IEA-AMF Annex 56:
Real Driving Emissions

EUDP J.nr. 64016-0005

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1. Contents

2. Background and purpose

IEA-AMF Annex 56 was initiated in October 2016 by delegates from Canada, Sweden, USA, Finland, Switzerland and Denmark. With this report, we wish to contribute to the understanding of interactions between fuel properties, engine and after-treatment technologies, use patterns, traffic, road and weather conditions, efficiency requirements and real-world emissions.

The data and analysis from the work intends to enable researchers to understand the differences of real-world emissions and energy consumption compared to type approval emissions and energy consumption. A secondary purpose is to understand what research (i.e. After-treatment systems, powertrain system control, modeling…) could reduce these potential gaps. The data and analysis is also intended to help policy makers to have more informed discussions.

The Danish test program was organized as a joint project between FDM – the Danish Motor owner's association, member of FIA, and Danish Technological Institute. Funding was raised through the national Energy Development and Demonstration Program, EUDP (Journal 64016-0005).

The test program covers real road driving in cold weather with a focus on smaller diesel vehicles. This vehicle category is especially popular in Denmark due to the low tax on diesel fuel and a progressive vehicle registration tax which favors vehicles with a low CO_2-emission.

The motivation for testing diesel vehicles in cold weather was to investigate the so-called Thermal Window Protection, which allows certain emissions control systems to be switched off at lower ambient temperatures. Typically, the Urea Dosing System (aka AdBlue system) which as part of the NOx abatement solution on newer vehicles, will be switched of at temperatures below e.g. 10°C. This is done, presumably, to protect the system from damage arising from crystallization of urea etc… However, it may also be a convenient way to save on urea. Some vehicles have reportedly been fitted with suspiciously small urea tanks which would indicate that the real consumption of urea is not sufficient to clean the exhaust gasses.

FDM has pointed out that some of the smaller diesel vehicles on the market hardly use any urea at all. That would lead to a strong suspicion that real life NOx emissions are higher than they should be.

3. Vehicles

The Danish team was focused on smaller vehicles with 4-cylinder turbocharged diesel engines certified to European EURO 6. For reference one gasoline vehicle was included. The vehicles are highly representative of the Danish car market. Especially Skoda Octavia, Renault Kadjar, Citroen C3 and Peugeot 208 are among the bestselling family cars today. BMW X1 is slightly higher priced than the others but still a very popular model.

Table 1 Technical data of the vehicles tested

Car model	Skoda Octavia 1.4 TSI	BMW X1 Sdrive 18D	Renault Kadjar 130 dCi	Citroën C3 1.6	Peugeot 208 BlueHDi 100
Fuel	E5 Gasoline	B7 Diesel	B7 Diesel	B7 Diesel	B7 Diesel
EURO Class	5b	6b	6b	6b	6b
Reg. year	2015	2017	2016	2015	2017
Displacement, configuration	1395 cm^3, I4, turbo	1995 cm^3, I4, turbo	1598 cm^3, I4, turbo	1560 cm^3, I4, turbo	1560 cm^3, I4, turbo
Engine power	103 kW	110 kW	96 kW	73 kW	73 kW
Transmission	Automatic	Manual	Manual	Manual	Manual
AdBlue/SCR	No	No	No	Yes	Yes
Engine code (family)	CHPA (EA211)	B47C20A	R9M E4	BH02	BH02
CE approval no.	e1*2007/46*0243*13	e1*2007/46*1676*02	e2*2007/46*0475*04	e2*2007/46*0003*38	e2*2007/46*0070*37
Approval date	02-04-2014	19-06-2017	02-02-2016	03-09-2015	16-08-2016
Directive	715/2007*195/2013J	715/2007*2015/45W	715/2007*2015/45W	715/2007*2015/45W	715/2007*2015/45W
CO2 declared [g/km]	116	109	113	79	79
CO declared [mg/km]	597	222.2	191	195.5	195.5
NOx declared [mg/km]	21.4	37.3	37.2	34	34

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4. Equipment

The Danish team used an AVL M.O.V.E. PEMS Is system with PEMS-Pn particle counter. Main components of the system are shown in Figure 1.

