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Review

State-of-the-Art of Establishing Test Procedures for Real Driving Gaseous Emissions from Light- and Heavy-Duty Vehicles

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Abstract: Air pollution caused by vehicle emissions has raised serious public health concerns. Vehicle emissions generally depend on many factors, such as the nature of the vehicle, driving style, traffic conditions, emission control technologies, and operational conditions. Concerns about the certification cycles used by various regulatory authorities are growing due to the difference in emission during certification procedure and Real Driving Emissions (RDE). Under laboratory conditions, certification tests are performed in a 'chassis dynamometer' for light-duty vehicles (LDVs) and an 'engine dynamometer' for heavy-duty vehicles (HDVs). As a result, the test drive cycles used to measure the automotive emissions do not correctly reflect the vehicle's real-world driving pattern. Consequently, the RDE regulation is being phased in to reduce the disparity between type approval and vehicle's real-world emissions. According to this review, different variables such as traffic signals, driving dynamics, congestions, altitude, ambient temperature, and so on have a major influence on actual driving pollution. Aside from that, cold-start and hot-start have been shown to have an effect on on-road pollution. Contrary to common opinion, new technology such as start-stop systems boost automotive emissions rather than decreasing them owing to unfavourable conditions from the point of view of exhaust emissions and exhaust after-treatment systems. In addition, the driving dynamics are not represented in the current laboratory-based test procedures. As a result, it is critical to establish an on-road testing protocol to obtain a true representation of vehicular emissions and reduce emissions to a standard level. The incorporation of RDE clauses into certification procedures would have a positive impact on global air quality.

Keywords: air pollution; real driving emission; driving cycles; portable emission measuring systems; air quality

1. Introduction

As the world progresses, technological development has resulted in the availability of machinery, which translated into the development of a machine-based industry, resulting in increased emissions. The imposed travel restrictions worldwide in 2020 due to the COVID-19 pandemic has resulted in a 6% reduction in energy demand compared to 2019 [1]. Despite the fact that the global energy-related CO_2 emissions declined by 5.8% in 2020, they still remained at 31.5 Gt, which contributed to CO_2 reaching its highest-ever average annual concentration in the atmosphere of 412.5 parts per million in 2020—around 50% higher than when the industrial revolution began [2]. While it would be ideal to have the latest data, at the time of publishing the report 'Emissions by sector' [3] (September 2020), the most recent comprehensive data set were available for 2016. The authors reported that the global greenhouse gas (GHG) emissions were 49.4 billion tonnes (Gtoe) of carbon dioxide equivalents (CO_2eq) at that time [3,4] (CO_2eq sums all of the warming impacts of the different greenhouse gases together. To calculate CO_2eq of non-CO_2 gases, their mass was multiplied by their 'global warming potential' (GWP). GWP measures the warming impacts of a gas compared to CO_2). They reported that the energy sector contributed almost 3/4th of the total GHG emissions (73.2%) [3]. Of this 73.2% emitted by the energy sector, the majority of contributors were the industry, transport and building sectors which consisted of 24.2, 16.2 and 17.5%, respectively (Figure 1). About 73.5% of transport sector emission is contributed by 'road transport', followed by 'aviation' and ''shipping' at 11.7 and 10.5%, respectively, as shown in Figure 1. A report claims that to achieve net-zero-emission by 2050, the world needs to maintain a drop in emissions of around 5% each year from now forth [5].

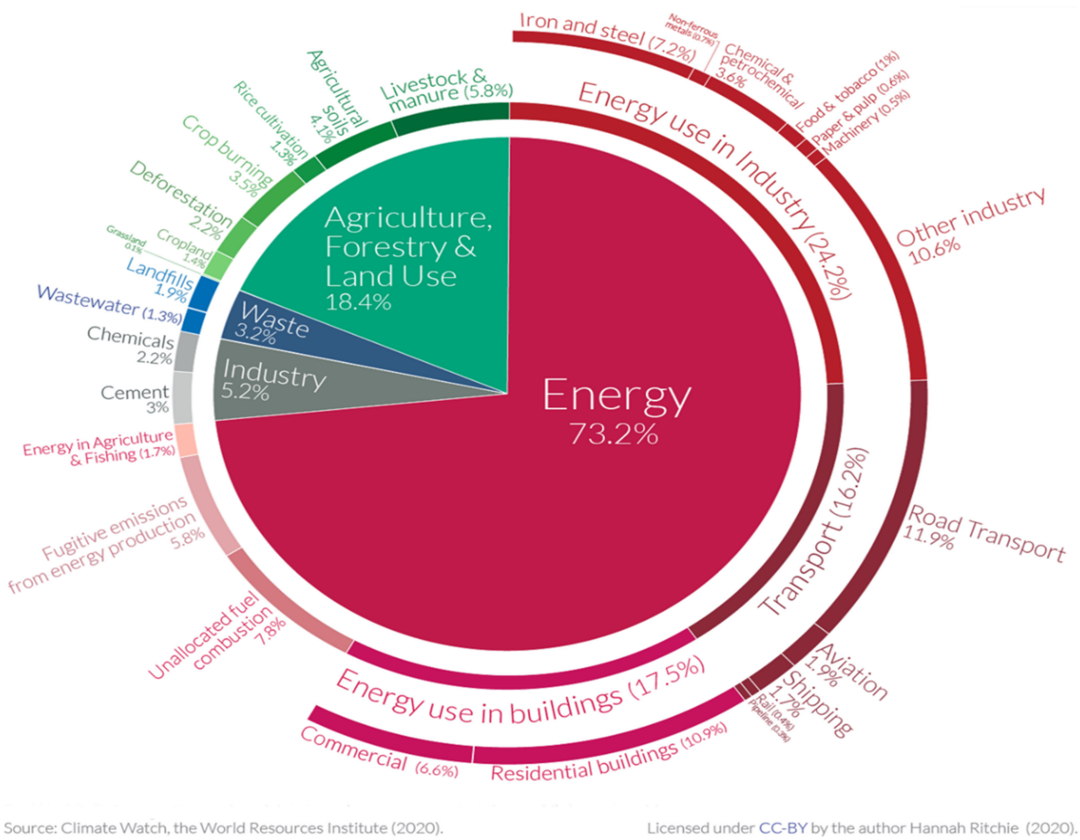

Figure 1. Global greenhouse gas emission by sector for 2016. Total greenhouse gas emissions were 49.4 billion tonnes CO_2 equivalent [3].

As of 16 March 2021, the total number of confirmed COVID-19 cases had surpassed 183 million, with the pandemic affecting more than 192 countries/regions [6]. COVID-19 has now resulted in the death of over 3,962,550 people [6]. More than a year into the pandemic, the countries worldwide are still struggling to combat the spread of COVID-19, which is hurting the economy. Thus, when the world returns to a new normal state, it will be hard to keep the energy demand low and reduce GHG emissions due to the sudden increase in social and economic activities. Decisive actions are needed to reduce transport emissions to achieve the zero-emission target. Thus, the vehicles that are used for everyday transport must follow the emission standards set by the regulatory body. Figure 2 shows the timeline of emission standards for passenger cars for the United States, Europe, China and Japan [7].

Figure 2. Timeline of emissions standards for passenger cars in different parts of the world [8].

There is ongoing concern about public health owing to air pollution caused by vehicle emissions. It is well-recognised that air pollution is a primary risk factor for chronic non-communicable diseases [9]. Pollutants carry microorganisms that are highly invasive to humans, affecting the immune system and making people more susceptible to pathogens [10]. The COVID-19 pandemic has also manifested the importance of a healthy environment. Vehicle emissions depend on the vehicle nature and mode of operation factors such as driving style [11], traffic conditions [11], fuel quality and specifications [12], the technology behind the vehicle design, such as emission control technology [13,14], and ambient conditions [14,15]. These factors determine the number and amount of pollutants emitted during the driving interval and cannot be replicated through engine test cycles. Hence, these pave the way for vehicle development and the consequent recent advance of vehicle technology and emission control strategies. This also depends on driving behaviour and traffic conditions—several factors such as changing lanes, overtaking or merging result in increased engine loads [16]. As a result, the engine operates in a rich fuel-air ratio, and thus emissions are increased [17]. Furthermore, vehicle acceleration and speed also affect emissions. Vehicle acceleration significantly impacts CO and HC emission, especially at high speeds and low vehicle speed in congested traffic results in increased emission. Auxiliary loads such as air conditioning system can increase CO and NOx emission and sometimes result in double the emissions. Road type is another critical factor, e.g., hill ascents result in high NOx emissions. Also, the horizontal curvature of roads and roundabouts increases engine load and thus results in increased emissions. Thus, the gap between regulated vehicle emissions from certification procedures and real-world driving emissions has become increasingly wider [16,18]. The inclusion of real driving test procedures can attenuate the discrepancies between emission values determined in laboratory tests and emission values produced during on the road driving because they take greater acceleration into account, along with gradients, stop-and-go, or higher speeds. Emission measurements under real driving conditions can significantly contribute to improving the air quality of the world. The development of an RDE test cycle has been thoroughly discussed in the literature, with many methods suggested [19–21]. It is to be noted that this review article does not focus on engines for non-road applications that constitute: handheld portable devices (lawnmowers, grass mowers, chainsaws, hedge trimmers, twig choppers, snow removal machines, and devices applied in forestry), power generators, and non-road vehicles also referred to as Non-Road Mobile Machinery (NRMM) [22]. The NRMM vehicle group includes construction machinery, farm tractors and machines, and special-purpose machinery [23,24]. This group of vehicles is subject to separate regulations on exhaust emissions which was detailed by Waluś et al. [25]. Emissions from such machinery are also tested against standards during approval; however, these tests are conducted in real operating conditions [24,26–28].

Previous reviews on emission test procedures generally focused on various aspects of vehicle certification procedures. For example, Mahlia et al. [29] reviewed motor vehicle fuel efficiency research procedures in order to establish a test protocol to endorse Malaysia's fuel economy standard, labelling, and other associated services. They came to the conclusion that Malaysia should use the Japanese JC08 fuel economy evaluation protocol for motor vehicles. Hooftman et al. [30] studied the history of European emission regulations and offered a comparative overview of the European market's approaches with the approaches of other major automotive markets around the world. They concluded that a significant revision of the European regulatory system governing automotive emissions is needed. Agarwal and Mustafi [31] conducted a more recent study of real-world vehicle emissions, focusing on the more recent methodologies for monitoring vehicular emissions under real-world driving conditions. This report would concentrate on research that has contributed to developing the RDE test protocol, which aims to minimise the gap between type-approval and real-world driving emissions.

2. Vehicle and Engine Test Cycle Basics

Vehicle emissions are one of the main sources of greenhouse gas (GHG) emissions in modern cities, leading to air pollution [32]. The rising number of passenger cars, especially in the last decade, has resulted in a complicated traffic issue with significant implications in terms of vehicular emissions [33,34]. Since the early 1960s, vehicles' compliance with emission regulations has been checked using standardised tests [35]. These have been known as driving/drive cycles, test cycles, or transient cycles. Even though these three terms are often used in the literature interchangeably, they might not mean the same test procedures or parameters. Driving test cycles involve testing the whole vehicle and typically comprise of a series of data points representing a speed-time profile that is representative of urban driving [36–39]. In particular, the test cycle consists of a series of test points, where the vehicle or engine in question has to follow a certain speed at each point. Thus, in this regard, test cycles are primarily classified as (a) chassis dynamometer cycles used for vehicle testing and (b) engine dynamometer cycles used for engine testing. Engine tests cycles are carried out for exhaust emission certification procedures for heavy-duty and off-road vehicles as it is often impractical to put those vehicles on a chassis dynamometer. These tests are performed in an engine test-bed following a pre-determined speed-time pattern which typically lasts from a few minutes to 30 min, with even lengthier cycles being developed. Applying transient cycles for the test cycle has an advantage of a relatively wide range of operations in terms of load and speed, which also accounts for serious discrepancies encountered during sudden load and speed changes [40]. It should be noted that the transient cycle is typically performed to determine the overall amount of exhaust emissions and fuel consumption rather than to identify the particular conditions or sections where these are produced.

