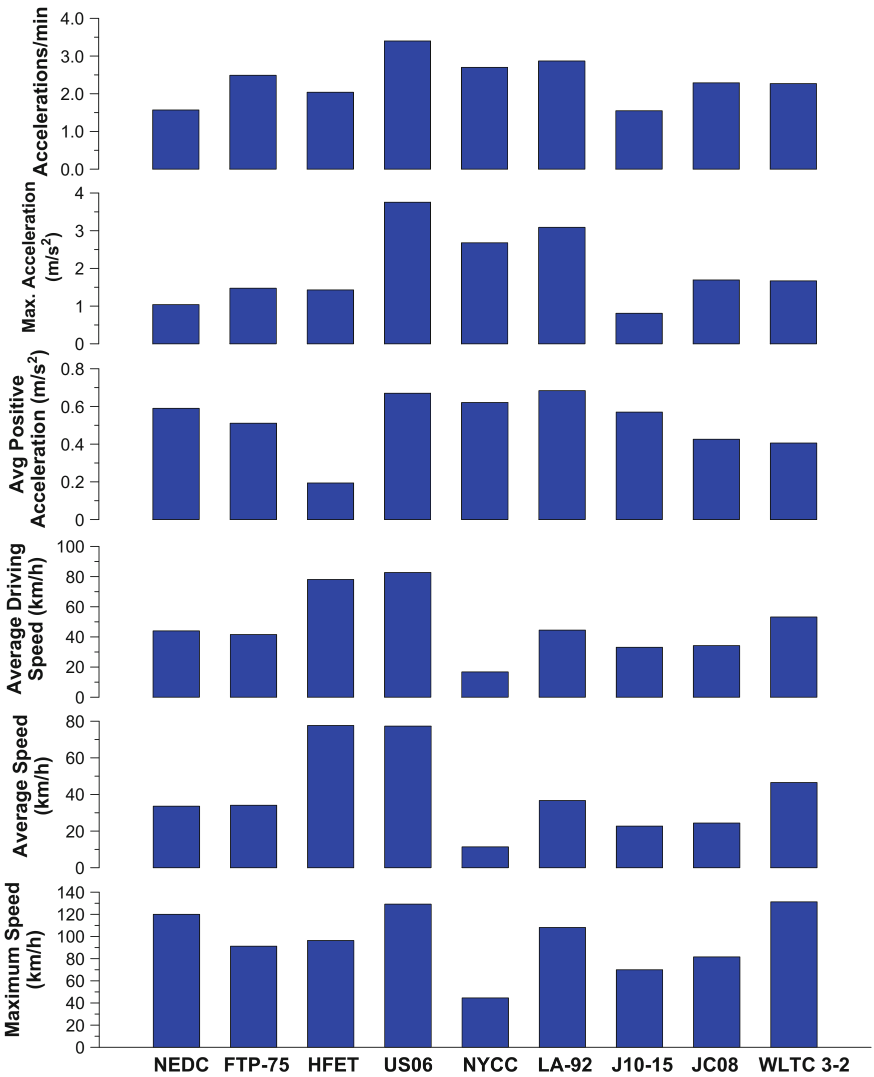

Fig. 2.60 (continued)

- The NYCC is the most extreme cycle. It covers the shortest distance (lower than 2 km), has the lowest average speed (approx. 11 km/h) and the longest idling period (32 %)—all indicative of cycles simulating exclusively congested urban driving.
- Both Japanese cycles, the earlier J10-15 and the subsequent JC08, exhibit idling values of more than 30 %, indicative of the heavily congested traffic conditions in a big Japanese city.

- The Japanese cycles have also rather low maximum, average and driving speeds, in contrast to the European NEDC and the WLTC, as driving habits are much different in Japan compared to Europe.
- In contrast to the NYCC, the US06 and HFET manifest the highest values of driving time (hence shortest idling period), of time spent accelerating, as well as the highest values of average vehicle speed; this is not surprising since both cycles simulate highway driving. The third ranking cycle in this regard is the WLTC 3-2, closely followed by the California LA-92.
- Oddly, the European NEDC is characterized by a very long cruising period (39 %), not compatible with the daily driving experience. It also shows the lowest acceleration time and second lowest maximum acceleration (after the Japanese J10-15).
- On the contrary, the NYCC, US06 and California LA-92 have the maximum number of accelerations/min and also the maximum acceleration and average acceleration; characteristics that strongly affect the amount of (engine-out) emissions particularly from turbocharged vehicles [14].
- RPA is highest for the mostly transient, exclusively urban NYCC, and lowest for the exclusively motorway HFET. Particularly low is the value for the NEDC. It is somewhat surprising that the 'stylized' J10-15 exhibits a RPA value of 0.17 (compared to 0.116 for the NEDC). This is due to the Japanese cycle's more transient profile.