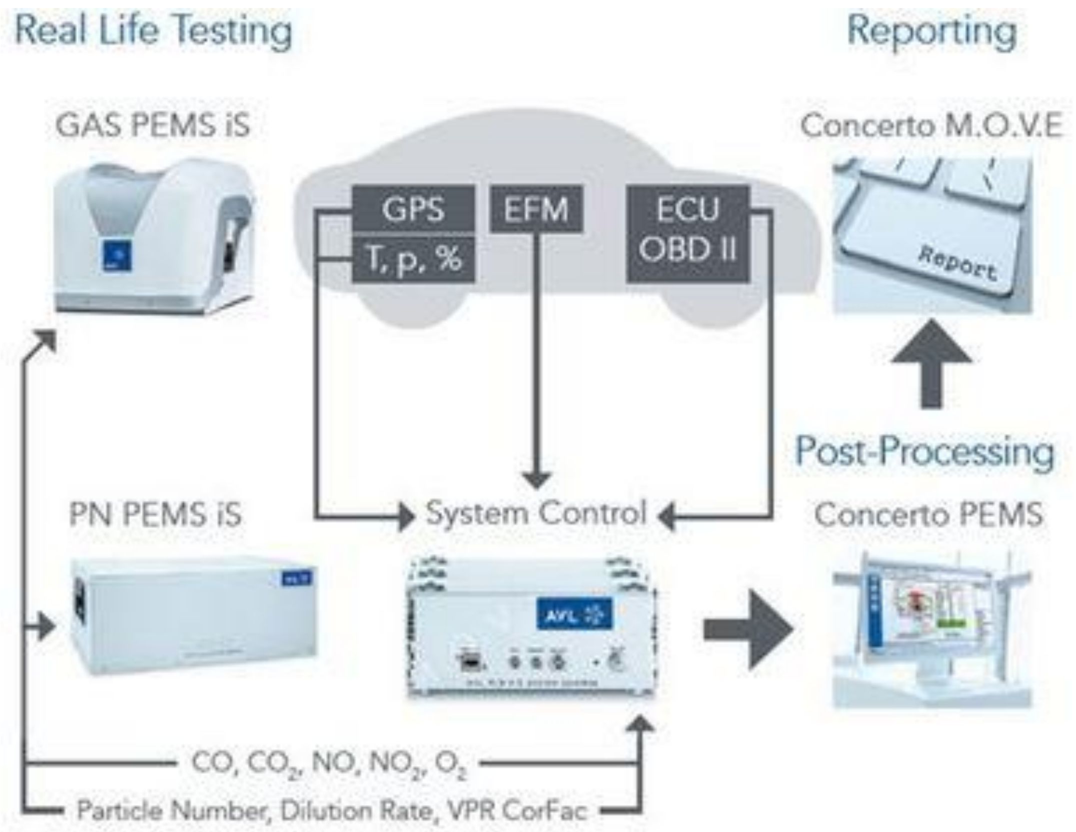

Figure 1 AVL M.O.V.E. PEMS Is measurement system

The measurement system itself is placed on the back of the vehicle on a trailer hook or inside the vehicle's luggage compartment. The latter option is best suited for station wagons, SUV's and hatchbacks, whereas the trailer hook is preferred for sedan type vehicles.

The measurement system includes a flow meter which is connected to the rear end of the exhaust pipe/s. The flow meter measures the total amount of gasses passing through the exhaust pipe, in m^3/h or in kg/h.

Inside the vehicle is an OBD-connector which allows monitoring of engine RPM, temperatures etc. On the roof sits a GPS-antenna and a weather station.

By combination of data from the gas analyzers, the flow meter and the GPS, it is possible to determine the exact amount of CO_2, CO, NO, NO_2 or particulates emitted for each kilometer driven.

The measurement system is designed to meet RDE Act 3 – Commission Regulation (EU) 2017/1154.