Standardised automotive drive cycles and engine duty cycles are important development techniques. These cycles include common metrics for measuring efficiency in assessing compliance with an emissions level and a fuel consumption/economy performance standard and comparing the performance of two technologies [41]. In many parts of the world, these cycles serve as a standardised measurement of vehicles' performance during type approval, i.e., certification procedure. In fact, emission standards heavily rely on the employed driving cycle and test procedures. Manufacturers often design and calibrate their vehicles using the test procedures standards to meet the standard. Comparing vehicles/engines from different manufactures are made possible through these standardised tests. Other applications of driving cycles include providing a long-term premise for design, tooling and marketing to vehicle manufacturers [42]. These also help traffic engineers in designing traffic control systems considering traffic flows and delays [43]. Environmentalists can negotiate specific driving patterns to reduce pollution generated based on these cycles [44]. Another use for driving cycles is in automotive modelling, where they can be used to estimate pollutant emissions and fuel consumption of cars in specific urban areas [37,43].

2.1. Chassis Dynamometer Cycle

Chassis dynamometer cycles are classified into two types viz. modal type developed initially and transient type adopted at a later stage. Driving surveys were conducted to create a driving cycle in the early 50s. Due to calculation limitations, only a few driving modes were initially identified: idle, constant rate of acceleration, acceleration from and up to specific speeds, steady driving speed, and deceleration at a fixed rate. These, though, are often incompatible with real-world driving habits, resulting in inaccurate pollution outcomes. To reliably reflect the driver pattern, chassis dynamometer cycles evolved to a transient style cycle. These cycles are generated using properly analysed data obtained from instrumented vehicles [45]. To carry out a driving cycle in the laboratory, critical experimental facilities such as an automatic dynamometer test-bed, quick responding exhaust gas analysers, dilution tunnels, and so on are required. Figure 3 shows a typical chassis dynamometer testing setup. As mentioned earlier, these cycles act as a standard test procedure for pollutant and CO_2 emission determination and heavily influence manufacturers' engine calibration procedures. In this respect, a strong relationship exists between the legislated test and anti-pollution measures of modern vehicles. These tests can be carried out in controlled environments where the variables such as ambient temperature and vehicle speed can be controlled, and unwanted effects such as weather variables can be eliminated. This ensures the reproducibility of the obtained results making the testing vehicle results comparable and the certification process reliable. The chassis dynamometer test procedure is generally employed for passenger cars, LDVs such as vans and trucks, and motorcycles where the whole vehicle can be handled easily.

2.2. Engine Dynamometer Cycle

Testing heavy-duty vehicles (HDVs) such as buses, trucks, and off-road vehicles in a chassis dynamometer is very demanding due to their enormous size and weight. In addition, in most cases, the different components of these vehicles are not designed together, and there might be a multitude of vehicle and engine combinations. As a result, emission certification for these vehicles is usually conducted on an engine and in an engine dynamometer. Figure 4 shows a typical chassis dynamometer testing setup. Engine dynamometer cycles are categorised into two types: steady-state and transient. Table 1 shows the benefits and drawbacks of heavy vehicle chassis dynamometer and engine dynamometer testing. This test is usually a transient cycle in which the engine is operated on a dynamometer over a variety of load and speed fixed points, and the emissions are calculated according to the stated protocol [46]. The emission results are generally given in g/kWh or g/HPh.

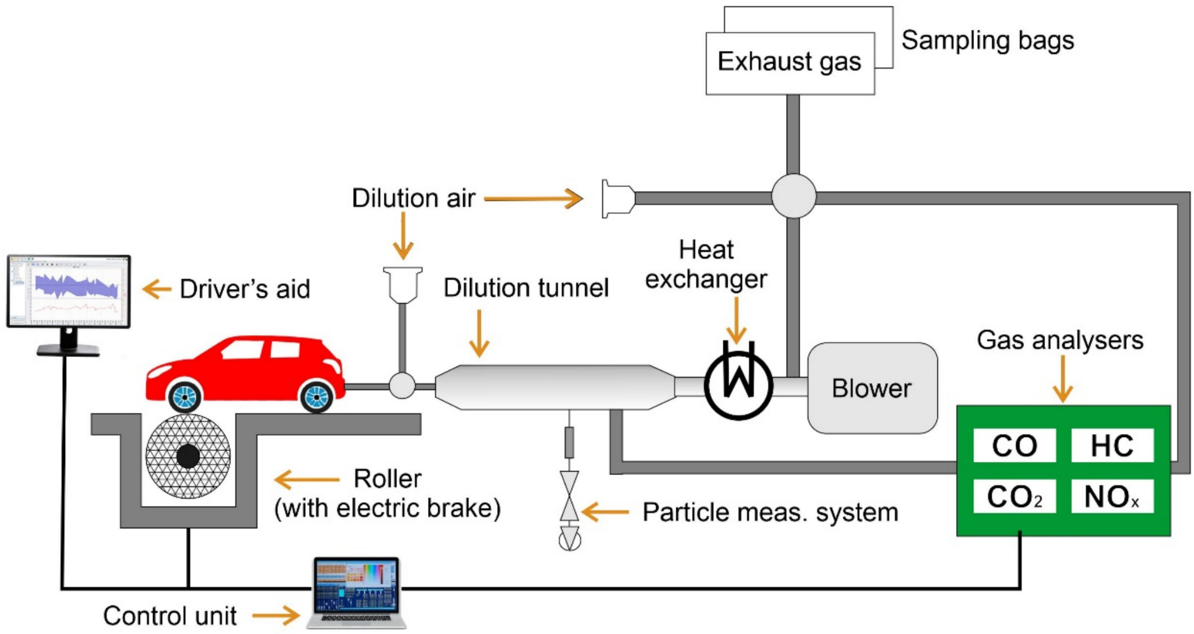

Figure 3. Typical chassis dynamometer testing setup.

Table 1. Merits and demerits of testing of heavy-duty vehicles in different dynamometer setups [35,47].

Test Type	Merits	Demerits
Chassis dynamometer	• Any vehicle configuration can be tested, such as a vehicle with various transmissions • The vehicle components can be tested as a whole system	• High capital cost for chassis dynamometer setup • Limited availability of adequate test facility • Inconsistent with pollution targets, which are determined based on engine dynamometer tests • Different emission limits will be required for each vehicle type.
Engine dynamometer	• Cost reduction due to the use of one engine for multiple applications • A unified range of pollution limits for a variety of applications	• Connecting an engine to a dynamometer takes more time. • It is not possible to test drive train subsystems such as transmissions and pollution control equipment. • Test results might differ during the certification process

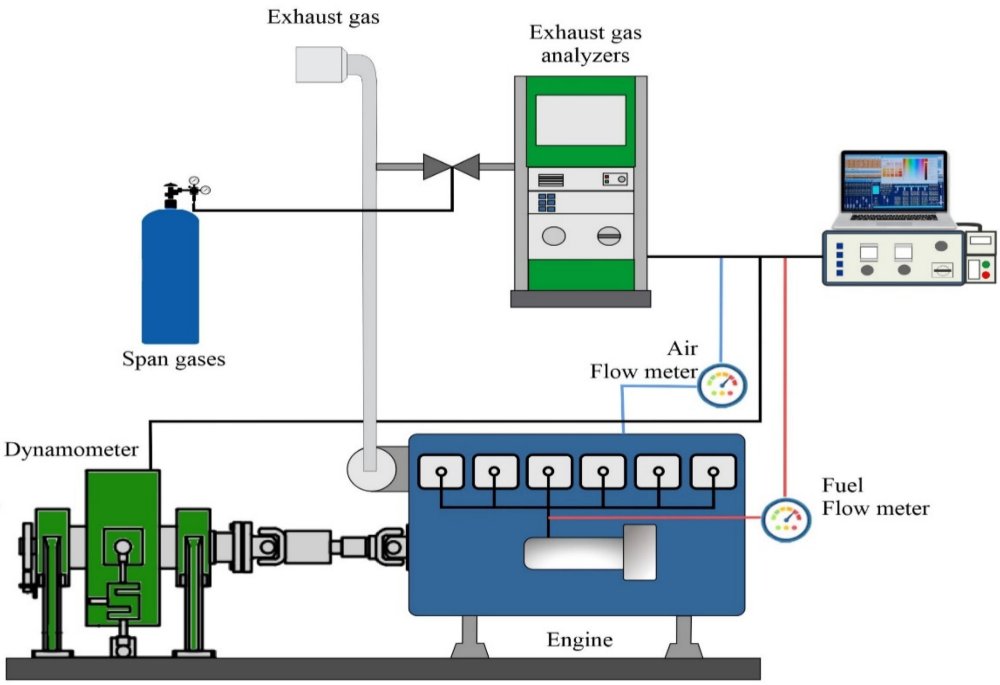

Figure 4. Typical engine dynamometer testing setup [48,49].

3. Legislative Test Drive Cycles for the Emission Type Approval

Regulatory and certification authorities often use two basic philosophies when designing a driving cycle [16]. In the first philosophy, the driving cycle consists of a sequence of repetitions of a combination of several vehicle operating modes that are representative of driving models. Based on this theory, the Economic Commission for Europe (ECE) and Japanese cycles were established. On the other hand, the driving cycle is a simulation of a real route that consists of a mixture of driving modes. United States, Australia, Canada, Sweden and Switzerland used this philosophy while devising their driving cycles.

3.1. Passenger and Light-Duty Vehicles

This section presents driving cycles used in various parts of the world for LDVs, including passenger vehicles, and is done in a chassis dynamometer. Despite the fact that the first emission regulations and test cycles for LDVs were enacted in the late 1960s, these cycles were only applicable to vehicles powered by gasoline engines. Even though the cycles were modal at first, they later developed into a transient type that included diesel engine driven vehicles.

3.1.1. European Union

As mentioned previously, the driving cycle for the certification procedure of LDVs has been in effect in Europe for many decades now [50]. Figure 5 depicts the European test cycle timeline for type approval (TA). This cycle was designed to reflect city driving conditions and was initially known as ECE. The ECE is an urban driving cycle (UDC) with low vehicle rpm, engine load, and exhaust gas temperature [51]. After the fourth ECE repetition, the Extra-Urban Driving Cycle (EUDC) section was introduced to accommodate for more aggressive, high-speed driving modes. With the introduction of the Euro 1 emission standard in 1992, the ECE+EUDC cycles, also known as the Motor Vehicle Emissions Group (MVEG)-A cycle, was introduced. Since 2000, this has been referred to as the 'New European Driving Cycle (NEDC)'. The cycle is divided into two stages, one representing ECE15 and the other representing EUDC [16]. Figure 6 represents the ECE+EUDC/NEDC driving cycle speed profile. These cycles were in effect from 1970 to 2017. In ECE+EUDC, an idling period of 40 s was present before the commencement of the cycle and the beginning of sampling. In NEDC, the start of the cycle and the sampling begins simultaneously with the cold engine start. Many researchers demonstrated that NEDC would not adequately reflect a vehicle's driving activity in real-world traffic because of the many constant-speed and constant-acceleration parts [38,52,53]. Thus, NEDC does not accurately reflect real-world pollutant emissions. Following the pressure generated by the diesel pollution scandal (dubbed "dieselgate") in 2015, the Worldwide Harmonized Light-duty Test Cycle (WLTC) was introduced in July 2017 for the European TA framework (Regulation 2017/1151, 2017) [54]. The rollout to WLTP started in September 2017, and any vehicle registered from the start of September 2018 needed a WLTP rating.