Since many of the cycles presented and compared earlier are either 'special purpose' (HFET, NYCC) or even non-valid any more (J10-15), in the next paragraphs the focus will be on the four 'primary' light-duty cycles in the world, namely the European NEDC, the U.S. FTP-75, the Japanese JC08 and the soon to be implemented WLTC (Class 3-2), comparing some of their specifications and pinpointing their differences and shortcomings; their main technical specifications have been summarized in Table 2.23.

Table 2.23 Comparison of the technical specifications between the NEDC, FTP-75, JC08 and WLTC Class 3-2

Cycle	Test run	Duration (s)	Distance (m)	Maximum speed (km/h)	Average speed (km/h)	Maximum accel. (m/s^2)	Idling time (%)	RPA (m/s^2)
NEDC	Cold	1180	11,000	120.0	33.6	1.04	23.7	0.116
FTP-75	Cold + hot phase	1877	17,769	91.2	34.1	1.48	18.0	0.184
JC08	Cold run + hot run	1204	8159	81.6	24.4	1.69	28.7	0.186
WLTC	Cold	1800	23,266	131.3	46.5	1.67	12.6	0.159

Each of the four driving cycles has advantages and drawbacks. The NEDC is quite simple to drive and thus easily repeatable. However, as already argued, it does not account for real driving behavior in actual traffic, containing many constant-speed and constant-acceleration segments. In fact, from several observations it has been shown that in Europe the gap between fuel consumption experienced by the vehicle users and that measured at type approval is higher compared to other areas of the world, as already discussed in Sect. 2.1.1. Its overall simplistic pattern and the exact gear-shift schedule make it easy for the manufacturers to implement cycle-beating techniques. Moreover, since it is only run once, cold started, its short distance might over-emphasize cold-starting emission effects. Oddly for its outdated structure, the encountered speeds are relatively high, at least compared to its Japanese and U.S. counterparts.

The JC08 is a truly transient cycle but the focus is to a large extent on congested-city traffic conditions. The idle period is long, the vehicle speeds relatively low, and the motorway part rather underestimated. This cycle exhibits the longest single stop phase (76 s, followed by the WLTC with 66 s) but has the highest RPA value, in part owing to the short distance covered and the small motorway segment. The cycle is run both cold and hot, with 75–25 % weighting factors.

The FTP-75 has a real transient pattern and covers a relatively wide range of driving conditions, albeit based on data from vehicles in the late 60s. It is run cold but also incorporates a hot-started segment after a 10-min engine shut-down. It is certainly not complete, in terms of both achieved vehicle speeds and accelerations. Oddly, its limited-duration high-speed part is at the beginning, a fact that influences decisively catalyst operation. As a result, it cannot be considered fully representative, hence it is supplemented in the United States by three additional cycles that address its shortcomings, the HFET, US06 and SC03. Collectively, these four cycles constitute a very good mix of daily driving activity, better than that from the NEDC, JC08 and WLTC, see for example Fig. 2.28.

The most recent WLTC was developed with the ambitious goal to form a universally accepted and applicable test cycle. Its long duration allows for simulation of all possible driving conditions, and has acceptable harshness. However, as the data in Table 2.23 suggests, the maximum speed of 131 km/h might not be considered high enough for the majority of today's passenger cars in Europe (recall that the motorway part of the NEDC reaches 120 km/h, and this is a cycle originally developed in the late 80s), whereas the maximum acceleration of the order of 1.67 m/s^2 or 6 km/h/s suggests moderate (certainly not aggressive) driving behavior. Other features of the WLTC are its highest maximum and driving speed, its fewer stops (only 7 instead of 19 for the FTP-75 lasting at least 4 s), and the shortest total idling period compared to the other three cycles.

One of the most indicative features of the harshness of a cycle is the frequency and degree of the encountered accelerations. The upper two sub-diagrams of Fig. 2.61 present the frequency distribution during the cycles for various acceleration bins; further, Fig. 2.62 compares the acceleration profiles from the NEDC,

