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Complex Independent Laboratory Tests to Signify Fuel Economy and Emissions under Real World Driving

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Abstract

We discuss the shortcomings of the current European Union emission rules, which are not likely to produce any improvement of fuel economy and emissions during real-world driving vs. the pre-Diesel gate rules, because of flaws in the prescribed laboratory and on-the-road tests. The present chassis dynamometer emissions certification test is oversimplified, not representative, and not properly performed. The simple addition of generic on-the-road real-world driving tests does not help, because these tests have poor accuracy and repeatability. Therefore, we suggest the use of a more realistic, complicated, suite of driving cycles, to be rigorously performed with chassis dynamometer equipment by independent bodies, rather than the Original Equipment Manufacturers (OEMs). Additionally, we suggest that emission limits be revised, to permit the optimal mix between different engine technologies and different fuels.

Keywords: internal combustion engine, emissions, fuel consumption, certification

1. Introduction

In the aftermath of the Volkswagen Group (VW) emissions scandal of 2015, Boretti [1], the move to real driving emissions (RDE) tests has been drastically accelerated. The new emission rules will have to be closer to real-world driving and designed to deliver the best global results in terms of environment, economy, and sustainability. Certainly, the emission tests will have to be much more complicated and performed by independent bodies. The new emissions tests must be carefully designed to not simply phase out the internal combustion engine (ICE) for the sake of electric mobility, which can in many cases have serious environmental and economic disadvantages.

For a historical perspective, VW was accused of having programmed their diesel engines to "*activate certain emissions controls only during laboratory emissions testing*" causing "*the vehicles' NOx output to meet US standards during regulatory testing but emit up to 40 times more NOx in real-world driving*". The accusation was technically flawed, as the emission standards solely required compliance during the prescribed procedure, the FTP, in full laboratory tests. There is no emission standard that requires a vehicle to comply with certain emissions or fuel consumption limits for any other vehicle use or test equipment. The VW cars homologated for the US market were compliant with the FTP. However, these vehicles were then emitting different amounts of pollutant and using different amounts of fuel when operated differently. This was no surprise. There is no reason to expect the same limits to be satisfied over every other possible operation of the vehicle under every possible condition.

The measurements collected by the consultants of the ICCT were performed without any scientific method by using inappropriate schedules vaguely defined "*real world driving*". Simply, the cars were tested on the road. They discovered what

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many automotive engineers already knew: the OEMs tune their products to perform well on the prescribed certification tests. Apart from the specific “defeat device” (en.wikipedia.org/wiki/Defeat_device) used to turn-off the NOx emissions control when not covering the regulatory cycle (so yielding better fuel economy and engine performance), every OEM uses techniques to deliver good performance on the homologation test without penalizing the real-world driving operation.

While VW certainly used defeat devices, it is not known if other OEMs manipulated their controls to identify testing conditions, intentionally turning on and off features during testing and not testing. It is however shared knowledge that a specific calibration is performed for the test cycle of the country of homologation. The calibration is not advanced, nor mature enough, to reduce emissions during off cycle as well as it does during the specific cycle of homologation. Until new emission standards are defined, a vehicle remains compliant if the emissions fall below the limits during the prescribed certification tests. Compliance is not determined in any other way.

As discussed in Boretti [1], the United States Environmental Protection Agency (EPA) and the United States prosecutes, initiated by the action of the International Council on Clean Transportation (ICCT) have forced the OEM towards a rapid transition to battery based electric mobility. The latest decision of the EU to ban the internal combustion engine (ICE) by 2030, which does not leave much opportunity to improve the ICE, is a logical consequence of the VW scandal, as predicted in Boretti [1]. However, electric mobility is very far from becoming a real substitute, Boretti [2]. Hence, there is a need to properly improve emission standards.

As Europe was the driving force behind the rise of the diesel for passenger car applications, it was not a surprise that Europe was the first to react to the scandal with different measures, including the definition of new emission standards. The procedure based on the anachronistic New European Driving Cycle (NEDC), a cycle designed by using a ruler, is being replaced by a procedure based on the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), with the transition from NEDC to WLTC occurring over the period 2017-2019. Passenger cars must still satisfy pollutant emissions below the Euro 6 thresholds and be labelled with their CO_2 emissions. While there are several WLTC test cycles applicable to vehicle categories of different power-to-mass ratio, a given passenger car must perform within the standards only over a single test cycle. A single test cycle was also only required by the NEDC. However, in addition, RDE supplementary tests have been introduced. The feedback from independent chassis dynamometer and RDE tests is still missing, as it is premature to expect such a feedback from new rules not even being completely introduced. However, these two measures – the NEDC replaced by the WLTC, and the introduction of RDE supplements - are not expected to ensure that the real-world emissions are really within the agreed Euro 6 emission standards.

Within Australia, the current minimum standard for new light vehicles is ADR 79/04, based on the Euro 5 standards, Australian Government Department of Infrastructure, Regional Development and Cities [3]. This rule is still being reviewed to consider whether Australia should adopt the Euro 6 standards for new light vehicles. It is still unclear if, and for how long, Australia will continue to accept vehicles declared compliant by the Original Equipment Manufacturers (OEM) with Euro 5 and Euro 6 standards. It is also unclear whether emissions compliance will be determined over the chassis dynamometer with the NEDC or WLTC, and/or over laboratory tests, and/or supplemented with RDE tests.

The requirement in Euro 6 regulations to further lower the NOx limit of diesel-powered vehicles down to the same limit as gasoline vehicles have significantly raised the cost of the diesel. At the same time, the regulations reduce the competitiveness of the diesel regarding fuel economy. The Euro 6 regulations drastically increased the cost of diesel, making them a very difficult commercial proposition for subcompacts and minicars, while still providing advantages for long highway drives in large sedans. The novel emission standards will also have to carefully weigh the minimum amount permitted for all the regulated pollutants, to permit the best mix of different solutions in the different segments, and for different uses, to achieve the best global outcomes.