5. Test routes

The Danish team designed two regional RDE routes, one in Jutland and one on Zealand. Both routes were designed to meet RDE Act 1 – Commission Regulation (EU) 2016/427 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6).

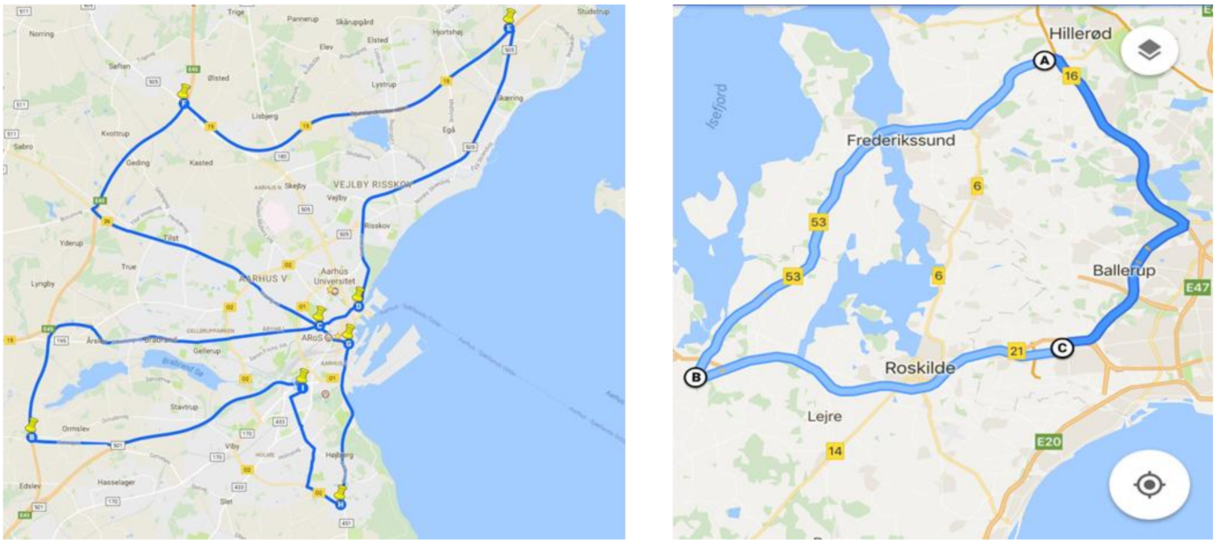

Figure 2 Two Danish RDE routes

The routes are 70-80 km long and the duration is 90 minutes.

The routes were positioned in connection to the DTI's main facilities in Aarhus and Taastrup respectively. This way, vehicles from the whole country can reach a test site in 1-2 hours.

Both routes are placed as public content on Google Maps:
https://drive.google.com/open?id=1Z26X_0OU6YqE3boxbpaCnfflP1o&usp=sharing
https://drive.google.com/open?id=1r5ejo9njd4dH_il9u5nfqbZyy18&usp=sharing

The routes will need minor adjustment as to comply with RDE Act. 4 from 2020.

As a supplement to the RDE routes a shorter track route was also used. The objective for this was to obtain result with a high reproducibility while using less time for testing. Inspired by the UITP SORT schedule, which is used for buses, the route was named SORDS (Standardized On-Road Driving Schedule). The SORDS route is a 3-minute drive over a 3 km track with 5 stops and speeds up to 130 km/h. The route is shown in Figure 3.