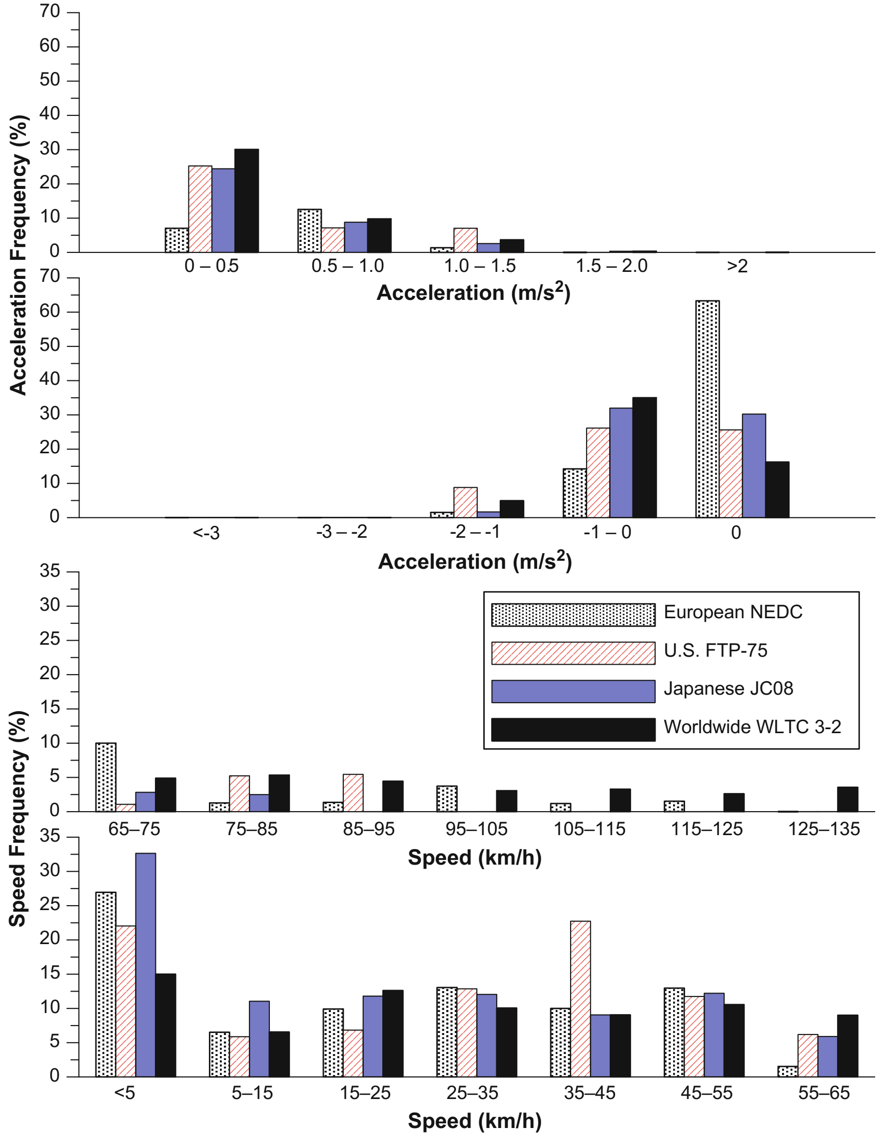

Fig. 2.61 Comparison of the speed and acceleration frequencies for the NEDC, FTP-75, JC08 and WLTC Class 3-2 (notice the increased frequency of the NEDC at zero acceleration owing to extended idling and cruise segments)

FTP-75, JC08 and the WLTC during the first 300 s (urban part). The most obvious remark is (again) the simplistic pattern of the accelerations during the NEDC (ECE-15 segment in particular). It is not only the rather low, by today's standards, maximum accelerations encountered, but also the fact that these accelerations are

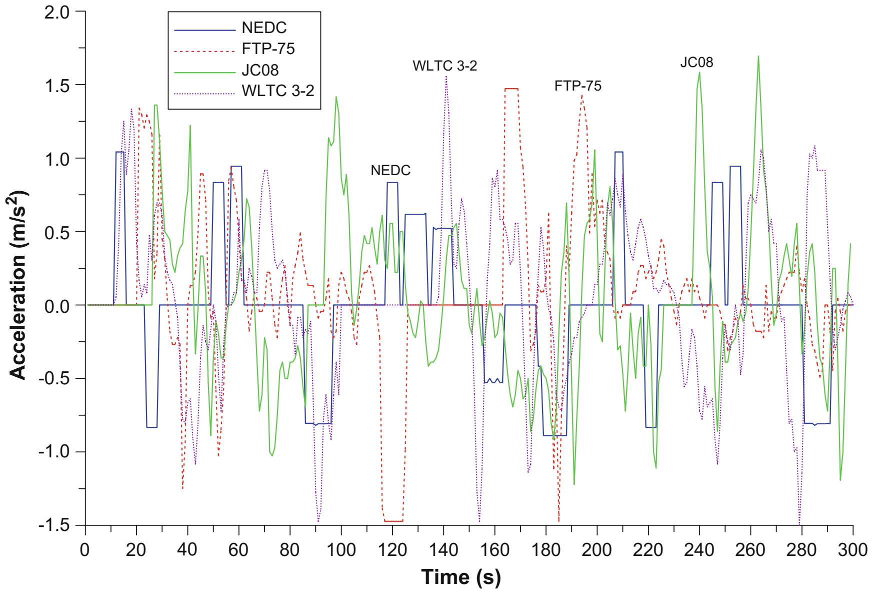

Fig. 2.62 Comparison of the acceleration profiles between various passenger cars driving cycles during the first 300 s of each cycle