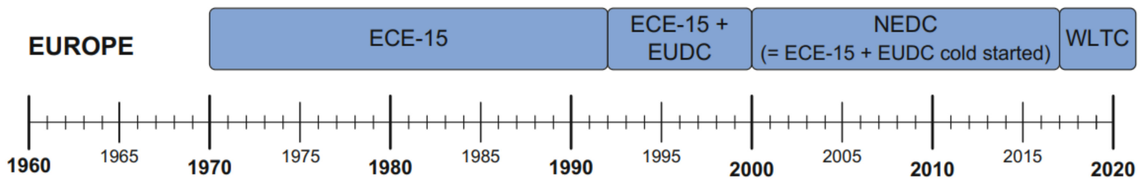

Figure 5. Timeline of test cycles used in Europe for tailpipe pollution TA.

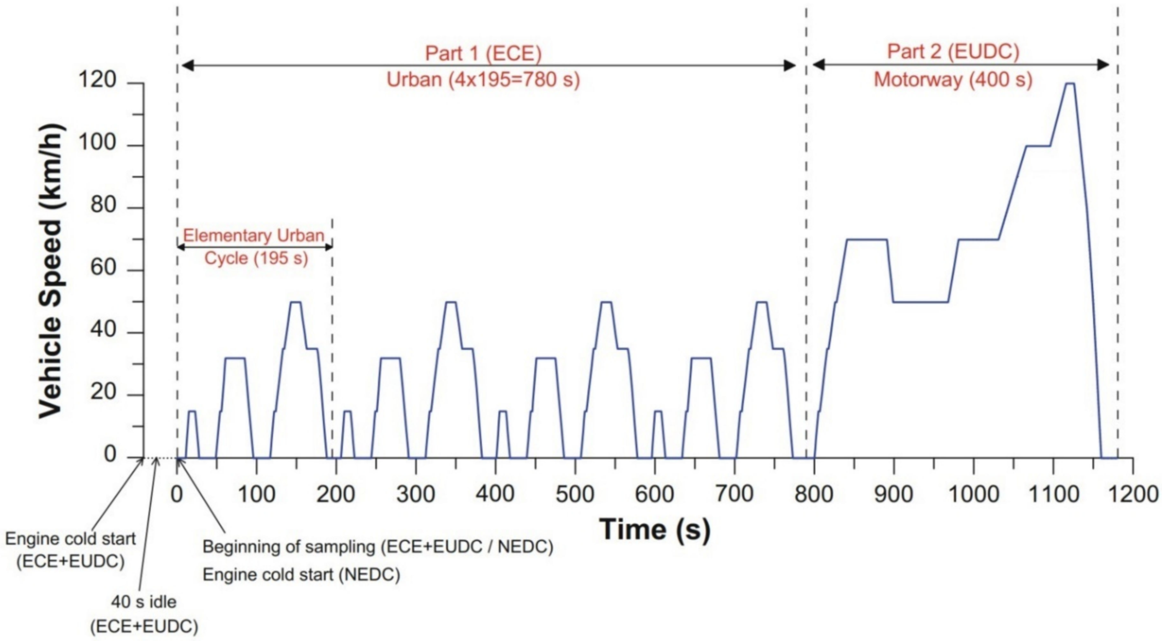

Figure 6. Speed-time cycle of ECE+EUDC/NEDC driving profile [55].

3.1.2. United States

The EPA Urban Dynamometer Driving Schedule (UDDS) is often referred to as the "LA4" or "city test." Since 1972, this cycle has become the standard driving cycle for TA of LDVs in the United States and is known as Federal Test Procedure-72 (FTP-72). FTP-72 cycle simulates urban/suburban routes. The cycle lasts 1372 s (approx. 23 min), and is divided into two segments: a cold-started 'transient' phase after overnight parking (lasting 505s) and a second 'stabilization' (in terms of the engine has reached its fully warmed-up condition) phase with frequent accelerations and stops (lasting 867 s). Overall, the maximum speed during the cycle reaches 91.2 km/h; the total travelled distance is 12 km, with 17.8% of the time spent idling. Figure 7 depicts the speed profile of the FTP-72. It is primarily used for LDV testing, which was classified as a motor vehicle built primarily for property transportation and rated at 6000 lbs GVW or less, or for personal means of transport with a capacity of 12 people or less at the implementation stage [56].

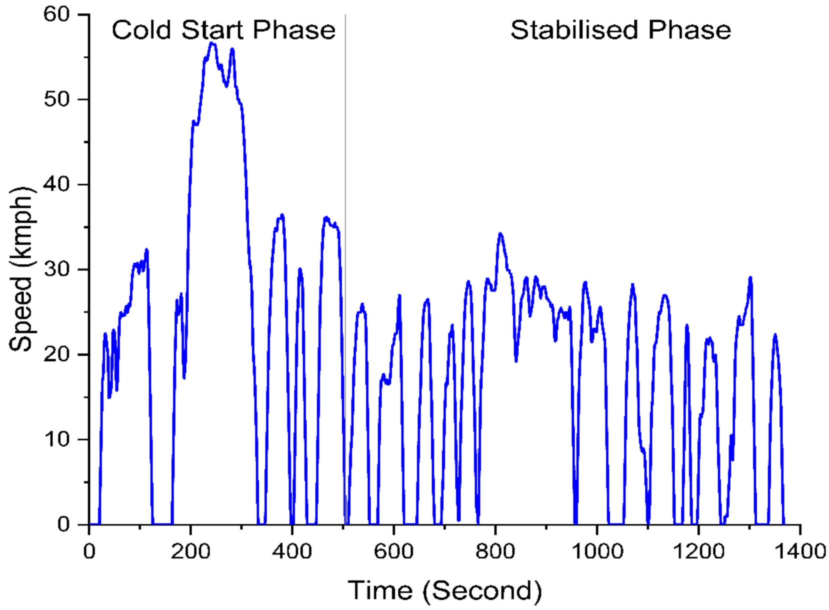

Figure 7. Speed-time cycle of EPA UDDS/FTP-72 (40 CFR 86, App. I).

Another cycle used for LDV certification is the FTP-75 cycle (also known as EPA75) which is derived from the FTP-72 and was introduced in 1975. Since then, it has been the 'primary' cycle used in the US for TA of LDVs. FTP75 was created by using the third phase of 505 s, similar to the first phase of FTP-72 but with a hot start. The third phase begins after the engine has been stopped for 10 min. Figure 8 illustrates the driving time speed profile of the FTP-75. Diesel engine cars were included as passenger vehicles starting with the 1975 model year. As opposed to running only one 12 km cycle from a cold start, this test provides a more realistic real-world driving experience.

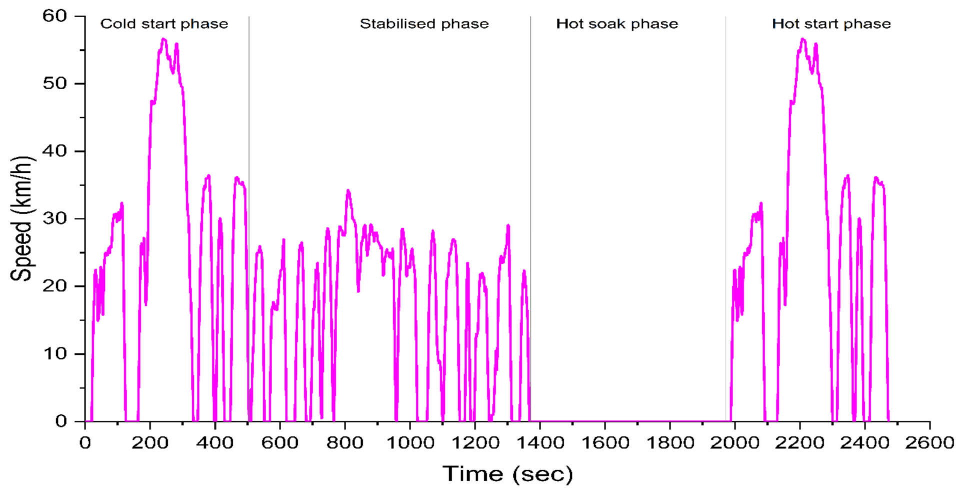

Figure 8. Speed-time cycle of the EPA75/FTP-75 driving profile.

3.1.3. Australia

In Australia, the current new vehicle emissions standard for both petrol and diesel is Euro 5 [57]. The Australian Design Rules (ADRs) dictates six different class of diesel vehicles shown in Table 2. The "Composite Urban Emissions Drive Cycle" (CUEDC) was first introduced for diesel vehicles in 1998. National Environment Protection Commission (NEPC) commissioned the development of CUEDC as part of the Diesel National Environment Protection Measure (DNEPM Project 2.1). This cycle comprises four segments representing driving in different urban traffic conditions with quite different speed profiles [58,59]. These four segments include congested, minor roads, arterial roads and highway/freeway driving. These segments have regular stops and starts, prolonged idle times for congested traffic, and highway/freeway travel with continuous cruising speeds of up to 80~90 km/h and only occasional significant changes in speed or periods at rest. A CUEDC for light-duty gasoline vehicles was created in 2005. A "Short Petrol CUEDC" (SPC240) was also developed, trying to replicate driving modes of the complete petrol CUEDC in a shorter and possibly easier to perform test [60]. Figure 9 shows the speed-time profile of the CEUDC.

Table 2. Australian Design Rule categories for vehicle classification [58,59].

ADR Category	Mass Category (Tonnes GVM or GCM)	Vehicle Description
MA/MB/MC		Passenger car (MA), forward control passenger vehicle (MB), and off-road passenger ≤ 9 seats (MC)
NA/MD	≤3.5	Light goods vehicle (NA) and light buses (MD)
NB/MD	>3.5 ≤ 12	Medium goods vehicle (NB) and light buses (MD)
ME	>5	Heavy bus
NC	>12 ≤ 25	Goods vehicle
NCH	>25	Heavy goods vehicle

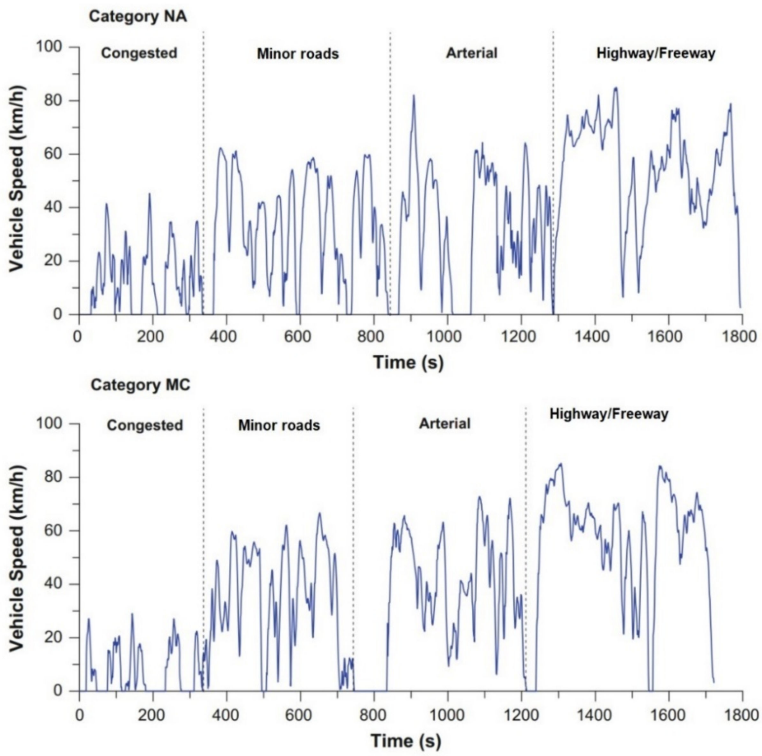

Figure 9. Speed-time profile of the Composite Urban Emissions Drive Cycle (CEUDC) driving cycle.

3.1.4. Japan

A new JC08 chassis dynamometer test cycle for light vehicles (<3500 kg GVW) was adopted in Japan's 2005 emission regulation which had been fully phased in by October 2011. The test simulates driving in congested city traffic, with intervals of idling and regularly alternating acceleration and deceleration. The measurement is performed twice, once with a cold start and once with a warm start. The test is used to determine emissions and fuel economy in gasoline and diesel automobiles.