Fig. 1 presents an example of traffic congestion, in Melbourne, Victoria, Australia. The drivers of passenger cars and light-duty vehicles experience real-world driving conditions that have very little in common with the short, highly stylized, simplified, driving schedule that are used for emission certification. Melbourne's suburban and city roads are struggling to meet the demands of the fast-growing population. Peak hour has stretched to six hours a day across Melbourne's congested road network, 6:30am to 9 am and 3 pm to 6:30 pm each day. This translates in longer, more frequent stops, and driving at a small fraction of the speed limit during the lengthened peak-congestion periods. According to www.tomtom.com, in 2016 the increase in the morning peak travel time for Melbourne was 55%, while the increase in the evening peak travel time was 58%. The global congestion level was 33% more time if compared to free flow uncongested conditions, or 34 minutes extra travel time per day, for two average rides of 103 minutes per day. Therefore, during peak hours, commuters may spend more than one hour and one half for every section of their return trip, experiencing driving conditions that have nothing to do with the New European Driving Cycle (NEDC) or the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) used in the certification test.

Fig. 1 Traffic congestion in Melbourne, Australia

The aim of the paper is to discuss the changes needed in the European Union emission rules to ensure that the compliant vehicles will then meet the expectations of emissions and fuel economy when driven on the road, while accounting for the use of all the available fuels and different engine technologies (e.g., stoichiometric, lean-burning homogeneous or stratified, premixed or diffusion combustion, spark or compression ignition, see Boretti and Watson [4], Boretti [5], Boretti and Watson [6], Boretti [7], Boretti, Paudel and Tempia [8]).

Diversification of engine technologies and combustion fuel supply, not only traditional fossil fuels, but also alternative fossil fuels and synthetic fuels and biofuels, see Dhinesh et al. [9], Annamalai et al. [10], Subramani, Parthasarathy, Balasubramanian, and Ramalingam [11], Dhinesh and Annamalai [12], Dhinesh, Raj, Kalaiselvan and Krishna Moorthy [13], should also be considered in determining the emission levels. This is because emissions cannot be the same for different fuels and different engine technologies, as every fuel and engine technology has its own emission advantages and disadvantages.

The paper first examines the flaws of the current laboratory procedures, then the pitfalls of the current additional on-road tests. A suite-of-cycles laboratory test is then proposed to address the issues of repeatability, representability, and reliability. A discussion and conclusion section then close the paper.