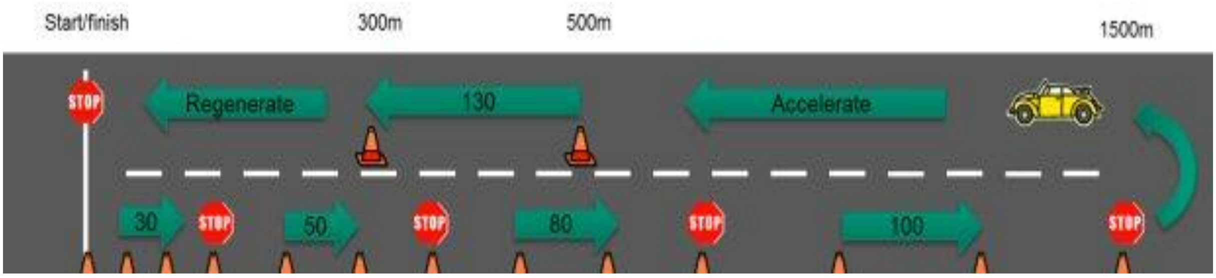

Figure 3 The SORDS track route layout

The SORDS route was set up on Roskilde Ring, a small racetrack/road safety center located near Taastrup. However, it turned out that the track was unsuited for SORDS testing due to being too short and the turns being too tight. It was not possible to safely reach 130 km/h with the PEMS equipment on board, so the test was restricted to 100 km/h. A perfect site for SORDS would be the old airfield at Værløse, also nearby Taastrup. However, that facility is nowadays used for recreative purposes and motor vehicles are not allowed.

6. Fuel and weather conditions

The fuel in Denmark is European spec. E5 gasoline and B7 diesel. This means that there is up to 5%vol ethanol in the gasoline and up to 7%vol biodiesel in the diesel. The Danish fuel companies do not currently add methanol to the gasoline. The biodiesel component is mostly hydrogenated vegetable oil (HVO) and rape-seed methyl-ester (RME) in winter months and animal-based tallow methyl-ester (TME) in summer.

Average density and energy content (LHV) are:

Diesel: 836 kg/m^3 and 35,7 MJ/l
Gasoline: 745 kg/m^3 and 32.2 MJ/l

The month of March was chosen for testing since it offers reasonably low temperatures without too much snow or ice on the roads.

The temperature profile for the Zealand region in that month is shown below.