The following are selected parameters of the JC08 driving schedule:

- Duration: 1204 s
- Total distance: 8.171 km
- Average speed: 24.4 km/h (34.8 km/h excluding idle)
- Maximum speed: 81.6 km/h
- Load ratio: 29.7%

Figure 10 depicts a schematic of the JC08 driving schedule.

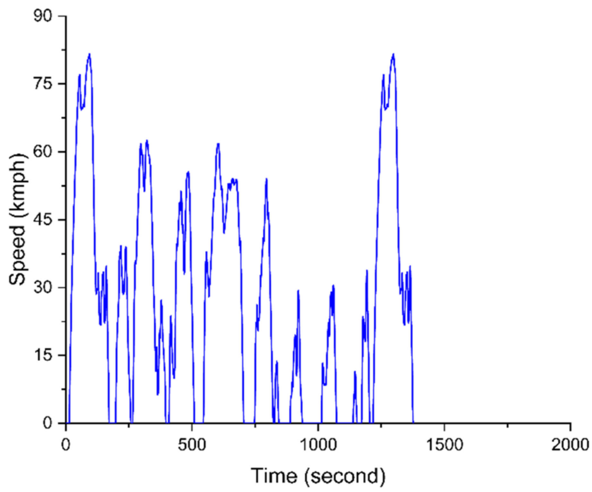

Figure 10. Speed-time profile of the JC08 driving cycle.

3.1.5. Worldwide

For many years, attempts have been made to standardise LDV chassis dynamometer testing procedures [61]. The United Nations Economic Commission for Europe (UNECE) introduced the 'Global Technical Regulation No. 15' concerning the Worldwide harmonised Light vehicles Test Procedure (WLTP) in 2014 [62]. As mentioned previously, following WLTP, a new test cycle was developed known as WLTC, which is applicable to LDVs worldwide [61,63]. As a major contributor to its development, the European Commission has introduced WLTP, replacing NEDC in September 2017. A comparison between WLTC and NEDC is shown in Table 3. The WLTP vehicle classification is determined by the ratio of rated power to kerb mass (pmr) [64]. Three classes of the vehicle were agreed upon: (1) Class 1: pmr <=22 W/kg, (2) Class 2: 22 W/kg < pmr <= 34 W/kg, and (3) Class 3: pmr >34 W/kg. Class 3 is further divided into two subclasses: Class 3a with max vehicle speed <120 km/h and Class 3b with max vehicle speed ≥120 km/h. As a result, three distinct WLTC models were created based on the dynamic potentials of the various classes. WLTC for 3 classes of vehicles is shown in Figure 11.

Table 3. Comparison of NEDC with WLTC (Class 3b).

	NEDC	WLTC (Class 3b)
Cycle Time	20 min	30 min
Cycle Distance	11 kilometres (6.83 miles)	23.25 km (14.44 miles)
Driving	2 phases: urban driving 66%/extra-urban driving 34%.	4 phases: urban driving 52%/extra-urban driving 48%
Average Speed	34 km/h (21.12 mph)	46.5 km/h (28.89 mph)
Maximum Speed	120 km/h (74.56 mph)	131 km/h (81.39 mph)
Influence of Optional Equipment	The options and their impact on regulated emissions and consumption are not taken into account.	Options and their impact on regulated emissions and consumption are taken into account.
Temperature Testing	Measurements are taken at temperatures between 20 and 30 °C	Measurements are taken at 23 °C, then at 14 °C for CO_2 emissions

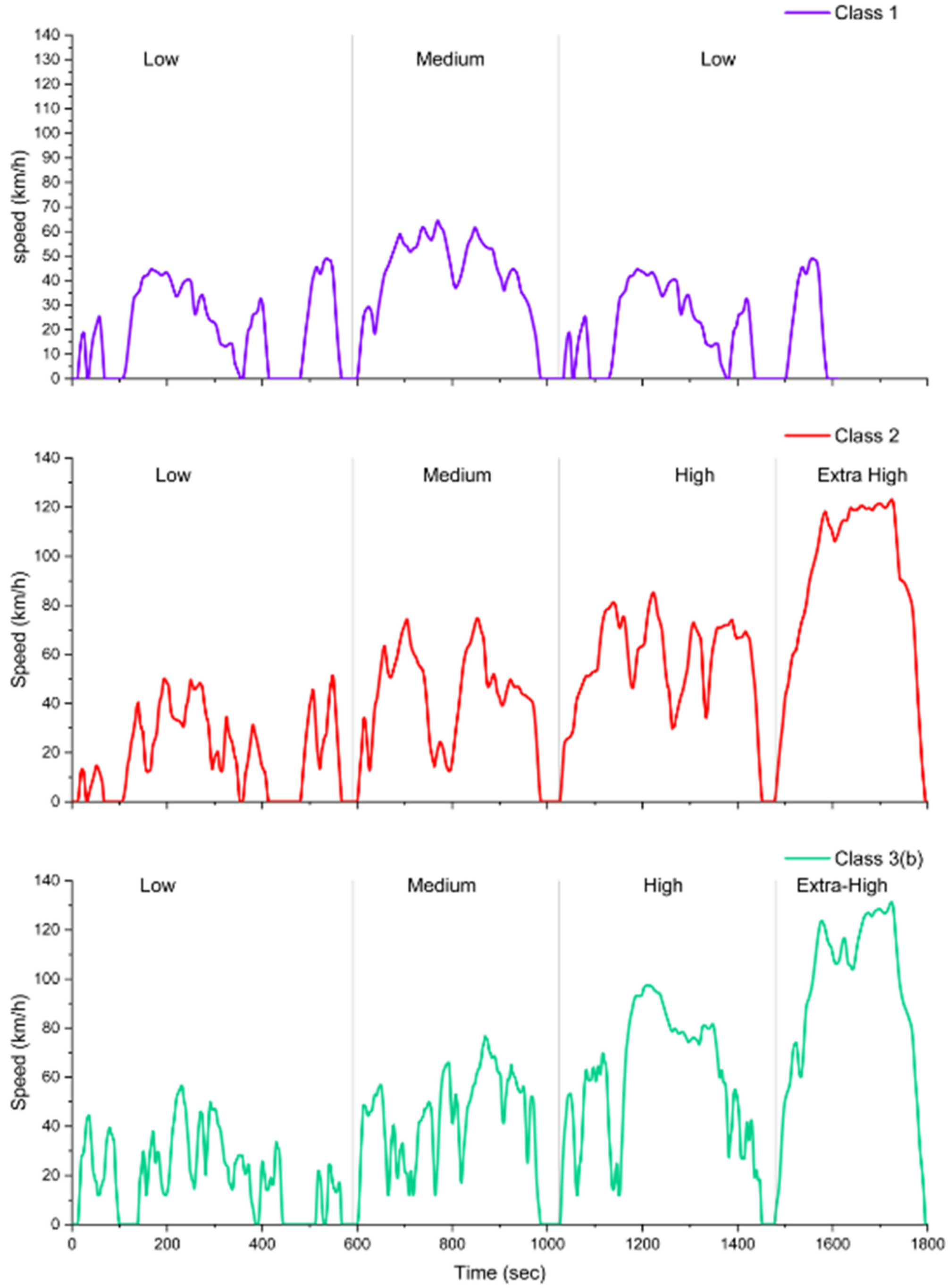

Figure 11. WLTC cycle for Class 1, Class 2 and Class 3(b) vehicles.

3.2. Heavy-Duty Vehicles

An HDV generally produces more oxides of nitrogen (NOx) than an LDV [45]. Since the emission testing for HDVs is more complicated due to the high investment, operational and maintenance costs of the device, the HD exhaust emission TA utilises an engine cycle instead of a vehicle cycle [65]. Nevertheless, both types of cycles are still prominent for HDV testing.

3.2.1. European Union

A sub-group of the UNECE Working Party on Pollution and Energy (GRPE) was tasked with designing a new exhaust emissions protocol for HDVs for use with the Euro III emission standard. In May 1996, they turned in their report. Based on their recommendation, the 'Directive 1999/96/EC', similar to 'UNECE R49/03' of 13 December 1999, adopted a new 13-mode steady-state cycle (later referred to as the European Stationary Cycle (ESC)). Beginning in the year 2000, the ESC cycle, along with the European Transient Cycle (ETC) and European Load Response (ELR) test, was used for emission certification of HD Diesel engines in Europe [66]. Both the ESC and the ETC were a considerable improvement over the ECE R49 test, which was a 13-mode steady-state test cycle for the Euro II standard [67].

European Stationary Cycle (ESC)

Beginning with the Euro III emission standard in 2000, the ESC replaced the R49. Initially, the test was known as the OICA cycle or ACEA cycle. This is a steady-state engine test cycle in which the engine is tested on a dynamometer via a sequence of steady-state modes [68]. In this step, the engine must be run for the specified time in each mode, with engine speed and load adjustments completed within the first 20 s. The specified speed and torque should be held within ± 50 rpm and ± 2% of the maximum torque at the test speed. Emissions are measured during each mode and averaged over the cycle using a set of weighting factors and are expressed in g/kWh [66]. Just engine-out emissions are included in this test, with no aftertreatment. Figure 12 depicts the series of measurement points and their proportional weight (%) in the ESC. The engine speeds A, B, and C are calculated based on specified parameters using preset equations.

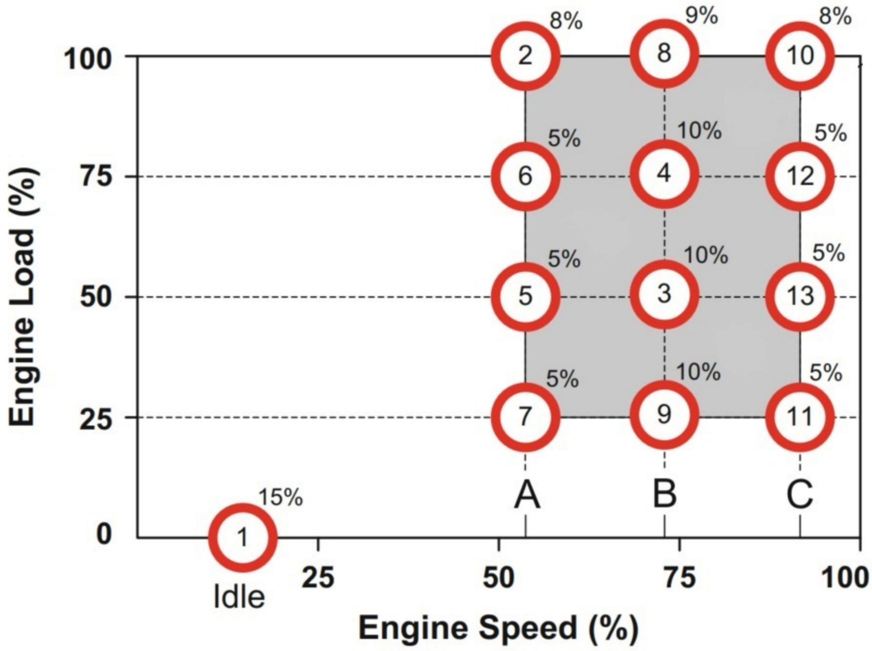

Figure 12. European Stationary Cycle (ESC) with the order of the measurement points and their relative weight (%) [66].