2. Flaws of Current Laboratory Procedures

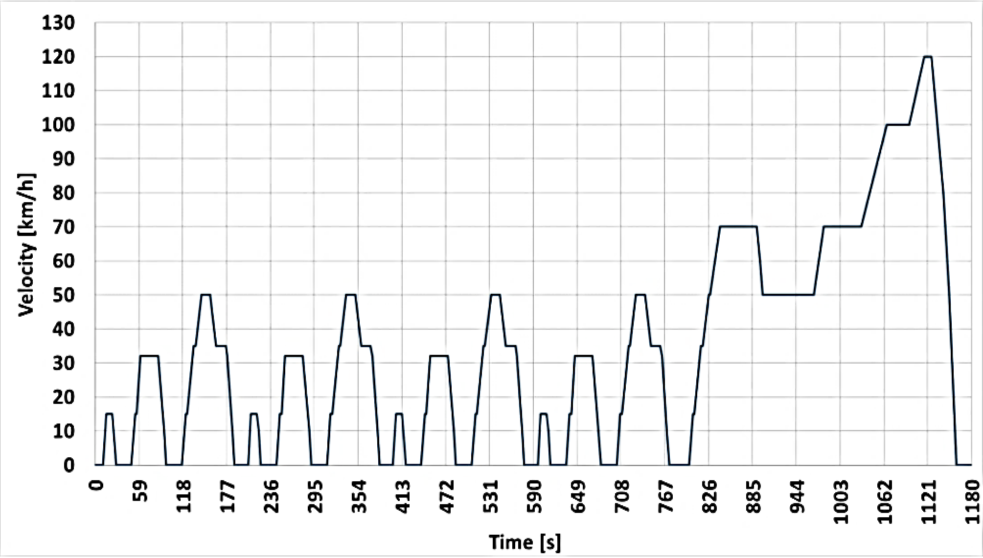

Fig. 2 NEDC cycle. Velocity vs. time

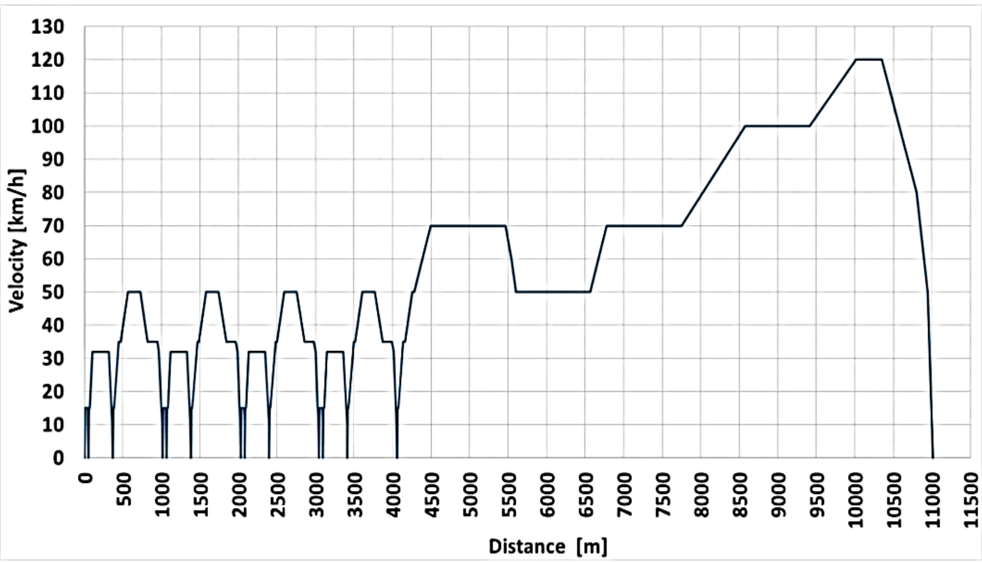

Fig. 3 NEDC cycle. Velocity vs. distance

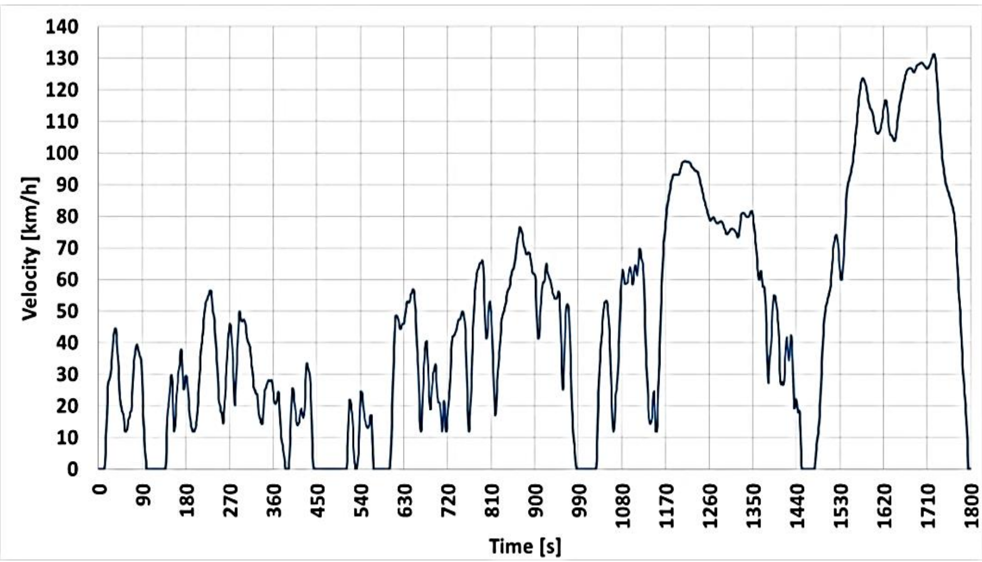

Fig. 4 WLTC cycle. velocity vs. time

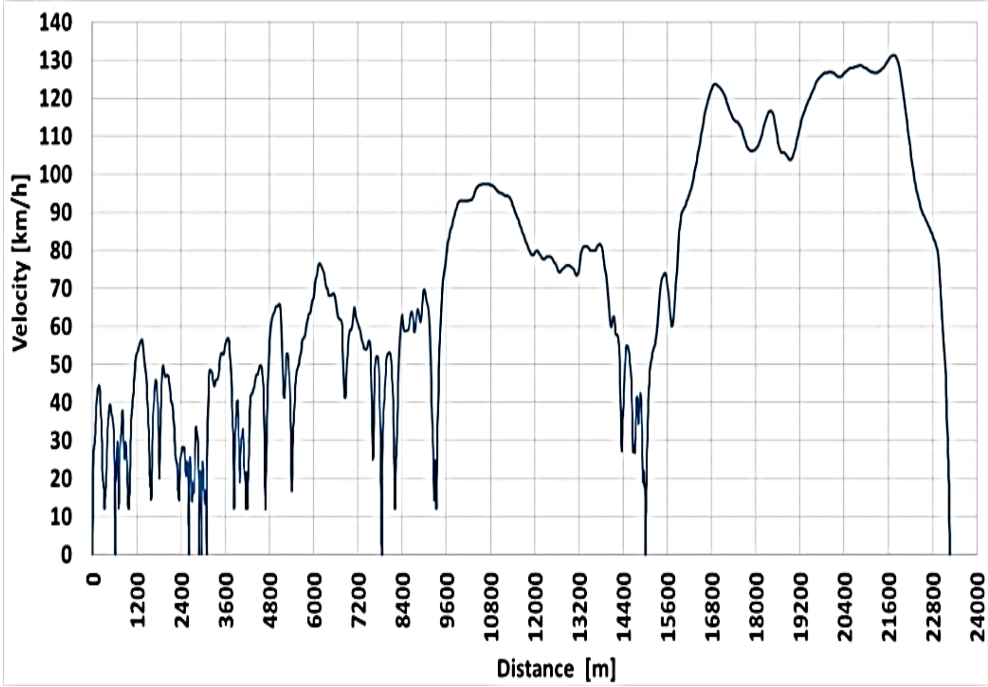

Fig. 5 WLTC cycle. velocity vs. distance

Figs. 2-3 and Figs. 4-5 present the NEDC and WLTC schedules, while Table 1 and Table 2 summarizes the main parameters of the two cycles. All the Euro rules, including the latest Euro 6 rules, have been based for many years on the unrealistic, simplistic, short, cold-start, New European Driving Cycle (NEDC). The NEDC is a stylized driving speed pattern with low accelerations, constant speed cruises, and many idling events. This cycle was designed by using a ruler, with 4 very simplistic city driving sections, followed by 1 extra urban driving section that is concluded with a sharp deceleration from 120 km/h to rest, as shown in Fig. 2. The NEDC cycle, and the procedure that was using this cycle had many critics, as it is reported in the literature:

Table 1 NEDC parameters

Phase	*Duration [s]*	*Stop Duration [s]*	*Distance [m]*	*Percentage stop*	*v_{max} [km/h]*	*v_{ave} w/o stops [km/h]*	*v_{ave} w/ stops [km/h]*	*a_{min} [m/s^2]*	*a_{max} [m/s^2]*
ECE15-1	195	57	994.1	29.23%	50	25.93	18.35	-0.93	1.042
ECE15-2	195	57	994.1	29.23%	50	25.93	18.35	-0.93	1.042
ECE15-3	195	57	994.1	29.23%	50	25.93	18.35	-0.93	1.042
ECE15-4	195	57	994.1	29.23%	50	25.93	18.35	-0.93	1.042
EUDC	400	39	6954.9	9.75%	120	69.36	62.59	-1.39	0.833
Total	1180	267	10931.3						