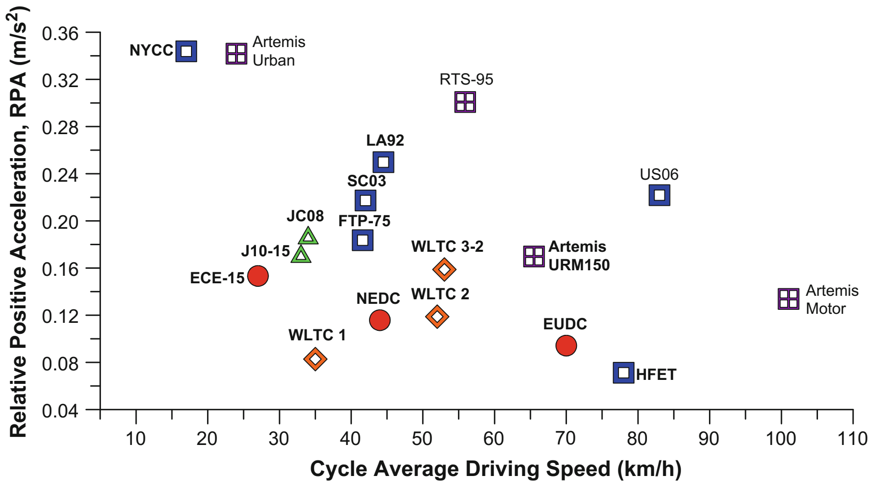

Fig. 2.63 RPA of various passenger cars cycles with respect to their average driving speed (the particularly harsh European non-legislated RTS-95 and the U.S. SFTP US06 seem to differentiate from the general trend of decreasing RPA with increasing driving speed)

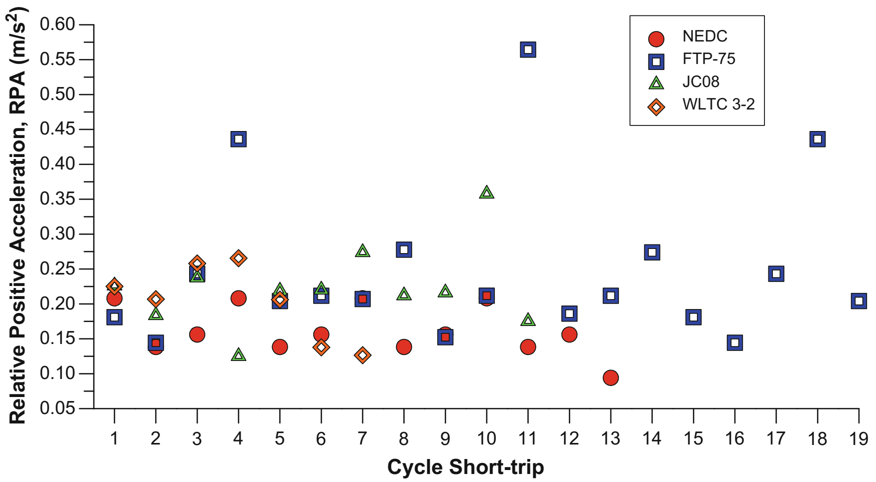

Fig. 2.64 RPA for each short-trip of the NEDC, FTP-75, JC08 and WLTC Class 3-2

for a considerable amount of time constant; for approximately two thirds during the NEDC, acceleration is zero (composed of 40 % cruising and 24 % idling time). Interestingly, the similarly structured Japanese J10-15 (Fig. 2.43) did not exhibit these non-realistic features.

The other three cycles possess a much more acceptable acceleration profile, with both higher values and greater frequency of accelerations, compatible with urban driving. Nonetheless, never is the highest acceleration encountered more than 1.7 m/s^2 (or 6.12 km/h/s, meaning that, at the minimum, 16 s are needed to reach 100 km/h from standstill). Interestingly, the maximum value of 1.7 m/s^2 is encountered in the Japanese cycle, which is, in general, more moderate, at least in terms of speeds, compared to the FTP-75 or the WLTC. From this point of view, even the newly developed WLTC does not seem to be a significant step towards acknowledging the hard driving behavior of many drivers or the increased capabilities of modern cars (cf. the acceleration profile of the FTP US06 in Fig. 2.24).

Figure 2.63 demonstrates RPA values for the four cycles, as well as from others discussed earlier, with respect to the average driving speed (excl. idling) during the cycle. The newly developed WLTC 3-2 lies almost at the same level as the U.S. FTP-75 and the Japanese JC08, being much more dynamic than the European NEDC. In general, urban cycles such as the NYCC or the Artemis Urban, comprising high frequency of hard accelerations from low speeds, are much more demanding, whereas highway cycles, such as the HFET or the EUDC, are usually less dynamic. RPA values for many important cycles are provided in the Appendix. An almost similar picture, as the one presented in Fig. 2.63 for the RPA, is drawn when the positive kinetic energy (Eq. 1.3) is calculated.