European Transient Cycle (ETC)

The ETC test cycle has been introduced, together with the ESC (European Stationary Cycle), for emission certification of heavy-duty diesel engines in Europe starting in the year 2000 (Directive 1999/96/EC of 13 December 1999). The ETC cycle has been developed by the former FIGE Institute (Aachen, Germany), based on real road cycle measurements of heavy-duty vehicles (FIGE Report 104 05 316, January 1994). The final ETC cycle is a shortened and slightly modified version of the original FIGE proposal. The entire cycle lasts 1800 s, with each step lasting 600 s. This cycle is divided into three sections to make for a thorough examination of the response to urban (first part), rural (second part), and highway (third part) driving conditions. The urban period is characterised by city driving (Vmax of 50 km/h, regular stops, starts, and idling). The rural driving phase follows, and it begins with a steep acceleration section at an average speed of around 72 km/h. The third phase is similar to highway driving, with an average speed of about 88 km/h and less engine torque shifts than the urban and rural stages. Figure 13 represents the ETC Cycle's normalised engine speed vs. time and normalised engine torque vs. time profiles [69].

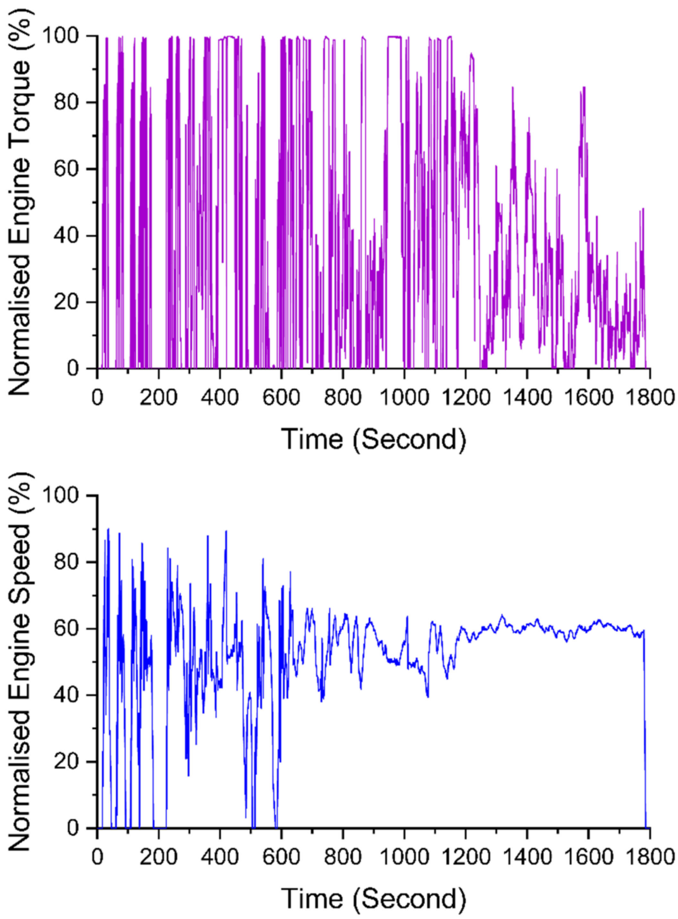

Figure 13. The European Transient Cycle (ETC) for heavy-duty engines.

3.2.2. United States

Both chassis and engine dynamometer tests are available in the US for emission testing.

Heavy-Duty-Urban Dynamometer Driving Schedule (HD-UDDS)

The EPA Heavy-Duty—Urban Dynamometer Driving Schedule (HD-UDDS) is a chassis dynamometer cycle developed for regulatory emission testing of HDVs (CFR 40, 86, App.I). This is different from the UDDS mentioned earlier. This test is also known as 'cycle D'. The HD-UDDS schedule was the basis for developing the FTP Transient engine dynamometer cycle mentioned later. The primary parameters of this cycle are [70]:

- Duration: 1060 s
- Distance: 5.55 miles ≈ 8.9 km
- V_{avg}: 18.86 mi/h ≈ 30.4 km/h
- V_{max}: 58 mi/h ≈ 93.3 km/h

Figure 14 depicts the driving schedule for the HD-UDDS cycle.

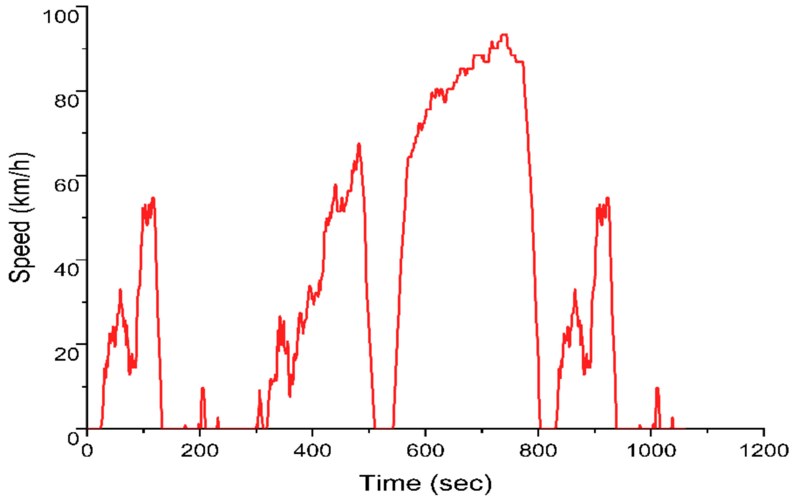

Figure 14. Speed profile of Heavy-Duty-Urban Dynamometer Driving Schedule (HD-UDDS) drive cycle.

Transient FTP

After 1985, the FTP transient cycle (Transient FTP) has been used in the United States for regulatory pollution monitoring of HD on-road engines [CFR Title 40, Part 86.1333] [71]. This cycle is now three decades old and does not accurately reflect new engines with high power density and turbocharger boost. The FTP cycle consists of four phases:

(1) NYNF phase representing light urban traffic with frequent starts and stops,
(2) LANF phase representing dense urban traffic with few stops,
(3) LAFY phase representing dense freeway traffic in Los Angeles,
(4) a repetition of the first NYNF phase [72].

The cycle contains "motoring" segments that necessitate the use of a DC or AC electric dynamometer capable of both consuming and supplying power. The average vehicle speed for the entire cycle is about 30 km/h, with a cumulative distance travelled of 10.3 km and a running time of 20 min. The average load factor of the cycle is approximately 0.20–0.25 of the full engine power available at a given engine speed. HD diesel engines emit medium to high-temperature exhaust gases during this period. The temperature varies between 250 and 350 °C on average, although several parts can exceed 450 °C. There are two FTP cycle versions: one for diesel engines and one for otto-cycle engines. Figure 15 depicts the two versions of the engine FTP cycle in normalised speed form. More specialised transient tests cycles are also available in the US [73].

3.2.3. Japan

For heavy vehicles with a gross vehicle weight (GVW) of more than 3500 kg, the new JE05 emission test cycle was introduced in Japanese emission regulations in 2005. The JE05 cycle is a transient test for diesel and gasoline cars based on Tokyo driving circumstances. The JE05 test is characterised by vehicle speed vs. time points, as illustrated in Figure 16. The test lasts roughly 1800 s, with an average speed of 26.94 km/h and a maximum speed of 88 km/h.

3.2.4. Worldwide

In June 1997, the UNECE Worldwide harmonised Heavy-Duty Certification (WHDC) group was tasked with developing a 'Worldwide harmonised Heavy-duty Certification' procedure. The team originally devised a representative worldwide transient vehicle cycle (WTVC) or worldwide harmonised vehicle cycle (WHVC), but it was never incorporated into legislation. It was later transformed into a reference transient engine test cycle known as the Worldwide harmonised Transient Cycle (WHTC), as shown in Figure 17. This cycle was specified in terms of normalised engine speed and load, and it was refined using a newly developed drive train model.

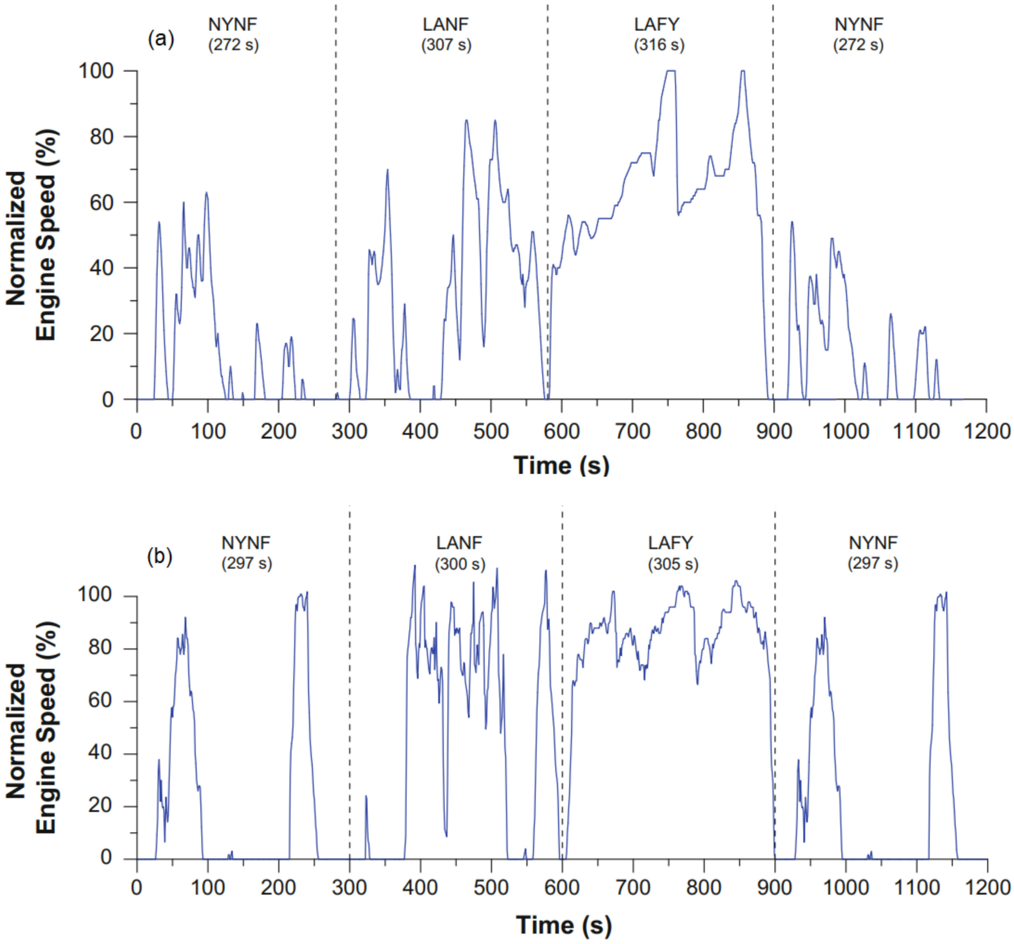

Figure 15. Heavy-duty transient FTP cycles in normalized speed for (**a**) Otto-cycle and (**b**) Diesel-cycle engines (40 CFR 86, App. I).

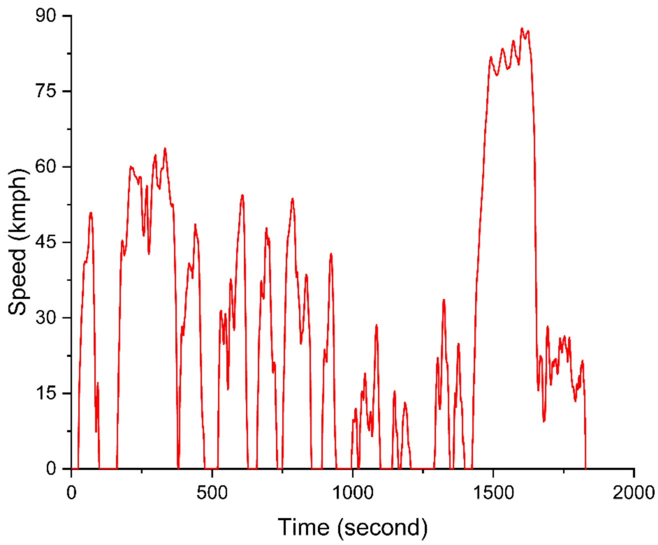

Figure 16. Speed-time profile of the JE05 driving cycle.