Table 2 WLTC parameters

Phase	*Duration [s]*	*Stop Duration [s]*	*Distance [m]*	*Percentage stop*	*v_{max} [km/h]*	*v_{ave} w/o stops [km/h]*	*v_{ave} w/ stops [km/h]*	*a_{min} [m/s^2]*	*a_{max} [m/s^2]*
Low 3	589	156	3095	26.50%	56.5	25.7	18.9	-1.47	1.47
Medium 3-2	433	48	4756	11.10%	76.6	44.5	39.5	-1.49	1.57
High 3-2	455	31	7162	6.80%	97.4	60.8	56.7	-1.49	1.58
Extra-High 3	323	7	8254	2.20%	131.3	94	92	-1.21	1.03
Total	1800	242	23267						

i. The NEDC cycle is out-of-date, it does not represent real-world driving conditions (Parker [14], Mock, German, Bandivadekar, and Riemersma [15], Plotkin [16], Kågeson [17], Steen [18], Shaw [19], Peker [20]).

ii. The procedure is not accurate (Parker [14]).

iii. The fixed speeds, gear shift points and accelerations of the NEDC offer possibilities for manufacturers to engage in "*cycle beating*" to optimize engine emission performance to the corresponding operating points of the test cycle, (Mock, German, Bandivadekar, and Riemersma [15]).

iv. Emissions from typical driving conditions would be much higher (Mock, German, Bandivadekar, and Riemersma [15]).

v. It is also claimed that the tests can be conducted at 2 km/h below the required speed for better fuel economy (Mock, German, Bandivadekar, and Riemersma [15]).

vi. Roof-rails and passenger door-mirror can be removed for the test (Mock, German, Bandivadekar, and Riemersma [15]).

vii. Tire-pressures for the test can be set above the recommended values thus reducing rolling-resistance (Mock, German, Bandivadekar, and Riemersma [15]).

viii. The cycle allows large emission differences between test and reality (Kågeson [17]).

ix. The cycle has numerous loopholes (Steen [18], Shaw [19], Peker [20]).

x. The NEDC tests are not necessarily repeatable and comparable (Steen [18]).

xi. The NEDC tests can be performed using optional economy settings which will not typically be selected by drivers (Steen [8]).

xii. The NEDC test-cycle is performed with air-conditioning switched off (Steen [18]).

xiii. No official-body polices the tests (Parker [14]).

xiv. Compliance is declared by the OEM without independent verification (Parker [14]).

xv. The latest sharp deceleration from 120 km/h to zero never occurs in real-world driving (Parker [14]).

xvi. This deceleration ending the cycle especially rewards hybrid vehicles (Parker [14]).

xvii. The last high-speed driving section in the NEDC reduces the fuel consumption over the cycle (Parker [14]).

xviii. The cycle does not include traffic congestion (Parker [14]).

xix. For diesel cars no significant NOx reductions have been achieved after 13 years of stricter standards (European Federation for Transport and Environment [21]).

xx. Similarly, to the NOx emissions, even if not claimed so far, it is also questionable whether there has been real improvement in CO2 emissions and fuel economy over the last 13 years.

About these two latter statements, it is a matter of fact (US Environmental Protection Agency [22]) that the EPA has resolved a civil enforcement case against VW alleging violations of the Clean Air Act by approximately 590,000 diesel vehicles sold in the United States. "*Specifically, the U.S. complaint alleges that each of these vehicles contains, as part of the engine control module, certain computer algorithms and calibrations that cause the emissions control system of those vehicles to perform differently during normal vehicle operation and use than during emissions testing. The U.S. complaint alleges that these computer algorithms and calibrations are prohibited defeat devices under the CAA, and that during normal vehicle operation and use, the cars emit levels of NOx significantly in excess of the EPA compliant levels.*"

It is a fact admitted by VW in a court-of-law settlement, that the emissions of their diesel cars under real-world driving were largely exceeding the present emission standards in the United States. The actual on-the-road NOx emissions of these 590,000 diesel vehicles were well above the thresholds, not only of the latest emission standards, but also on the prior emission standards, Franco, Sánchez, German, and Mock [23], Thompson, Carder, Besch, Thiruvengadam, and Kappanna [24].

The lack of any improvement of the diesel in real-world driving has been the result of flawed procedures and lack of any independent control on the compliance and CO_2 performances that are declared by the OEM. This is not addressed by simply replacing the NEDC cycle of Fig. 2 with the WLTC of Fig. 4 and introducing inaccurate and irreproducible RDE supplementary tests.

Despite being longer (1,800 s vs. 1,180 s, or 23,262 m vs. 11,013 m), the WLTC is still a single cycle, hence the engine and vehicle control can still be highly optimized to perform well over this cycle, leaving other vehicle operation condition unassessed. The WLTC still closes with the unrealistic final deceleration from 130 km/h to rest, that disproportionately rewards hybrids and electric vehicles. The WLTC still has a significant highway driving component resulting in much lower fuel consumption than during the real-world driving in congested city traffic. The WLTC does not have the many stops of normal city driving.

The reasons why the NEDC test procedure failed was not only because the driving schedule was simplistic and unrealistic. It was also because the results of the fuel economy and emissions tests were declared by the OEM and not measured by independent organizations. This yielded claims of fuel economy and CO_2 emissions that were inconsistent, Parker [14]. This meant that the consumption of one litre of nominally equivalent petrol or diesel fuel produced very different CO_2 emission results. In addition, real-world driving fuel economy and emissions were largely underrated.