Figure 2.64 expands on the previous results by highlighting RPA values for each individual short-trip of the four cycles under comparison. It is the FTP-75 that

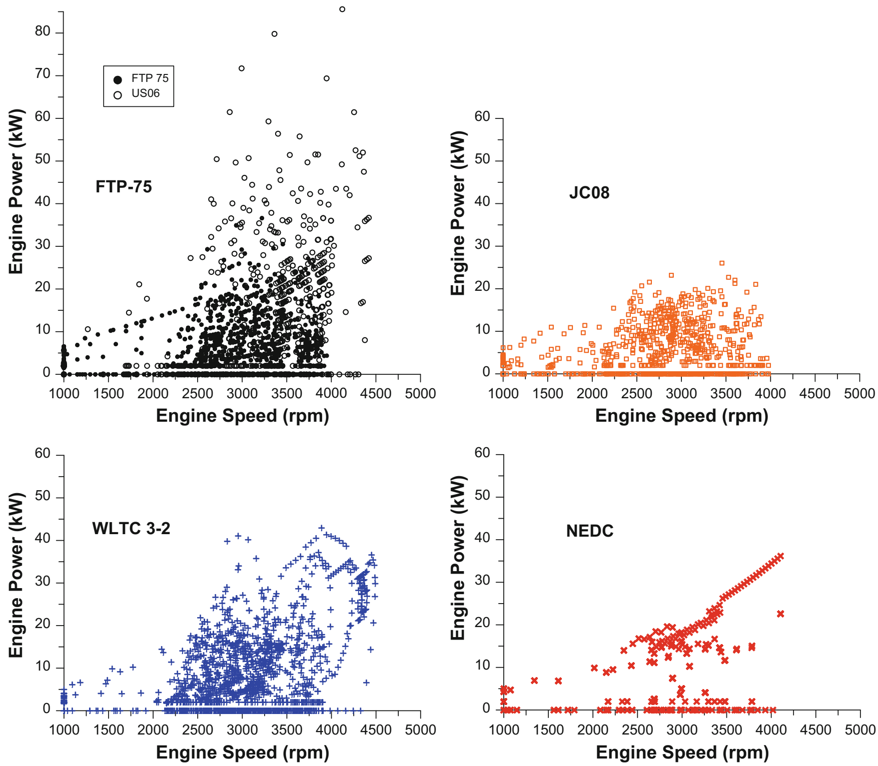

Fig. 2.65 Comparison of the engine speed/power distribution between the WLTC Class 3-2, FTP-75, NEDC and JC08 for a SI-engined passenger car; notice the considerable expansion in the U.S. cycle speed/power range when the tested points during the supplemental US06 are incorporated

differentiates now by a lot from the other three cycles, with three micro-trips having RPA higher than 0.40. Not surprisingly, all micro-trips of the (repetitive-type) NEDC are equally 'soft'.

Further comparative results between the NEDC, FTP-75, JC08 and the WLTC are presented in Fig. 2.65. For the analysis, the engine map coverage was calculated for all four cycles in terms of engine speed and power regarding a small-to-medium, SI-engined passenger car, applying the same gear-shift strategy in order for the results to be comparable. Predictably, the WLTC shows the broadest engine speed range (the JC08 the narrowest) as this correlates with the maximum cycle speed. Further, the WLTC proves to be the most demanding in terms of engine power. Notice the much narrower distribution of the modal NEDC compared with the broader ones from all transient cycles.

