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Does the New European Driving Cycle (NEDC) really fail to capture the NO_X emissions of diesel cars in Europe?☆

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A B S T R A C T

Tests with Portable Emissions Measurement Systems (PEMS) have demonstrated that diesel cars emit several times more NO_X on the road than during certification on the New European Driving Cycle (NEDC). Policy makers and scientists have attributed the discrepancy to the unrealistically low dynamics and the narrow temperature range of NEDC testing. Although widely accepted, this assumption was never been put under scientific scrutiny. Here, we demonstrate that the narrow NEDC test conditions explain only a small part of the elevated on-road NO_X emissions of diesel cars. For seven Euro 4–6 diesel cars, we filter from on-road driving those events that match the NEDC conditions in instantaneous speed, acceleration, CO_2 emissions, and ambient temperature. The resulting on-road NO_X emissions exceed by 206% (median) those measured on the NEDC, whereas the NO_X emissions of all unfiltered on-road measurements exceed the NEDC emissions by 266% (median). Moreover, when applying the same filtering of on-road data to two other driving cycles (WLTP and CADC), the resulting on-road NO_X emissions exceed by only 13% (median) those measured over the respective cycles. This result demonstrates that our filtering method is accurate and robust. If neither the low dynamics nor the limited temperature range of NEDC testing can explain the elevated NO_X emissions of diesel cars, emissions control strategies used during NEDC testing must be inactive or modulated on the road, even if vehicles are driven under certification-like conditions. This points to defeat strategies that warrant further investigations by type-approval authorities and, in turn, limitations in the enforcement of the European vehicle emissions legislation by EU Member States. We suggest applying our method as a simple yet effective tool to screen and select vehicles for in-depth analysis by the competent certification authorities.

1. Introduction

Investigations into the application of defeat devices and manipulated NO_X emissions have sparked a debate about the effectiveness of regulatory emissions testing. In view of persisting NO_2 pollution in many cities across Europe (EEA, 2015), policy makers are more than ever urged to ensure that regulatory procedures (i) accurately capture the on-road emissions of vehicles and (ii) prevent the improper use of defeat strategies. Since 2007, on-road tests with Portable Emissions Measurement Systems (PEMS) in Europe have demonstrated that light-duty diesel vehicles, certified according to Euro 4 up to Euro 6 standards, emit a multiple of the amount of NO_X permitted by the respective emissions limit (Franco et al., 2014; Kadijk et al., 2015b; Ligterink et al., 2013; Rubino et al., 2007; Weiss et al., 2012). These exceedances were attributed to shortcomings in the type approval procedure, namely the low accelerations and the narrow ambient temperature range of 20–30 °C during vehicle certification with the New European Driving Cycle (NEDC) (ACEA, 2015; EEA, 2016; Weiss et al., 2012), and are currently addressed through the development of the Worldwide harmonized Light vehicles Test Procedure (WLTP) and the complementary Real-Driving Emissions (RDE) on-road test. With both procedures being at the verge of implementation, little attention has been paid to understand the actual origin of the elevated NO_X emissions of diesel cars on the road. We argue here that, contrary to the common view, insufficient driving dynamics and an overly narrow temperature range of NEDC testing may not

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be the root cause of the diesel-NO_X problem. Instead, we seek to demonstrate through a statistical analysis of emissions and driving data that large parts of the elevated on-road NO_X emissions can neither be explained by transient driving nor by the variability of ambient temperatures during on-road driving but may instead be related to the use of defeat strategies. We include in our analysis 10 light-duty vehicles that are tested on the NEDC in the laboratory and over various routes on the road. Our research can provide technical services and type-approval authorities with a simple yet effective tool for vehicle screening and may point to vehicles that warrant an in-depth assessment by the competent authorities.

2. Methods

2.1. Test vehicles and test routes

We test 10 light-duty vehicles of category M1 comprising 3 Euro 5 gasoline vehicles and 7 Euro 4–6 diesel vehicles (Table S1 in the Supplementary Information). With the exception of one, the Volkswagen Passat, all vehicles are obtained from third parties without involvement of the respective vehicle manufacturer. The emissions tests are conducted by the Vehicle Emissions Laboratories (VELA) of the Joint Research Centre (JRC) in Ispra, Italy. Market fuels, complying with Directive 2009/30/EC (EC, 2009) and the manufacturer's specifications for the operation of the respective vehicle, are used for all laboratory and on-road tests. In the laboratory, we conduct emission tests on a roller bench, manufactured by MAHA GmbH, with a 48 inch diameter, an inertia range of 454–4500 kg, and a maximum speed of 200 km/h. NO_X and CO_2 emissions are sampled in Tedlar® bags; component concentrations are determined with a Horiba MEXA-7400HTR-LE analyser in accordance with Regulation 83 (UNECE, 2015).