A major flaw was that the tests were performed without any detailed specification of the actual fuel properties, and the fuel economy is not directly measured, but rather, it is indirectly computed from inaccurate formulae that use the emitted pollutant levels.

In the UNECE R101, the fuel consumption is calculated from the measured emissions of hydrocarbons, carbon monoxide, and carbon dioxide. The fuel consumption (FC), expressed in liters per 100 km is calculated by means of the following simplistic formula for petrol engines

$$FC = (0.118/\rho)\cdot[(0.848\cdot HC) + (0.429\cdot CO) + (0.273\cdot CO_2)] \tag{1}$$

And the following formula for diesel engines

$$FC = (0.116/\rho)\cdot[(0.861\cdot HC) + (0.429\cdot CO) + (0.273\cdot CO_2)] \tag{2}$$

In the previous equations HC, CO and CO_2 are the measured emission of hydrocarbons, carbon monoxide and carbon dioxide in g/km, while ρ is the (specific) density in kg/liter of the test fuel. As explained in Parker [14], the above simplistic procedure is significantly inaccurate. Pump gasoline and diesel fuels are refined products containing mixtures of many different hydrocarbons. In the case of gasoline, they may also contain a significant amount of oxygenates. The fuel properties, including the density, carbon and energy content strongly vary from one fuel pump to another. The above equations are theoretically valid only for a precise C/H ratio for gasoline or diesel.

Diesel fuel may have a carbon content that varies from C_3 to C_{25}, or a mass percentage of carbon in the range 84-87% with a hydrogen range of 13-16%. The specific density may range from 0.81 to 0.89. The lower heating value may range from 41.87 to 44.19 MJ/kg. Boiling temperatures, Cetane number, and viscosity also vary significantly.

A gasoline fuel may vary even more, even before accounting for mixing with methanol CH_3OH and ethanol C_2H_5OH. A gasoline fuel may have a carbon content ranging from C_4 to C_{12}, or a percentage of carbon in weight 85-88% and hydrogen 12-15%. The specific density may range from 0.72 to 0.78. The lower heating value may also range from 41.87 to 44.19 MJ/kg. Boiling temperatures, Reid vapor pressure, Octane number, and viscosity also vary significantly.

The UNECE R101 procedure simply does not work with real petrol and diesel fuels available at commercial pumps, because of their significantly variable properties.

As an additional remark, the concentrations of HC, CO, and CO_2 are difficult to measure with the same accuracy as the mass of fuel consumed, the density of the fuel and the lower heating value of the fuel.

It is no surprise that the actual CO_2 emission and fuel economy figures may differ largely from the certified values. The analysis of the 2014 UK government data for 2,358 types of diesel and 2,103 petrol vehicles of Parker [14] showed that same volume of pump fuels used during the certification test by the OEM, unfortunately, produced very different CO_2 emissions. Very likely, these pump fuels also had very different energy contents in addition to very different carbon contents. The CO_2 emission per liter of diesel fuel was shown in Parker [14] to range from a maximum of 3,049 g for a minimum of 2,125 g, with an average of 2,625 g. The CO_2 emission per liter of petrol fuel was shown in Parker [14] to vary even more, from a maximum of 3,735 g to a minimum of 1,767 g with an average of 2,327 g.

The analysis in Parker [14] was based on the UK government data (UK Vehicle Certification Agency [25]). Because of fuel price (fuel consumption) and taxation (CO_2 emission) both contribute to the vehicle cost, CO_2 and fuel economy data were supposed to be consistent.

Apart from Parker [14], the scientific literature does not report any technical discussion of the European certification test regarding the reliability of the CO_2 and the fuel economy figures declared by the OEMs. This lack of a healthy, technical discussion is what then generated the VW emissions scandal.

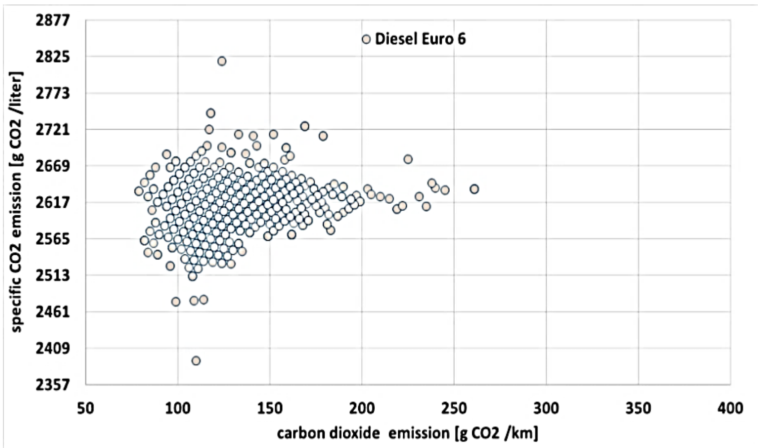

Fig. 6 Relative CO_2 per litre of theoretically same diesel fuel as accepted by the UK Govt. Data August 2017 as retrieved from UK Vehicle Certification Agency [25]

Figs. 6 - 7 present the latest data collected by the UK government for 2,560 diesels and 2,379 petrol vehicles satisfying Euro 6 emission standards that were available for sale in the UK during August 2017. These are the data declared by the manufacturers and not the result of independent tests.

Fig. 6 shows the carbon dioxide emissions in g CO_2 per litre of diesel fuel consumed. The average is 2,617 g of CO_2 per litre. However, apart from outliers which are very likely errors in the transcription, there is a large spreading between different cars of several percentage points that is illogical, as a litre of diesel should produce the same CO_2 emission, if one assumes that all pump fuels are equivalent for emissions purposes.

Fig. 7 shows the carbon dioxide emission in g CO_2 per litre of petrol fuel consumed. The average is 2,310 g of CO_2 per litre. However, apart from outliers which are very likely errors in the transcription, there is also here a noticeable spreading between different cars of several percentage points that is illogical, as the same litre of petrol should produce the same CO_2 emission.