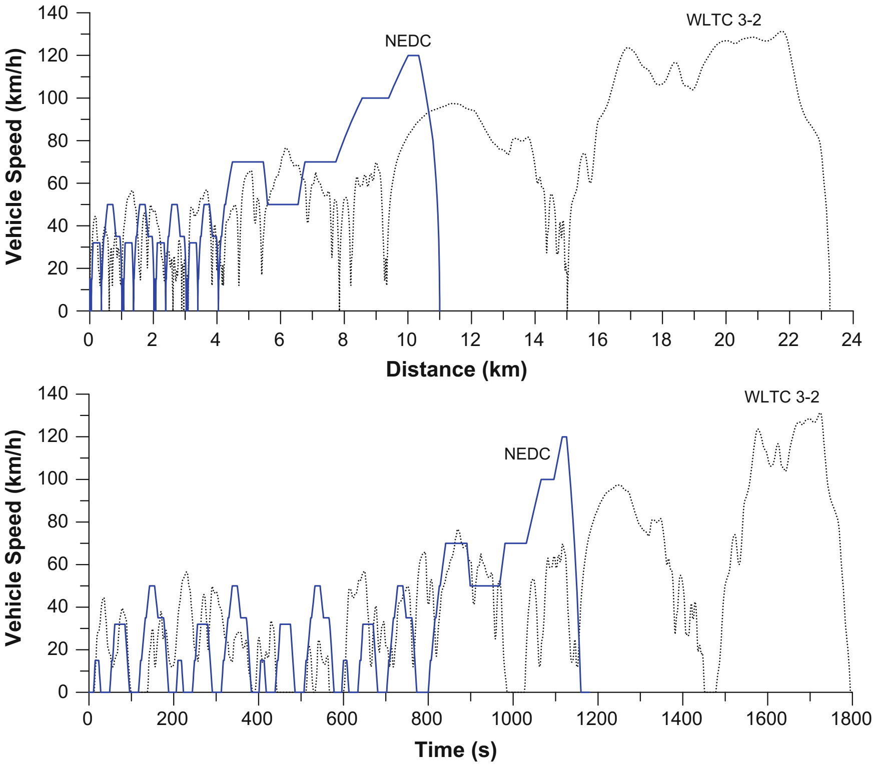

Fig. 2.66 Comparison of the speed versus time (*lower sub-diagram*) and speed versus traveled distance (*upper sub-diagram*) profile between the NEDC and the WLTC Class 3-2

Comparison between the WLTC and the NEDC

Since the beginning of the WLTP process, the European Union had already set a strong political objective by its own legislation (Regulations 443/2009/EC and 510/2011/EU) to modernize the employed test cycle by 2014. This became a major political motivation for the development of the WLTC test cycle and its time frame. The plan of the European Commission is to introduce the new test procedure together with the step ‘c’ of the Euro 6 standards. This means that starting on September 1, 2017, all new types of M_1 and N_1-class I vehicles should be tested according to the new procedure, with all M_1 and N_1-class I vehicles from September 1, 2018; for the N_1-class II and III vehicles applies the same with a delay of one year [92].

The following paragraphs provide a more detailed comparison between the NEDC and the WLTC. Initially, Fig. 2.66 compares the speed profiles between the NEDC and the WLTC Class 3-2; the latter is the class primarily suited to the majority of European cars. Further, Table 2.24 quantifies the differences between major technical specifications of the two cycles.

Table 2.24 Differences in major technical specifications between the WLTC 3-2 and the NEDC

Specification	NEDC	WLTC 3-2	Difference (from NEDC data) (%)	Effect
Duration (s)	1180	1800	+53	Lower influence of cold-start emissions
Distance (m)	11,000	23,266	+112	
Average speed (km/h)	33.6	46.5	+38	Most probably, better fuel efficiency
Maximum speed (km/h)	120	131.3	+9	More realistic of today's driving habits
Idling time (%)	23.7	12.6	−47	Lower influence of start-stop systems
Cruising (%)	39.6	3.7	−91	More transient, hence higher pollutant and CO_2 emissions
Transient time (%)	36.7	83.7	+128	
RPA (m/s^2)	0.116	0.159	+37	

The WLTC, compared to the NEDC, lasts longer and covers more than double distance. This is then reflected into cold-start emission effects being relatively lower. From a purely measurement/experimental point of view, the longer duration of the WLTC poses a burden on the test-bed capacity (e.g., sampling bags). Furthermore, the WLTC has higher maximum, average and driving speeds, and almost half the idling period (although the single stop with the longest duration is 66 s for the WLTC and only 27 for the NEDC). For approximately 84 % of the time during the WLTC the vehicle operates in transient conditions (accelerating or decelerating), in contrast to only 37 % during the NEDC. Cruising time is almost absent during the WLTC, and RPA is much higher. These are expected to result in higher engine-out pollutant emissions, and higher CO_2.

In Fig. 2.62 both cycles were compared with regard to vehicle acceleration; Fig. 2.67 expands these results by illustrating the respective acceleration rate (m/s^3) during the urban and motorway parts. Notice in this figure the continuous 'microscopic' changes in the WLTC profile compared to the more 'constant' development during the NEDC. Further, Fig. 2.68 compares the speed/acceleration distribution between the two cycles. The much broader speed/acceleration distribution of the WLTC confirms the considerable progress over the current NEDC in terms of simulated real-world driving behavior.