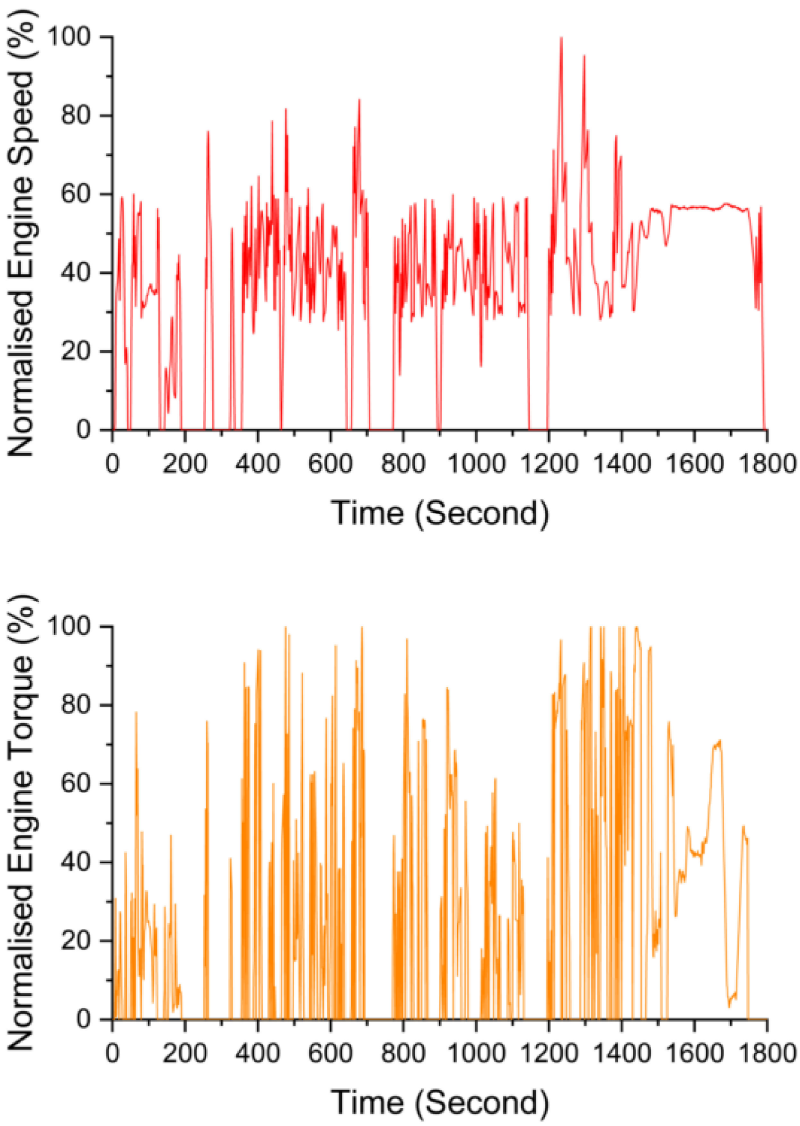

Figure 17. Engine speed and torque profile of the WHTC transient cycle.

3.3. The Controversy over Defeat Devices

The chassis dynamometer test has been the most popular and standard choice for evaluating vehicle emissions for a long time. However, in recent years, researchers have found discrepancies between the chassis dynamometer test results and results obtained from on-road emission testing. In some cases, researchers have found a significant increase in emissions from on-road emission tests compared to the type of emission test discussed earlier [74]. Previously, one of the major drawbacks where the availability of an emission measuring system for on-road testing; however, recent improvements in the portable emission measuring system, known as Portable Emission Measurement System (PEMS), has enabled researchers to conduct on-road tests. PEMS provides a complete and very accurate real-time monitoring of the pollutants emitted by the engines (HC, CO, CO_2, NO_x, PM) together with the associated engine, vehicle and ambient parameters. In 2015, US EPA reported that a leading German auto manufacturer was using 'defeat devices' to reduce vehicle emission during type emission tests [75]. This is commonly known as 'dieselgate'. The vehicle was programmed to trace when it is being used in a chassis dynamometer, and it would activate its emission controls to reduce the NO_X emission. The agency found that this would result in NO_X emission within the standard limits. However, the vehicle in real-life emits 40-times more NO_X emission [76,77]. In 2017, the company was fined US$2.8B by the federal court [78]. This was not the only company to use the defeat devices. Recently in 2020, another giant auto manufacturing company was fined US$1.5B for violating the Clean Air Act and California law due to the use of defeat devices. The vehicle was programmed in a way that while testing, it would increase the fuel mileage and thus reducing the emission levels to meet the standard value. These two incidents and ongoing discrepancies found from type emission tests and on-road emission values have resulted in a significant inclination towards real drive emissions in recent years. The development of PEMS to accurately measure real-time on-road emission has also helped researchers move towards introducing RDE tests [79]. The following section will discuss RDE test significance and design policy and review the literature to show why it is important to do on-road emission tests to reduce real emissions to meet emission standards.

4. Development of Real Drive Emission Tests and Cycle

Though stricter emission norms for automobiles have been introduced to improve the ambient air quality, the desired improvement has not been achieved, which can be attributed to the differences between the legislative and real-world vehicle use [80]. As discussed previously, several factors, such as road and climate conditions, affect the vehicle performance and makes chassis dynamometer emission testing not a reliable source for real emission from vehicles [81,82]. Furthermore, chassis dynamometer tests do not account for actual street layout and driver behaviour. If there is a difference in altitude or temperature, it will have an impact on parameters such as oxygen content, air intake and air-fuel ratio of the engine and which will vary the vehicles real drive emission [83].

EU has mandated RDE norms or in-use compliance standards since September 2017 to minimise this difference [84,85]. This mandate required vehicle emissions to be measured on the road with a PEMS in addition to measurements taken during the driving cycles performed under controlled laboratory conditions on a chassis dynamometer. RDE emission limits are defined by multiplying the respective NEDC emission limit by a "conformity factor (CF)" for a given emission. During a real road drive, a vehicle may initially emit 'CF' times as much as it does when tested under laboratory conditions.

The RDE legislation, which was introduced within the Euro 6 regulation, has been developed in 4 packages [86]. The first RDE package that defined the RDE test procedure was ratified in May 2015. The second package, which defined the NOx CFs and their introduction dates, was adopted in October 2015. The third package adopted in December 2016 included a Particle Number (PN) CF and RDE cold-start emissions. The fourth and final package adopted in May 2018 dealt with 'In-Service Conformity' RDE testing and market surveillance and lowered the 2020 NOx CF error margin from 0.5 to 0.43. NOx CF was mandated at 2.1 beginning in September 2017 (phase 1 of RDE) for new models and increasing to 2.1 beginning in September 2019 for all new vehicles. This factor was required to be 1.5 for new models beginning in January 2020 (phase 2 of RDE) and all new vehicles beginning in January 2021. A PN CF of 1.5 was mandated for new models beginning in September 2017 and for all new vehicles beginning in September 2018. Table 4 shows the TA tests and real operating conditions requirements for passenger vehicles between 2015 and 2022.

Table 4. Requirements for TA tests and real operating conditions for passenger vehicles in 2015–2022.

2015	2016	2017	2018	2019	2020	2021	2022
Euro 6b			Euro 6c			Euro 6d	
NEDC			WLTC				
Development & Measurement Phase			Conformity Factor (CF)				
			CF_{NOx} = 2.1, CF_{PN} = 1.5			$CF_{NOx, PN}$ = 1.5	
RDE for CO, NOx, PN emissions: EC 427/2016 and EC 646/2016						CO, NOx, PN and CO_2	

Commission Regulation (EU) 2016/427 outlines the primary trip conditions for an RDE cycle. This regulation determines the route's characteristics (speeds, lengths, durations, and so on) as well as the ambient conditions. A concurrent regulation, Regulation 2016/646 includes criteria for trip dynamics as well as other specifications [87]. Table 5 presents the trip requirements for RDE.

Table 5. EU RDE route design specification (Regulation 2016/427).

	Unit	Urban	Rural	Motorway	Notes
Speed (V)	km/h	$V \leq 60$	$60 < V$	$90 \leq V \leq 145$	V > 100 for at least 5 min in motorway
Distance	% of total distance	29–44	33 ± 10	33 ± 10	
Minimum distance	km	16	16	16	
Avg speed (V_{avg})	km/h	$15 \leq V_{avg} \leq 40$	-	-	
Number of stops	s	several > 10	-	-	
Max speed	km/h	60	90	145	
Total test time	min	90 to 120			
Elevating difference	m	100			Between the start and endpoint

Some factors to consider while developing an RDE route [88]:

- Urban driving must be achieved on routes with a maximum speed limit of 60 km/h.
- If the urban driving segment includes any road with a speed limit greater than 60 km/h for any reason, the vehicle speed shall not exceed 60 km/h.
- Roads with speed limits lower than the classification can exist in rural and freeway sections.
- The road must be built such that the urban segment is travelled first, then the rural, and eventually the highway sections (using a topographical map).
- It is necessary to operate the vehicle above 100 km/h (measured by the GPS) at least for 5 min.
- The car must be capable of travelling at speeds ranging between 90 to 110 km/h.

There might be country-specific additional RDE criteria. For example, According to the "Pollutant Emission Limits and Measurement Methods of Light Vehicles (China phase 6)" standard, the proportions of urban, rural and highway are 34, 33 and 33%, respectively [89]. However, it is not always possible to fulfil all the criteria and develop a satisfactory RDE route.

In general, drive cycle development phases include three main components: test route discovery, data collection, and cycle design methods [90]. Route selection is an important aspect of the cycle development process where considerations are given on travel activity patterns as well as traffic flow characteristics. The data collection should consider driving both weekends and weekdays so that collected data represent different driving conditions based on the selected routes. Cycle construction is done by feeding driving data records into the representative cycle and then modifying and smoothing the cycle based on statistical analysis.

5. Real Drive Emission Cycle Tests

Yang et al. [91] evaluated diesel and gasoline vehicle real drive emissions. The authors developed an RDE route of 60 km consisting of urban, rural and motorways. The speed limit for the respective parts was 50, 90 and 130 km/h, which falls within the design specification. The vehicles were equipped with different emission reduction techniques. For emission measurement, a PEMS consisting of a Horiba OBS 2200 was used to collect unit to collect instantaneous and cumulative data of gaseous emissions (CO_2, CO, THC, and NOx). The authors reported a higher gaseous emission for urban roads due to poor driving conditions and for motorways which may be due to excessive energy demand. CO and THC emission for all the vehicles were below the specific limit (for gasoline CO: 1.00 g/km and THC: 0.10 g/km, for diesel CO: 0.50 g/km and THC: 0.09 g/km). However, NO_X emission was above the vehicle types' limits (gasoline: 0.06 g/km, diesel: 0.08 g/km).

Diesel vehicles emitted lower average trip CO_2 compared to gasoline vehicles which might be associated with better thermal efficiency.

Thomas et al. [92] tested EURO V compliant gasoline vehicles fitted with a 3-way catalyst for emission reduction. The RDE tests were performed using PEMS devices: the Horiba OBS-ONE-GS PEMS equipment and the AVL MOVE Gas PEMSiS equipment. The trials started with urban driving, followed by rural and motorway driving sections. Urban, rural and motorway roads were approximately 34, 33 and 33% of the total route. RDE CO_2 emissions were higher than the EU passenger car CO_2 goal for 2015 (130 g/km). However, RDE CO emissions were 60% lower than the WLTC (well below the Euro 5 limit of 1 g/km), and RDE NO_X emission was 34% lower compared to the WLTC emissions.