On the road, NO_X and CO_2 emissions are measured with a Semtech®-DS or a Semtech® Ecostar PEMS from Sensors Inc., comprising a tail-pipe attachment, heated exhaust line, exhaust flow meter, component analysers, a data logger to the vehicle network, and a GPS. The ambient temperature is measured at 1 Hz with a plug-and-play weather probe being part of the PEMS equipment (see also Weiss et al., 2011). In line with Regulation 2016/427 (EC, 2016), we calculate the instantaneous on-road NO_X and CO_2 emissions [mg/s] at a frequency of 1 Hz by multiplying pollutant concentration, determined on a wet basis, and exhaust mass flow. The distance-specific emissions [mg/km] are then calculated by dividing the instantaneous emissions over the considered period by the distance driven in that period.

Our data analysis comprises two parts (Fig. 1). The first part serves the purpose of data exploration (Fig. 1, left). We make box plots of the instantaneous NO_X emissions [mg/s] of each vehicle during (i) NEDC testing in the laboratory (yellow box plot), (ii) selected on-road driving conditions that are similar to those of NEDC testing (green box plot, arrow 1), and (iii) on-road driving of all trips available over the various test routes (blue box plot, arrow 2). As conditions similar to NEDC testing we selected from all available on-road NO_X emissions [mg/s] those whose instantaneous (i) speed-acceleration combinations lay within the values attained by NEDC testing, (ii) ambient temperatures fall within the type-approval range of 20 to 30 °C and (iii) driving events occurred in flat terrain at road grades between −0.1 and + 0.1%. The results of this analysis are presented in box-plots depicting the median as well as the 2nd and 3rd quartile of the values. The box plots can already provide a first hint on the question whether deviations between laboratory and on-road NO_X emissions can be linked to variability in driving dynamics and ambient temperature.

The second part of our analysis consists of a second-by-second comparison of the NO_X emissions observed over the NEDC with those found on the road under similar operating conditions. This comparison requires controlling for ambient temperature and for the working points of the engine. Controlling for temperature is straightforward and achieved through excluding all on-road emissions data obtained outside of the type-approval temperature range of 20–30 °C. Controlling for the working points of the engine is more difficult and requires matching engine speed, angular acceleration and torque, as well as engine oil and coolant temperatures. Controlling for these parameters is standard practice in the bench testing of engines but it is less straight forward when testing passenger cars on the road as engine data are usually not available. We therefore approximate engine speed by vehicle speed. This approximation holds if vehicles are driven on the road and in the laboratory in the same gear at a given speed. Although this assumption may not always hold, averaging over a large amount of driving data likely renders deviations in the gear shift strategy as a random error. Second, we take vehicle acceleration as a proxy for the angular acceleration of the engine. Finally, we approximate torque by the CO_2 emissions generated by the engine. At a given engine speed, torque is proportional to the instantaneous fuel consumption [g/s] and thus to CO_2 emissions [g/s]. The chosen approximations make it possible to apply our method without the need to obtain engine data, e.g., through connection with the engine control unit, thereby decreasing the risk that vehicles detect an emissions test. Taken together, we characterize working points by vehicle speed, vehicle acceleration, and the instantaneous CO_2 emissions - three parameters that are readily available from on-road emissions testing with PEMS.

We now take the second-by-second vehicle speed, acceleration, CO_2 and NO_X emissions of each vehicle during NEDC testing in the laboratory and collect from our on-road PEMS data the NOx emissions for speed, acceleration, and CO_2 events that match within a margin of 2 km/h, 0.02 m/s^2 and 0.5 g CO_2/km, respectively those found during NEDC testing (Fig. 1, arrow 3). In terms of ambient temperature, we make two choices. First, we apply our method only to on-road data recorded at the temperature interval permitted for type approval, i.e., 20 to 30 °C. This approach allows us to control for temperature as an explanatory variable for on-road NO_X emission levels but, at the same time, reduces the amount of test data available for our analysis. In fact, Table A1 in the Appendix shows that out of the seven diesel cars tested on the NEDC, five are driven on the road at type-approval temperatures. Two diesel cars, as well as the three gasoline cars, are tested on the road at ambient temperatures below the range of 20–30 °C. This in turn results in a lack or absence of emissions data in the range of permitted type-approval temperatures (see Table A1). Therefore, the analysis is also conducted without controlling for ambient temperature (see Table A1). After matching the working points, their average NO_X emissions are calculated (Fig. 1, arrow 4) and summed over an entire NEDC. This result is compared with the unfiltered PEMS data (Fig. 1, arrow 5) and the bench data (Fig. 1, arrow 6).

Given the availability of on average 23 ± 16 h of on-road driving data for each car comprising various trips and routes, we expect to find many speed-acceleration-CO_2 points that correspond to those observed in the laboratory over the NEDC. In fact, driving conditions similar to those of the NEDC may not represent rare exceptions but rather common encounters on the road. Uphill and downhill driving is purposefully included in our data for the following reasons:

- For NEDC testing in the laboratory, a lower vehicle load than during on-road driving is used. This fact explains part of deviations in the fuel consumption and CO_2 emissions determined during certification and found later by the consumers during normal vehicle use (Tietge et al., 2015; van Mensch et al., 2014).