In addition, more realistic and demanding conditions of the WLTC compared to the NEDC result in increase in total energy demand when tested on a chassis dynamometer in accordance with the new WLTP requirements, such as new/higher test mass, road-load calculations, gearshift strategy, etc. For example, both kinetic energy and active resistance (rolling resistance and air drag) have been found significantly higher over the WLTC compared to the NEDC for the same gasoline vehicle [92]. Figure 2.69 regarding a diesel-engined, light-duty van and Fig. 2.70

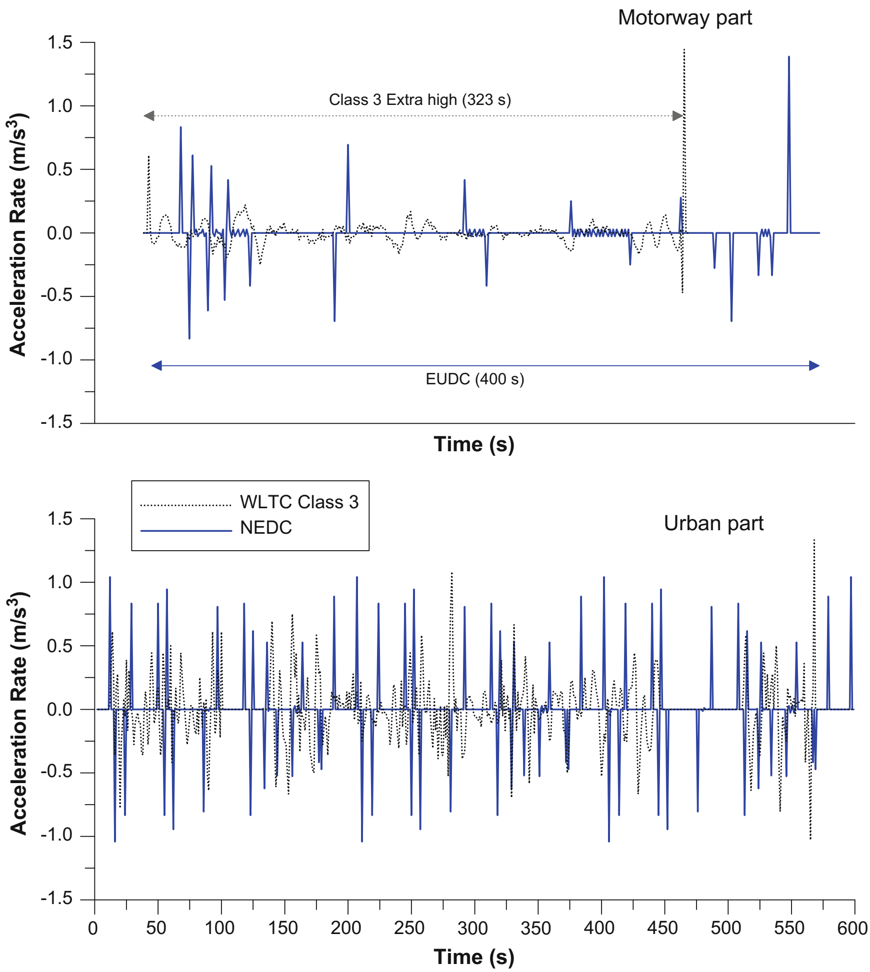

Fig. 2.67 Comparison of the rate of change of acceleration ('jerk') between the NEDC and the WLTC Class 3 for urban and motorway (extra high for the WLTC) driving segments

for a SI-engined passenger car support this argument by illustrating engine speed/power distribution during a whole run for both cycles. Higher values of power and speed as well as broader distribution are evidenced for the WLTC over its NEDC counterpart, a fact that is expected to affect accordingly the emitted pollutants [14]. Overall, 78 % of the operating points during the NEDC correspond to lower than 3000 rpm engine speed and 82 % to lower than 20 kW power in Fig. 2.69; for the WLTC, the respective numbers are much lower, 55 % and 68 %.

The transition from the NEDC to the WLTC in the EU will not be limited to the change of the test cycle; instead, several modifications in the test procedure will take place as well, namely

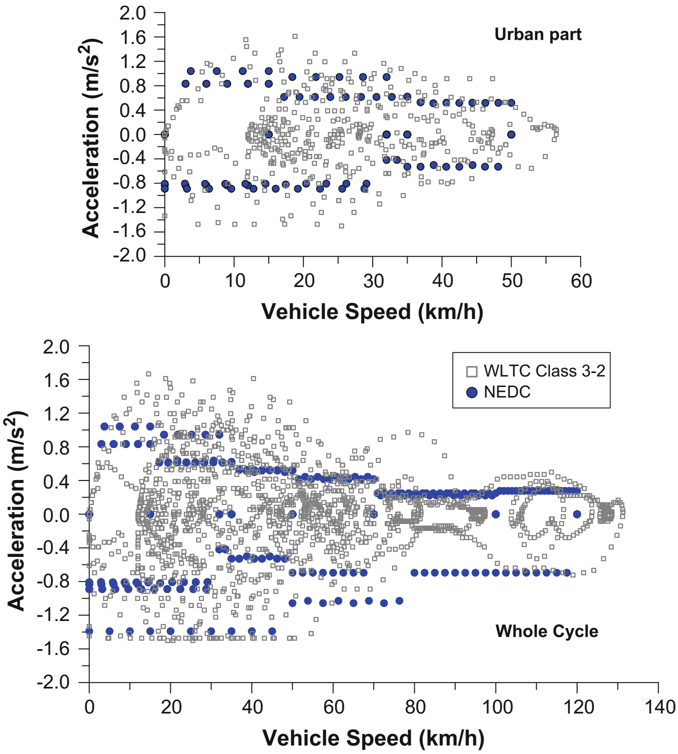

Fig. 2.68 Comparison of the speed/acceleration distribution between the NEDC and the WLTC Class 3-2 (the WLTC has 1800 operating points and the NEDC 1180)