Wang et al. [93] evaluated volatile organic compounds emission from 4 different vehicles, including gasoline cars, light-duty diesel trucks, heavy-duty diesel trucks, and LPG-electric hybrid buses. The authors used two routes. Route A was approximately 68 km, including urban, suburban and highway roads, while route B was 18 km long route of No. B12 bus in Zhengzhou, China, which includes 29 stations. To simulate passengers dropping off and getting on, the bus was stopped at each station for 10 s. A SEMTECH ECOSTAR PLUS with an extra VOC sampling unit comprising three units: micro proportional sampling system (MPS), gas analyser, particulate matter (PM) analyser was used to measure emissions. The VOC emissions were different for different vehicles. The major VOC species for vehicles were as following:

- Gasoline cars: i-pentane, acetone, propane, and toluene.
- Light-duty diesel truck: mainly long-chain alkanes- dodecane, n-undecane, naphthalene and n-decane, which in total contributes to 70.4% of total species
- Heavy-duty diesel truck: naphthalene contributed 31.8% of total VOC, which might be due to the engine operating conditions and the pyrolysation from incomplete combustion (Lin et al., 2019a, 2019b).
- LPG bus: short-chain hydrocarbons, acetone, *i*-pentane, *i*-butane, *n*-butane and propane (46.7% of the total VOCs).

For the gasoline cars, aromatics take up 39.4, 35 and 41.7% of the tailpipe VOCs under the urban, suburban and highway conditions, respectively. The higher aromatic emission at highway may be caused by the lower air/oil ratio of port fuel injection (PFI) under ultra-high-speed working conditions. Heavy-duty diesel trucks emitted 8.6 times higher VOC than light-duty diesel trucks which can be attributed to poor vehicle maintenance as exhibited by the inefficient Selective Catalytic Reduction (SCR) device. Gasoline and LPG vehicles produced relatively lower VOC emission compared to diesel vehicles. This could be attributed to TWC of gasoline vehicles which might have reduced the VOC emissions. Highway operating conditions emitted much lower VOC emissions compared to the urban road conditions.

Du et al. [94] tested the effect of cold-start on primary emission parameters. For the experiment, light-duty gasoline vehicles were selected which were equipped with TWC converter, closed-loop control of fuel injection and gasoline particle filter (GPF). The PEMS used in the tests was a HORIBA OBS-ONE. A route of 75.4 km was selected, which consisted of an urban section (32.6%), a rural one (32.4%) and a motorway section (35.0%). The altitude of the route ranged from 192.7–313.2 m, which satisfies the RDE test regulations requirements. The authors reported a significant increase of CO, CO_2 and PN emission at the cold-start compared to a hot start.

Habib [95] studied three vehicles of varying age groups (BS-II/post- 2000; BS-III/post-2005, and BS-IV/post-2010). The fuels used in the vehicles were also different: gasoline, compressed natural gas (CNG) and diesel. The author selected a route of 10 km consisted of heavy traffic, lean traffic and traffic signals. On-road emissions were measured using Aerosol Emission Measurement System (AEMS), which consists of heated duct, dilution tunnel, zero air assembly, heated particle sampling probe and power supply unit. The author reported that diesel emitted the lowest CO, where gasoline emitted the highest.

CO_2 of gasoline vehicles were dependent upon acceleration and deceleration. Furthermore, the gasoline vehicle emitted a higher amount NO_X of compared to the other two vehicles.

Cao et al. [96] also evaluated on-road VOC emission; however, they opted for a car chase method. The emission measurement system included an exhaust flow meter tube, mobile emission analyser, micro proportional sample system and VOC sampling unit. The test route included arterial roads (19.5 km) and highway roads (14.2 km). The route was divided into three defined driving cycles: arterial road hot start (ARHS), highway hot running (HWHR) and arterial road hot running (ARHR). The test vehicles were light-duty gasoline conformed to diverse emissions standards (Pre-China I to China IV). The authors reported that, for most of the vehicles, hot start resulted in the highest VOC emission and highway hot running produced the lowest emission, which can be attributed to the low average speed and the effect of the hot start.

Daham et al. [97] investigated the impact of micro-scale driving actions (left and right turns, stops and start at traffic lights, etc.) on on-road vehicle emissions. The authors selected a route of 0.6 km, which consisted of four left-hand turns. They used several manual vehicles which conformed to Euro I to IV. They evaluated several driving variations, left turn (anticlockwise) with and without a stop at intersections; right turn (clockwise) with and without a stop at crossroads. The HC emission for the tests was well below the corresponding legislation. However, the NOx emission for all the vehicles were all above the legislative limits. The authors reported that aggressive driving behaviour heavily affects NO_X and CO emission; a three times increase was observed. Aggressive driving also increased CO_2 emissions significantly.

Roso and Martins [98] compared two different methods to develop an RDE cycle: average method and cumulative method. The emissions were evaluated using computational models developed through GT-Suite software. The authors used two vehicles to develop the cycle: bus and passenger vehicle and reported a significant increase of emission for cumulative methods compared to the FTP-75 cycle.

Zhou et al. [83] evaluated the effect of various environmental constraints on real drive NO_X emission. If there is a difference in altitude or temperature, it will have an impact on parameters such as oxygen content, air intake and air-fuel ratio of the engine and which will vary in-cylinder combustion, amount of pollutants and fuel consumption of vehicles. Emission varies with temperature and speed. For example, with vehicle speed <20 km/h, low altitude NO_X emission is higher than that of moderate altitude. High temperature and oxygen enrichment result in reduced NO_X emission, and thus high altitude produces a lower emission. Akard et al. [99] also reported the influence of altitude on CO_2 emission. The authors reported that a change in altitude of 90 m might result in a change in CO_2 emission by 10 gm/mile.

Ren et al. [100] evaluated the effect of various alternative fuels on the emission of buses on their usual daily route. The fuels considered were diesel, 20% Waste cooking biodiesel+ 80% diesel (B20) and liquid natural gas (LNG). The PEMS was composed of a gas test unit: an onboard emissions measurement system and a particle test unit: engine exhaust particle sizer. Compared to diesel-operated buses, B20 and LNG buses had a reduction in PM emissions; however, NOx and PN emissions were higher.

Braisher et al. [101] evaluated on-road emission against legislative cycles such as NEDC, WLTC. The test cell is equipped with the Horiba MEXA-2000SPCS, and PN was measured using the pre-series instrument Nanomet3-PS where particle detection was based on aerosol particles corona charging. The selected driving route consists of an urban route (max speed of 50 km/h) and short segments (speed 70 km/h). The second route includes a long autobahn (high-speed road network) route with a max speed of 100 km/h. the complete PEMS evaluation run consists of two urban routes and one autobahn route. The total run time was approximately 90 min. Cold-start tests were conducted at different ambient temperatures (8 to 28 °C). The on-road measurements were performed using gasoline operated Euro-5 compliant passenger vehicle. The obtained results show that 60% of the trip PN emission is generated while the vehicle operates during the cold-start period.

Braisher et al. [102] reported that during the NEDC cycle, 77% of the total PN emission is generated during the cold-start period. Furthermore, the tests also reveal that driving style is an essential parameter with a substantial impact on the PN emission. The autobahn trips show a significant change in PN emission (10× increase) when switched from normal to severe driving. This can be attributed to larger accelerations, higher velocities, and higher power demand.

Khalfan et al. [103] evaluated the effect of traffic congestion on vehicle emissions. A portable Fourier Transform Infrared (FTIR) spectrometer was used to measure real-world on-road emissions. The total route distance was 5 km, and the speed limit was 48 km/h. Two different cycles were conducted with varying numbers of right and left turns, traffic lights and pedestrian crossings. These dynamic factors would result in numerous stop/start events. The authors reported that congestion affected the CO_2 emission; most of the trips produced more than 180 g/km CO_2, which is above NEDC certification limits. THE CO and THC, and NO_X emissions were dependent upon the traffic speed. These emissions were higher than the legislative limits at lower speeds.

Rosenblatt et al. [104] tested three variants of a motorbike on a 30 min test cycle, which consists of a cold-start phase, intermediate speed and high speed, with each stage being weighted equally at 0.33. The authors found that the PM emission was lower than the current Tier 3/LEV III light-duty highway vehicle limit of 3 mg/mile. A considerable fraction of CO and HC emissions were produced over the cold-start phase and/or high-speed phases, whereas NO_X emission was most influential over the high-speed stage.

Modern-day vehicles have new technologies that help the driver, such as adaptive cruise control (ACC) and start-stop systems. ACC assists the driver in maintaining longitudinal control of their car when travelling on the highway, automatically adapting to different traffic situations. The system regulates the accelerator, engine powertrain, and vehicle brakes to maintain the desired time gap to the vehicle ahead. The start-stop system is a simple and low-cost solution in which the internal combustion engine is automatically turned off when the automobile is stopped and re-started at the driver's request or as necessary. As a result, it avoids idle fuel use, such as that caused by traffic lights or congestion, which may account for up to 10% of overall consumption [105]. It is to be noted from the research of Warguła et al. [24] that a system similar to the start and stop system is only used in a machine (wood chipper), where idling occurred more frequently. This did not turn off the engine rather reduced its rotational speed, reducing fuel consumption [106], CO, CO_2 and NOx emissions with increasing HC emission [24]. This confirms the fact that the internal combustion engine performs best under constant operating conditions. Limiting the idling fuel consumption as well as exhaust emission can be further achieved through cylinder deactivation [107]. This is also known as variable displacement engine technology. The method entails deactivating one or more cylinders by inhibiting valve actuation, causing the engine to run at a greater specific load across the remaining cylinders to provide the required torque [108,109]. Operating at such a position with a wider throttle opening decreases the engine's pumping losses and, as a result, fuel consumption.

Dvorkin et al. [110] evaluated the effect of ACC on vehicle emissions on-road. The performance of ACC depends upon two factors: platooning and controlled acceleration. When vehicles closely follow each other to reduce aerodynamic drag, it is known as platooning, which is most effective in highway conditions where aerodynamic drag dictates road load forces. The author reported that active ACC resulted in less CO_2 g/miles, and optimum GHG reduction is achieved when the following distance is 20–40 m and vehicles operating at highway speeds. In another study [111], the authors concluded that if households switched from conventional vehicles to electric vehicles, they could reduce their GHG emissions significantly.

Andersson et al. [112] evaluated two EURO 6 compliant light-duty diesel vehicles. These vehicles had two different technology installed to reduce NO_X emission. One vehicle had SCR while the other had exhaust gas recirculation. Both consisted of diesel particulate filters for PM reduction. Furthermore, the vehicles were tested in two different routes, one with 60% urban condition and another with 60% motorway. The authors reported that both vehicles produced significantly higher NO_X and CO_2 emissions compared to the EURO 6 legislation limit; however, THC and CO emissions were within the limit.

Wang et al. [113] compared PEMS with a mobile monitoring system for on-road emissions. The authors selected heavy-duty diesel trucks that complied with China III to China V emission standards. The authors reported that the mobile monitoring system reported similar NO_X results compared to that of the PEMS.

Park et al. [114] studied the on-road emission of 109 gasoline and diesel vehicles using PEMS on roads in Seoul (South Korea). The authors compared the emission results against laboratory experiment results and found that Euro 5 and Euro 6B standard vehicles emitted 5 times more on-road NO_X compared to laboratory-based tests. The authors also reported that the on-road NO_X emission is also dependent on factors such as driving dynamics and ambient temperature. One drawback of the study is that the stop ratio of more than 30%, which does not meet the EU RDE regulations. However, the average speed of the vehicles was within 15 to 40 km/h, which is within the regulations.

Bischoff et al. [115] compared the on-road emission of motorcycles. The authors evaluated two driving styles, normal and dynamic driving, where the latter represents a sporty driving style with increased longitudinal dynamics. The authors reported that CO and NO_X emissions were 58 and 36% higher than that of WMTC certification limits. Furthermore, CO, CO_2 and NO_X emissions increased significantly when switched from normal driving to dynamic driving. Table 6 presents a summary of RDE route descriptions and emission results from various literature.

Table 6. Summary of RDE tests.