It stands to reason that one standard liter of diesel produces the same amount of CO_2, and a similar argument can be made for a standard liter of gasoline, only when the combustion of the fuel and the after treatment of the exhaust gases is complete, converting all the hydrocarbons to CO_2 and H_2O. As evidenced by exhaust measurements, this complete conversion is indeed the case for modern vehicles. In carefully designed experiments where the fuel economy and the carbon dioxide emissions are both measured with accuracy, and the same fuel is used, the spreading as found in the UK data is unlikely to occur. In addition to verifying that vehicles pass newly defined emission limits over a suite of more realistic and complicated schedules, there is also the need to make the measurements more rigorous and to perform these measurements in independent laboratories.

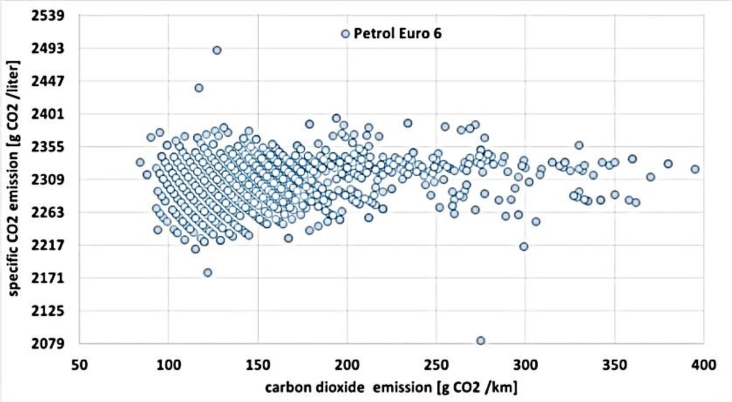

Fig. 7 Relative CO_2 per litre of theoretically same petrol fuel as accepted by the UK Govt. Data August 2017 as retrieved from UK Vehicle Certification Agency [25]

3. Flaws of Current Real-World-Driving Tests

The controversy over dynamometer vs. real-world driving testing, and the criticisms of emission standards, has increased after the VW emission scandal, Costlow [26]. The discussion generated various solutions aimed at closing the gaps, such as the use of Portable Emissions Measurement Systems (PEMS) for real-world mobile emissions testing, Birch [27], or Birch [28]. On the road measurements with PEMS are becoming more and more popular. The EU has been the first to adopt RDE tests to measure the pollutants emitted on the road, Association des Constructeurs Européens d'Automobiles [29], with PEMS. These RDE tests do not replace the chassis dyno full laboratory test, but they complement the standard test.

It is very questionable to claim that compliance with the standard flawed procedure, plus compliance of the RDE tests, ensure that cars will now deliver low emissions for on-road conditions. Every RDE test is different from another. There are major factors (e.g., traffic, weather, stops) that are beyond control and the measurements are inaccurate. Apart from road and weather conditions, there is also no "*standard*" PEMS equipment defined, and equipment manufactured by different suppliers may deliver different results. PEMS measurements cannot provide the same accuracy as a full laboratory experiments on a chassis dynamometer.

RDE step 1 (with a NOx conformity factor of 2.1) has applied since 1 September 2017 to new car types. It will apply to all types as of September 2019. RDE step 2 (with a NOx conformity factor of 1.0 plus an error margin of 0.5) will apply in January 2020 for new types and then from January 2021 for all types. As Association des Constructeurs Européens d'Automobiles [29] admits, conformity factors are defined to account for errors, as the PEMS tests are not as accurate as a full laboratory system, so they will not measure to the same level of repeatable accuracy. While Association des Constructeurs Européens d'Automobiles [29] states that the OEMs must set their design objectives well below the legal limit to be certain about complying, it is still unclear which legal limit they are referring to. So far, there is no legislation prescribing threshold pollutant emissions other than the full laboratory cold start NEDC.

As an example of RDE tests on Australian roads, ABMARC [30] presents a summary of the emissions and fuel consumption test results from seventeen different passenger and light-duty vehicles measured by PEMS. The number of vehicles powered by petrol, diesel, and LPG were 10, 6 and 1 respectively. Each vehicle was tested twice, with one cold and one warm. The testing was conducted on Melbourne roads between May 2016 and March 2017, i.e. winter to summer, under strong variable weather conditions. The vehicles tested were 2014-year models or newer taken from the general service fleet and they have driven at least 2,000 km but no more than 85,000 km. The tests were conducted by driving each vehicle around a route consisting of urban, extra-urban and freeway driving, with approximately one-third of the test being driven in each segment. Each test is driven in normal traffic conditions. The covered distance is more than seven times the distance covered during the NEDC.

The actual velocity schedule is not provided in the report ABMARC [30]. It would have been interesting to compare the NEDC velocity schedule with the RDE velocity schedule, and possibly compute the energy requirements and the stop timings of both. Similarly, relevant, especially for NOx, could have been a comparison of the temperature traces of air, metal, and media, also not provided in ABMARC [30].

On average, the real-world fuel consumption across all vehicles tested was 25% higher than the official fuel results based on the cold start NEDC tests. This is not a surprise. The fuel economy always changes to the driving schedule. The average fuel consumption of vehicles improved when tested with a warm engine. The real-world average fuel consumption for warm engines was 22.9% higher than the official results on the NEDC tests. The few percentages penalties due to cold start are also not a surprise.

One interesting result was that fuel economy penalties were larger for diesel than petrol vehicles. On average, diesel vehicles have the highest variation between real-world fuel consumption and the laboratory results, with 30.4% higher consumption during the cold test. ABMARC [30] suggests that the real-world fuel consumers of diesel vehicles is harder to predict based on the NEDC laboratory results. We add those individual drivers may provide different fuel economies covering the same path.