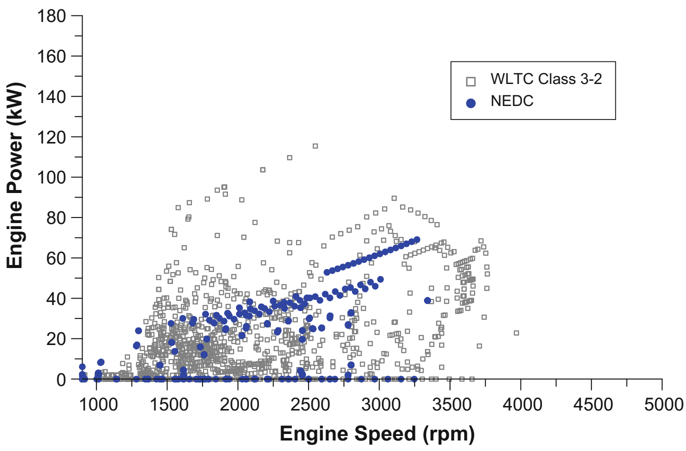

Fig. 2.69 Comparison of the engine speed/power distribution between the NEDC and the WLTC Class 3-2 for a diesel-engined van

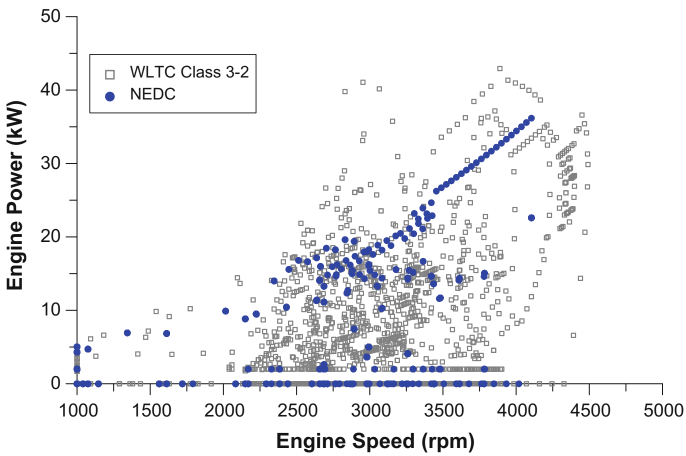

Fig. 2.70 Comparison of the engine speed/power distribution between the NEDC and the WLTC Class 3-2 for a gasoline passenger car

- more stringent requirements will be imposed in determining the representative road load for the dynamometer inertia;
- the test temperature will be somewhat lower, 23 °C instead of 20–30 °C, with a possibility to adopt 14 °C in Europe;
- instead of using discrete classes, the dynamometer inertia will correspond exactly to the vehicle reference mass;
- hybrid-electric and pure electric vehicles will be tested on dedicated to these vehicles procedures;
- one set of sampling bags for each phase of the cycle, with bag analysis conducted in parallel to the test run, etc. [23, 90].

With the introduction of the WLTP although the regulated pollutant emission limits will not be affected, the CO_2 targets (NEDC-based fleet-average value of 95 g/km for 2020–21) will, most probably, need to be adapted. The longer distance of the WLTC over the NEDC, its higher velocities and accelerations and its lower idle phase are significant parameters that will influence these new CO_2 limits (see also Table 2.24). Consequently, correlation parameters have to be determined in order to reflect any change in the regulatory test procedure for the measurement of specific CO_2 emissions referred to in Regulations 715/2007/EC and 692/2008/EC [90, 97]. As has been reported in [90], the impacts of cold start are lower on the WLTC (due to the longer duration) compared to the NEDC, the higher speeds and loads of the WLTC have the counter effect on engine efficiency, typically increasing with load, the new gearshift schedule on the WLTC can help reduce engine-speed (hence friction) effects, and the lower idle percentage on the WLTC might actually penalize enhanced systems such as start/stop. From the same analysis, it has been estimated that the NEDC-based CO_2 target for 2020 (95 g/km) might increase to 100 or even 102 g/km owing to the transition to the WLTP test procedure.

This increase is composed from: (a) 2 g/km due to the change of the certification driving cycle, (b) 3 g/km owing to changes in the definition of the vehicle's mass for the test, and (c) 2 g/km owing to lower test temperature (2 g/km might be added if the test temperature is further lowered to 14 °C).

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