Reference	Vehicle	Comparison Criteria	Route Information	Impact on Primary Emission	Remarks
[116]	Diesel-electric hybrid bus	China City Bus Cycles	1270 s Average speed 24.3 km/h Proportions: Idle 14.6%, Cruise 13.3%, Acceleration 43.6% and Deceleration 28.6%	NO_X ↓ THC, CO, PM & PN ↑	
[101]	EURO V, gasoline, passenger vehicle	NEDC, WLTC	90 min, Avg engine rpm: 1494–2256 Idle time variation: 4–24.8% 2 × Urban route & 1 Autobahn route Equal distance Cold-start test: Urban route 8–28 °C	PN in similar range compared to cycles	Driving style significantly increased PN emission on the same route
[91]	Gasoline and diesel passenger vehicle	Vehicles	60 km consist of urban, rural and motorway	THC and CO ↓ for all NO_X: Gasoline: ↑ for rural and motorway Diesel: significantly ↑ for all roads	Gasoline emission ↑ motorway Diesel emission ↑ urban
[93]	Gasoline cars, light-duty diesel trucks, heavy-duty diesel trucks and liquefied petroleum gas-electric hybrid bus	Vehicles VOC	Route A: 68 km Route B: 18 km, 29 stops of 10s		VOC: highest- Heavy-duty diesel truck. Lowest- Gasoline Emission of urban roads significantly higher compared to rural and highway
[95]	Diesel, gasoline and CNG	Vehicles	10 km consisting of heavy traffic, lean traffic and traffic signals	Gasoline vehicles produced the highest CO and NO_X	CO_2 of gasoline vehicles varied significantly with acceleration and deceleration

Table 6. *Cont.*

Reference	Vehicle	Comparison Criteria	Route Information	Impact on Primary Emission	Remarks
[96]	light-duty gasoline vehicles	China emission standard	Route 33.7 km (arterial road and highway), divided into 3 cycle Duration: arterial road hot start (ARHS): 21 min, highway hot running (HWHR):17 min and arterial road hot running (ARHR): 21 min Avg speed: ARHS 17.7–22.9 km/h HWHR 42.8–54.9 km/h ARHR 29.6–42.4 km/h		hot start resulted in the highest VOC emission, and highway hot running produced the lowest emission
[94]	Gasoline vehicles	Cold-start vs. hot start	75.4 km: urban section (32.6%), rural (32.4%), and the motorway section (35.0%). Altitude variation: 192.7–313.2 m. The authors reported a significant increase of CO, CO_2 and PN emission at the cold-start compared to a hot start.	CO, CO_2 and PN: Significant ↑ for cold-start	NO_X emission depends on driving behaviour
[97]	SI gasoline cars with compliance to EURO I to IV	Euro I to IV	Four left-hand turns and the total circuit length was 0.6 km with very little other traffic	THC and CO: within legislation limits NO_X and CO increase for aggressive driving	
[112]	light-duty diesel Euro 6b standards	New European Drive Cycle (NEDC), Common Artemis Drive Cycle (CADC), WLTC and 3 'Random cycles'	60 min (minimum) Route 1: 60% urban Route 2: 60% motorway	NO_X ↑ THC and CO: similar CO_2: Significant ↑	
[98]	Bus Passenger car	Average vs. Cumulative cycle FTP-75	11.8 km including varied driving conditions including ascents, descents, urban and highway traffics Bus: 2674–8321 s, Acceleration 50.86–52.54%, Deceleration 47.46–49.145 Car: 2016–6013 s, Acceleration 38.25–50%, Deceleration 50–61.25%	Car: Significant increase of NO_X, THC and CO for a cumulative cycle, compared to FTP-75 Bus: Significant increase of NO_X, HC, CO and soot for a cumulative cycle, compared to FTP-75	
[117]	Euro 6 standard vehicles	NEDC, WLTP, Transport for London Urban Inter-Peak Cycle	105 min	NO_X: ↓ compared to EURO 6, ↑ compared to NEDC, WLTP CO: ↓ PN: ↓ compared to EURO 6 CO_2: ↑ compared to EURO 6	CO_2 higher than EURO 6 limits. Depending on the vehicle technology, some cars were able to control NO_X emission from cold-start, and some were able to control NO_X after 2–3 min of warm-up
[99]	Light-duty vehicle	Grade variation	Two routes duration 40 min and 45 min 90 m altitude change		Altitude difference 10 g/mile of CO_2
[110]	2018 Cadillac CT6	Adaptive Cruise Control	Most of the driving occurred at highway speeds; over 66% of the data were captured at and above 55 mph	CO_2: ↓ for active ACC	
[104]	compact sport bike (296 cc), cruising bike (749 cc) and high performance touring bike (1198 cc)		1.1 h cold-start phase (505 s and 7.47 km), intermediate speed (525 s and 8.45 km) and high speed (832 s and 14.72 km)	NO_X, THC, CO, PM: significant ↑	PM emission below the current Tier 3/LEV III light-duty highway vehicle limit
[92]	Spark ignition passenger vehicles of class M1 (3-way catalyst)	WLTC	34% urban 33% rural 33% motorway	NO_X, CO, and CO_2: ↓	

Table 6. *Cont.*

Reference	Vehicle	Comparison Criteria	Route Information	Impact on Primary Emission	Remarks
[103]	Euro4 emission compliant manual transmission petrol	Traffic congestion	5 km, Speed limit 48 km/h Route A: 8 right and 3 left turn Route B: 5 right and 6 left turn 3 sets of traffic lights 4 pedestrian crossing	NO_X, CO, THC: higher at lower speeds and reduced as the speed increased CO_2 were higher than the limit	
[100]	Bus	Waste cooking biodiesel & LPG	Daily operating route	NO_X, PN: ↑ PM: ↓	
[83]	Diesel truck	Environmental constraint	Altitude ranges < 1000 m, 1000~1500 m and 3000~4000 temperature range: 10~20 °C	NO_X: high altitude reduces emission	
[114]	109 diesel and gasoline vehicles	On-road NO_X vs. lab-based tests	Average speed 15-40 km/h Metropolitan area (50–60 km/h), Downtown areas (80–90 km/h) & Rural areas (100–110 km/h)	On-road emissions 5 times lab-based experiments	

6. Comparison of RDE and Laboratory Testing

Degraeuwe and Weiss [118] compared NO_X emissions from on-road testing and laboratory-based NEDC tests for diesel and gasoline vehicles. According to the authors, the NO_X emissions of diesel engines in laboratory tests are below the emission level limit, but on-road emissions are far above the limit. The on-road emissions from gasoline vehicles are higher than the NEDC pollution values, but they are still within the emission limits. On-road NO_X emissions for diesel cars are 181 percent higher than the NEDC average. Several national form approval authorities confirmed that tested vehicles emit emissions below the limit in a laboratory setting, but 4.5 to 4.7 times higher than the limit for EURO 5 and EURO 6 vehicles [119,120]. In contrast to laboratory-based experiments, on-road tests released 50% more NO_X, according to Pirjola et al. [121]. Valverde et al. [122] conducted on-road and in-laboratory NEDC studies on diesel and gasoline vehicles. On-road emissions for diesel vehicles were 14 times higher than NEDC tests and 6 times higher than type approval limits, according to the authors. The authors also stated that PN emissions for diesel cars were below the TA limit in both on-road and laboratory tests, and CO_2 emissions for on-road were marginally higher than the TA limit. On-road and in-lab NO_X emissions from gasoline vehicles were within the TA cap. On-road emissions and chassis dynamometer-based in-lab measurements were compared by Besch et al. [123]. The authors used two different routes with a Jeep Grand Cherokee and found that NO_X emissions were significantly higher on both routes as compared to chassis dynamometer cycles. Park et al. [114] also reported that on-road NO_X emission was five times higher than laboratory-based emission tests. On the contrary, Thomas et al. [92] reported 34% lower NO_X emission and 60% lower CO emission compared to laboratory cycle-based emission results. The major factors for such discrepancies between on-road and laboratory-based emission findings are that on-road emissions are affected by various factors that are not considered in laboratory-based driving cycles, such as driver aggression, congestion, road gradient, etc. Furthermore, most authors indicated that NO_X and PN emissions are the ones that differentiate from laboratory studies.

7. Conclusions

The transport sector significantly contributes to global GHG emissions. In order to achieve the zero-emission target, it is important to reduce these emissions. The paper discusses several current techniques to evaluate vehicle emissions. Conventional testing procedures include engine emission testing and vehicle chassis dynamometer testing. For several decades, these two testing procedures were the most used ones. However, in recent years researchers have found a significant difference in emissions reported using type emission tests and on-road emission tests. The test drive cycles employed to measure the emissions produced by vehicles are expected to adequately represent the vehicle's real-world driving pattern to provide the most realistic estimation of these levels. However, which is not the case. Furthermore, two recent scandals have identified that auto manufacturing companies use emission defeat devices that would reduce vehicle emission by tracking when used in chassis dynamometer and enabling emission reduction techniques. These have resulted in researchers prioritising on-road emission tests known as RDE testing. The paper discusses RDE development methods and reviews past works.

The review shows that various factors such as traffic signal, driving dynamics, congestions, altitude, ambient temperature etc., have a significant impact on on-road emissions. The literature review shows that driving behaviour, along with the driving route, significantly impacts vehicle emission, which is not represented in type emission tests. For example, aggressive driving behaviour increased NOx and CO emissions three times than normal driving behaviour. Route characteristics such as traffic lights, right/left turns, roundabouts, gradients all found to have a significant impact on vehicle emissions. The literature review also indicated that modern vehicle technologies such as start-stop systems also affect vehicle emission. The start-stop system results in increased emission due to the engine not operating in conditions intended, i.e., stoichiometric operation and operating temperatures because of frequent stops and starts. This contributes to the disturbance of the mixture composition (enrichment during acceleration, idle when reducing the rotational speed). These factors cause the engine to work on mixtures other than stoichiometric, i.e., unfavourable from the point of view of exhaust emissions and exhaust after-treatment systems. This also corroborates the fact that an internal combustion engine performs best under constant operating conditions. The driving dynamics are not represented in the current laboratory-based test procedures. Thus, it is important to consider all these factors when developing a real drive emission cycle to evaluate the emission level of any vehicle. This, in turn, will significantly improve the air quality around the world.

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Nomenclature

ACC	Adaptive cruise control
ADR	Australian Design Rules
AEMS	Aerosol Emission Measurement System
ARHR	Arterial road hot running
ARHS	Arterial road hot start
CADC	Common Artemis Drive Cycle
CNG	Compressed natural gas
CUEDC	Composite Urban Emissions Drive Cycle
DNEPM	Diesel National Environment Protection Measure
ECE	Economic Commission for Europe

EGR	Exhaust Gas Recirculation
ELR	European Load Response
ESC	European Stationary Cycle
ETC	European Transient Cycle
EUDC	Extra Urban Driving Cycle
FTP	Federal Test Procedure
GPF	Gasoline particle filter
HDV	Heavy-duty vehicle
LANF	Los Angeles Non-Freeway
LDV	Light-duty vehicles
LNG	Liquid natural gas
LPG	Liquified petroleum gas
MPS	Micro proportional sampling system
NEDC	New European Driving Cycle
NEPC	National Environment Protection Commission
NRMM	Non-Road Mobile Machinery
NYNF	New York Non-Freeway
PEMS	Portable Emission Measurement System
PFI	Port fuel injection
PM	Particulate matter
PN	Particle Number
RDE	Real driving emission
SCR	Selective Catalytic Reduction
TA	Type approval
TWC	Three-way catalytic converter
UDC	Urban driving cycle
UDDS	Urban Dynamometer Driving Schedule
UNECE	United Nations Economic Commission for Europe
VOC	Volatile Organic Compound
WHDC	Worldwide harmonised Heavy-Duty Certification
WHTC	Worldwide harmonised Transient Cycle
WHVC	Worldwide harmonised vehicle cycle
WLTC	Worldwide harmonised Light-duty Test Cycle
WLTP	Worldwide harmonised Light-duty Test Procedure
WTVC	Worldwide transient vehicle cycle

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