Regarding the exceedance of specific laboratory pollutant limits during real-world driving, all the NOx limit failures were by diesel vehicles. Only 1 of the 6 diesel vehicles satisfied the limit when tested on the road. Diesel vehicles have been otherwise usually compliant for PM emissions with 1 exception of the cold test only. PM emissions were comfortably met for the cold test, but not during the hot test. Two of the 10 petrol vehicles exceeded the CO limits both hot and cold.

In the summary table of ABMARC [30], which only showed data for cold conditions, the 3 diesel Euro 4 vehicles exceeded the NEDC NOx and HC+NOx limits, while they complied with the CO limit. One of the three failed the PM limit. The 2 petrol (gasoline) Euro 4 vehicles passed the NOx, CO and NHMC tests. The only one Euro 5 diesel vehicle failed the NOX and HC+NOx tests, but passed the CO and PM. Of the 7 Euro 5 petrol vehicles, 2 failed the CO test, and 1 the NHMC test while passing all the other tests. Finally, of the 2 diesel Euro 6 vehicles, 1 failed the NOx and HC+NOx limits and the only one euro 6 petrol vehicle passed all the tests. The additional vehicle tested was an LPG fueled Euro 4 compliantly and passed all the tests.

It is not a surprise that the diesel struggled with the NOx test. The NOx exceedance may be the result of higher temperatures during real-world driving. Higher ambient air temperatures, as well as higher temperatures of metal and media in the longer RDE, may contribute to the higher NOx.

These tests only demonstrate that different driving schedules may yield different fuel economies and that the lean burning diesel engines struggle with NOx emissions. There is a significant in-cylinder production of NOx and an inadequate reduction of it by the after treatment relative to the certification test emission requirements. The CO from 2 petrol vehicles and the PM of 1 diesel were probably the result of lack of service.

4. Proposed Suite-of-Cycles Laboratory Tests

Fig. 8 and 9 are examples of results from this independent laboratory testing of a diesel 2014 Chevrolet Cruze Diesel, and of a gasoline Mazda 3 with iEloop. These data are from the Downloadable Dynamometer Database and were generated at the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory under the funding and guidance of the United States Department of Energy (DOE), Argonne National Laboratory [31]. The figures summarize the fuel economy results

Simplistic and anachronistic driving cycles such as the NEDC, but also a single more complex cycle, such as the WLTC, must be replaced with a suite of more difficult cycles. An example of the use of a limited suite of cycles, but only for fuel economy tests, is from Argonne National Laboratory [31], which offers in their The Downloadable Dynamometer Database (D3) publicly available testing data regarding advanced technology vehicles including a few conventional vehicles.

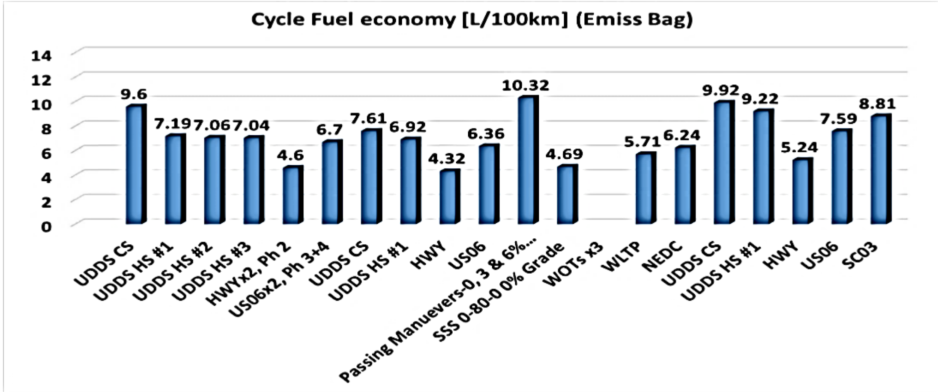

Fig. 8 Fuel economy of a 2014 Chevrolet Cruze Diesel. Test Fuel is type 2007 Cert Diesel HF0582, Fuel density 0.851 kg/litre, Fuel Net LHV 42.796 MJ/kg

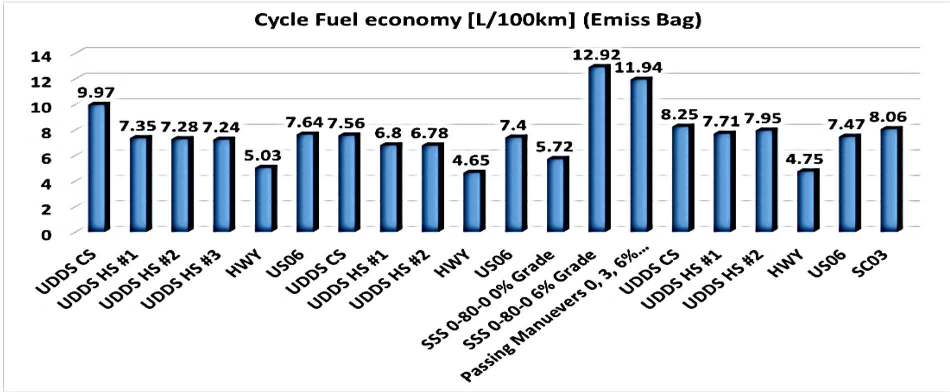

Fig. 9 Fuel economy of a 2014 Mazda 3 with IEloop. Fuel type EPA Tier II EEE HF0437, Fuel density 0.742 kg/litre, Fuel Net LHV 42.68 MJ/kg

A solution to the flaws of the current procedures is to perform the tests independently from the manufacturers, by using the same certification fuel of the same properties, starting from the C/H ratio and the lower heating value, and to measure the fuel consumption and the emissions with accuracy.

5. Discussion and Conclusions

Even without using defeat devices, the OEMs have found their way to achieve fuel consumption and emissions results during the cold start NEDC that drastically differ from the real-world driving emissions and fuel economy that the customers will then experience in their every-day use of the vehicle, ABMARC [30]. The new emission rules will have to address this major pitfall, to make mass mobility more fuel efficient and less polluting. To prevent the sale of vehicles whose real-world driving emissions are far from the current certification levels, it is not acceptable to have uncertain measurements by the OEM on a single certification cycle, followed by independent, poorly defined, inaccurate and irreproducible RDE tests on the road.