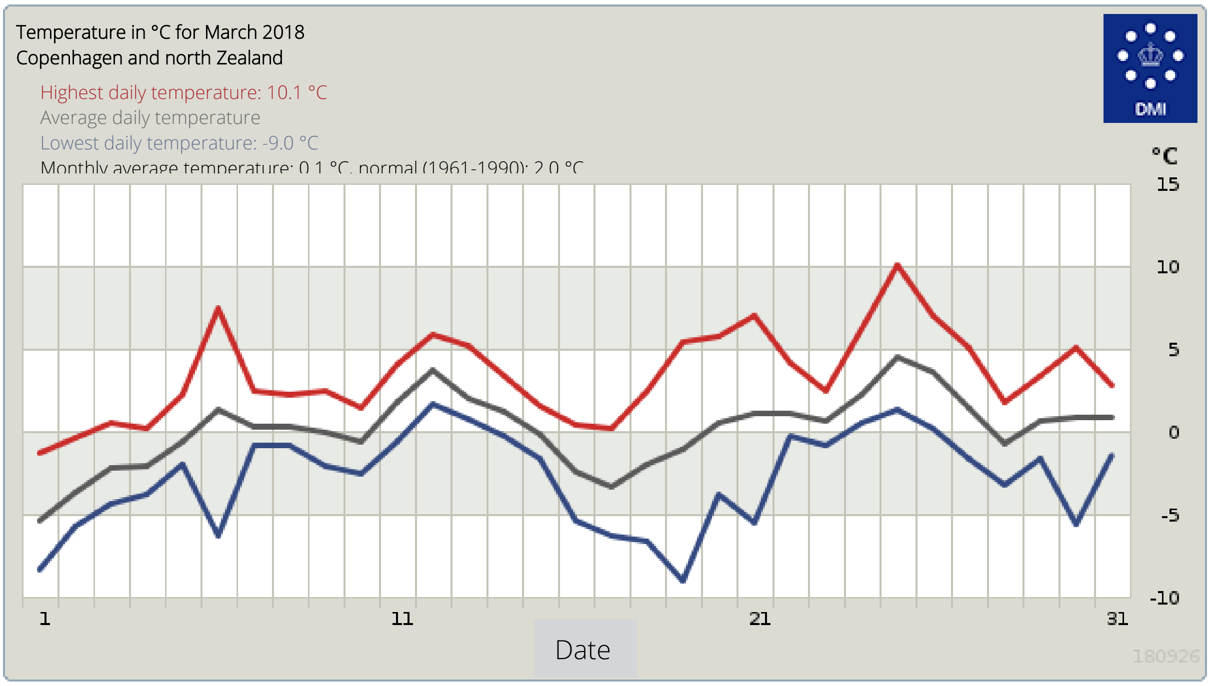

Figure 4 Temperature in Zealand during RDE testing

7. On-road results

The tests show clearly that NOx emissions lie above those mandated by EURO 6 (Figure 5). The highest average was 18 times the limit. Only the Skoda Octavia, which was running on gasoline and the more expensive BMW diesel showed acceptable NOx levels.

The Skoda was equipped with a 3-way catalyst which is effective in eliminating NOx because it operates in an almost oxygen free environment. This is not possible for diesels, due to the oxygen rich exhaust gas. However, as shown by BMW, diesels can also manage low NOx levels. This model didn't even have an SCR-type catalyst and thus did not use AdBlue. Even though it hardly seems necessary, an AdBlue system was added to the next X1 model shortly after, to the 2018-model, and is now standard on all BMW diesels.

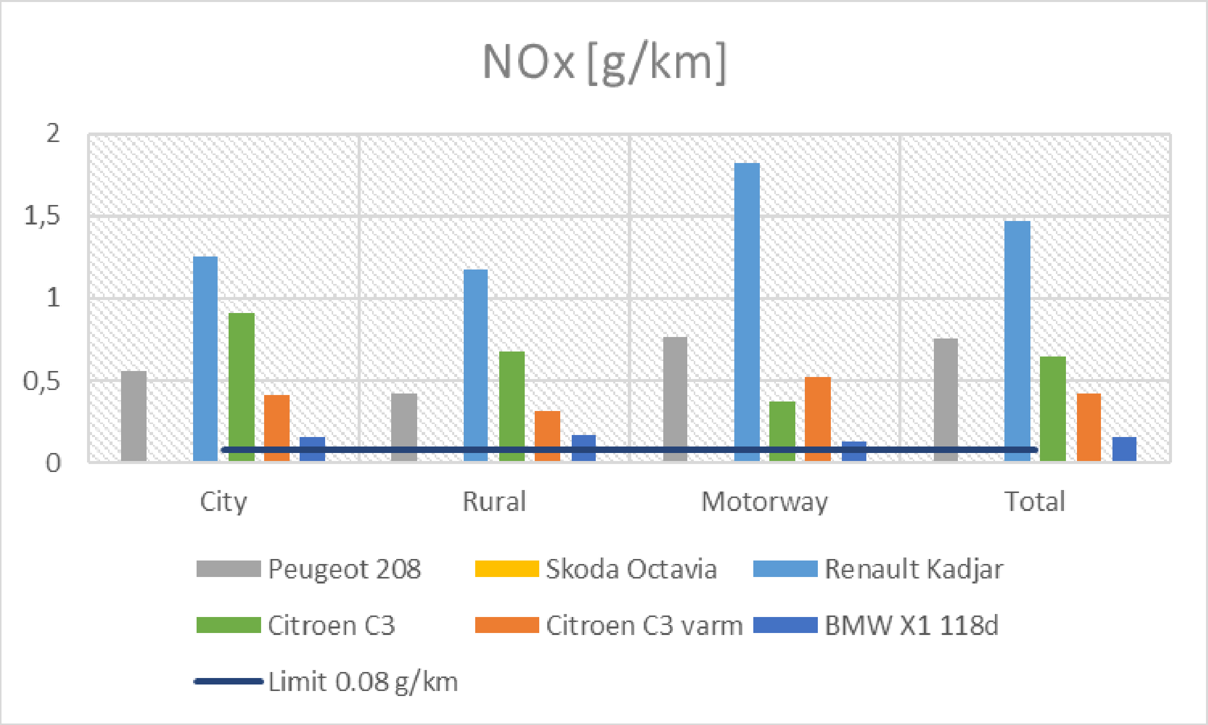

Figure 5 NOx emissions for EURO 6b diesels were significantly above the limit except for BMW X1. The gasoline from Euro 5b did not emit any significant amount of NOx.

