Real Driving Emissions

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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 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 affect 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.

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 the 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].

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].

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 [8]. Pollutants carry microorganisms that are highly invasive to humans, affecting the immune system and making people more susceptible to pathogens [9]. 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 [10], traffic conditions [10], fuel quality and specifications [11], the technology behind the vehicle design, such as emission control technology [12][13], and ambient conditions [13][14]. 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 [15]. As a result, the engine operates in a rich fuel-air ratio, and thus emissions are increased [16]. 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 systems can increase CO and NOx emission and sometimes double 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 [15][17]. 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 [18][19][20]. 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) [21]. The NRMM vehicle group includes construction machinery, farm tractors and machines, and special-purpose machinery [22][23]. This group of vehicles is subject to separate regulations on exhaust emissions which was detailed by Waluś et al. [24]. Emissions from such machinery are also tested against standards during approval; however, these tests are conducted in real operating conditions [23][25][26][27].

Previous reviews on emission test procedures generally focused on various aspects of vehicle certification procedures. For example, Mahlia et al. [28] 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. [29] 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 [30] 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 [31]. 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 [32][33]. Since the early 1960s, vehicles' compliance with emission regulations has been checked using standardised tests [34]. 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 [35][36][37][38]. 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 [39]. 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 [40]. 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 [41]. These also help traffic engineers in designing traffic control systems considering traffic flows and delays [42]. Environmentalists can negotiate specific driving patterns to reduce pollution generated based on these cycles [43]. 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 [36][42].

3. Legislative Test Drive Cycles for the Emission Type Approval

Regulatory and certification authorities often use two basic philosophies when designing a driving cycle [15]. In the first philosophy, the driving cycle consists of a sequence of repetitions of a combination of several vehicles 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.

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 [44]. 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 [45][46]. 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 vehicle real drive emission [47].

EU has mandated RDE norms or in-use compliance standards since September 2017 to minimise this difference [48][49]. 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 [50]. 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 1** shows the TA tests and real operating conditions requirements for passenger vehicles between 2015 and 2022.

Table 1. 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, NO_X, PN emissions: EC 427/2016 and EC 646/2016						CO, NO_X, 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 [51]. **Table 2** presents the trip requirements for RDE.

Table 2. EU RDE route design specification (Regulation 2016/427).

	Unit	Urban	Rural	Motorway	Notes
Speed (V)	km/h	V ≤ 60	60 < V	90 ≤ V ≤ 145	V > 100 for at least 5 min in motorway
Distance	% of total	29–44	33 ±	33 ± 10	

	Unit	Urban	Rural	Motorway	Notes
	distance		10		
Minimum distance	km	16	16	16	
Avg speed (V_{avg})	km/h	15 ≤ V_{avg} ≤ 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 [52]:

- 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 [53]. 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 [54]. 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. [55] 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 motorways 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. [56] 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. [57] 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 the 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 emissions compared to diesel vehicles. This could be attributed to the TWC of gasoline vehicles which might have reduced the VOC emissions. Highway operating conditions emitted much lower VOC emissions compared to urban road conditions.

Du et al. [58] tested the effect of cold-start on primary emission parameters. For the experiment, light-duty gasoline vehicles were selected, which were equipped with a 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 in CO, CO_2 and PN emission at the cold-start compared to a hot start.

Habib [59] 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. [60] 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. [61] 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 [62] 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. [47] 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. [63] 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. [64] 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. [65] 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. [66] 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. [67] 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. [68] 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 [69]. It is to be noted from the research of Warguła et al. [23] 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 [70], CO, CO_2 and NOx emissions with increasing HC emission [23]. 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 [71]. 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 [72][73]. 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. [74] 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 [75], the authors concluded that if households switched from conventional vehicles to electric vehicles, they could reduce their GHG emissions significantly.

Andersson et al. [76] 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. [77] 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. [78] 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. [79] 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.

6. Comparison of RDE and laboratory testing

Degraeuwe and Weiss [80] 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 [81][82]. In contrast to laboratory-based experiments, on-road tests released 50% more NO_X, according to Pirjola et al. [83]. Valverde et al. [84] 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. [85]. 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. [78] also reported that on-road NO_X emission was five times higher than laboratory-based emission tests. On the contrary, Thomas et al. [56] 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. Conclusion

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. In addition, 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 were 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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