The new rules will have to address other major failures of the regulations, such as the one concerning plug-in hybrid vehicles. Instead of the current protocol of testing plug-in hybrids over one drive cycle discharging the battery, the revised rules should add a test without the battery connected. The added test would compensate for the unrealistic zero fuel consumption and emissions during the first cycle. Similarly, the new rules will have to prevent the recharging of the traction battery of the hybrid electric vehicles during the final sharp braking event 120 km/h (NEDC) or 130 km/h (WLTC) to rest that is nowhere to be experienced during real-world driving in Europe but helps hybrid electric vehicles. Also relevant is a different weight of city and highway driving, as hybrids have advantages in stop-and-go traffic, but shortcomings in highway driving, and the length of the travel.

Properly designed new real-world driving emissions tests will completely change the powertrain mix from the present regulations. In addition to lower cost ICEs that can run on gasoline, diesel and alternative fuels, such as ethanol, methanol, LPG, CNG, LNG, DME and ammonia, the new emission rules should promote a hybridization of powertrains.

A major hurdle to better cars powered by ICEs is the proposed ban of the ICE in favor of electric cars in Europe, Oltermann [32], Castle [33], Freedland [34], Adepetu and Keshav [35]. As the electric vehicle mass mobility is still far from being demonstrated to be superior under the economic and environmental criteria of ICE based mobility, this ban will be hopefully revised. Otherwise, the car makers will not invest in improving the ICE technology. As discussed in Boretti [2], it is not feasible in a growing world to completely phase out the ICE in favor of electric cars recharged by renewable energy sources. Hence, better emission standards for ICEs powered vehicles are needed more than ever.

The use of PEMS on vehicles tested on the road is not a reliable solution to the present unrealistic certification tests. Consistent test conditions cannot be enforced, and the results will be inaccurate. On the road, real-world driving tests cannot produce fair assessments. The only positive aspect of these tests is that they are performed by independent bodies and not the OEM, and they use longer and more realistic driving conditions than the NEDC.

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There is certainly a need for standardized and repeatable procedures, but still using rigorous chassis dynamometer tests, that are based on more complex and realistic driving conditions. Hence, what is needed is a chassis dynamometer full laboratory procedure that comprises multiple driving schedules, this time performed by independent bodies. This novel testing procedure will reduce the ability of the manufacturers to implement "*defeat devices*", but also limit the use of emissions reduction technologies that are only effective on a single, test cycle such as the NEDC or the WLTC.

It is proposed that the pollutant thresholds should be dynamically adjusted to permit the best tradeoff. For example, the larger NOx emissions of the diesel engine (relative to the gasoline engine) should be compensated by its much larger fuel conversion efficiencies over most of the load and speed map.

Apart from combined cycle gas turbine (CCGT) power plants and large stationary diesel power generators, most fossil fuel powered electrical generators in the world operate at a fraction of the thermal efficiency of diesel engines for transport. This means that the diesel engine is still needed, and more stringent emission standards can be applied to diesel generators to compensate for possible laxer regulations in transport diesel.

We suggest the definition of new emission rules be used as an opportunity to revise current policies that fail to produce balanced societal outcomes for the environment and a sustainable economy. New emission rules should be universally applicable to all alternative vehicles ranging from electric cars to vehicles powered by hydrogen carrier fuels.

We have discussed the pitfalls of the current European Union emission rules, that will not produce any improvement of fuel economy and emissions during real-world driving vs. the pre-Diesel gate condition. This is because of the flaws in the prescribed laboratory and on-the-road tests that have been evidenced in the paper.

Present laboratory tests are based on a given, simplistic velocity schedule. However, they may be accurate and reproducible, and thus reliable, if performed by independent bodies. On the other hand, real-world driving tests are not very well defined and not repeatable, while emissions and fuel economy measure with poor accuracy. To ensure that emission compliant vehicles will meet expectations in terms of emissions and fuel economy when driven in the real world, it is necessary to introduce accurate, repeatable, representative, complex, laboratory tests independently performed by the certification bodies.

As a further measure, to ensure the optimal mix between different engine technologies (e.g., stoichiometric, lean-burning homogeneous or stratified, premixed or diffusion combustion, spark or compression ignition) and different fuels, such as diesel, gasoline, LPG, CNG, LNG, ethanol, methanol, DME, ammonia, there is a need to dynamically adjust the pollutant emissions thresholds to compensate fuel economy and carbon dioxide emission.

It is to be noted that although lean-burn, compression ignition, diffusion combustion engines may fail to meet extremely stringent emissions of nitrogen oxides, they provide the opportunity to use combustion fuels more efficiently. They also can drastically clean-up the air of extremely polluted areas where some pollutants in the air such as particulate matter, are an order of magnitude more concentrated than at the tail-pipe after the particle trap. This is not only the case for many cities in China, but also the case of some cities in Europe, especially during the winter season. Hence, policy makers should keep in mind all the issues in designing certification tests if targeting the best outcome for real-world consumers.

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Nomenclature

CCGT	Combined Cycle Gas Turbine
EPA	Environmental Protection Agency (US)
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engines
LHV	Lower Heating Value
NEDC	New European Driving Cycle
OEM	Original Equipment Manufacturers
PEMS	Portable Emissions Measurement Systems
RDE	Real Driving Emissions
FTP	Federal Test Procedure (US)
UDDS	Urban Dynamometer Driving Schedule
SFTP	Supplemental Federal Test Procedures (US)
WLTC	Worldwide Harmonised Light Vehicles Test Cycle
WLTP	Worldwide Harmonised Light Vehicles Test Procedure
VW	Volkswagen Group

Conflicts of Interest

The authors declare no conflict of interest.

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