Warm weather was tried on the Citroën C3 and improved the NOx performance but not enough to meet the limit of Euro 6. Weather had little influence when driving on motorways. Probably because the engine always maintains good temperature on motorways.

NOx emission from the gasoline car was practically nil.

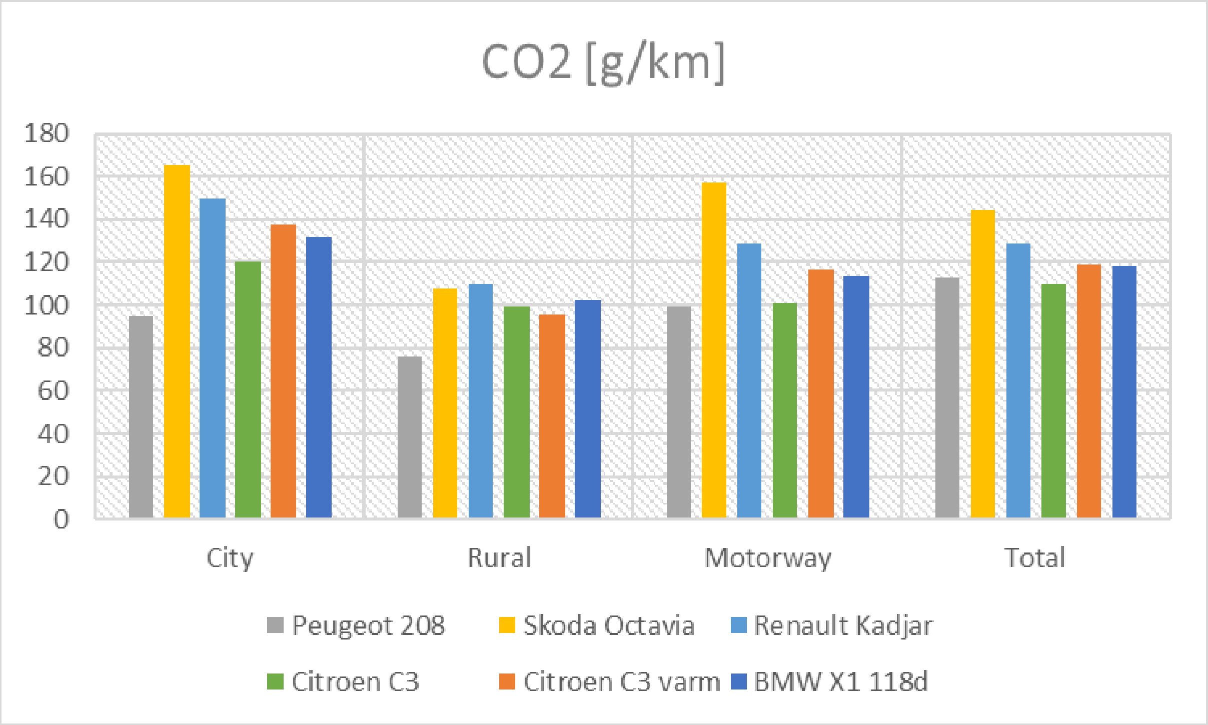

Figure 6 The CO2 emissions measured in RDE were fairly low, with diesels clearly lower than gasoline

The CO_2 emissions were somewhat higher than the declared values for each vehicle. This is mainly because type approvals were still based on the older NEDC drive cycle. It is a well-established fact that NEDC, and the way it has been practiced, delivers too low CO2 values. The values measured in RDE should correspond better to the new WLTP driving cycle. As WLTP figures were not available, however, an exact comparison could not be made.

The gasoline car had the highest CO_2 emission of the cars tested, as expected. The difference was also higher than expected from the declared values. The reason could be that the gasoline car was the only car with automatic transmission.

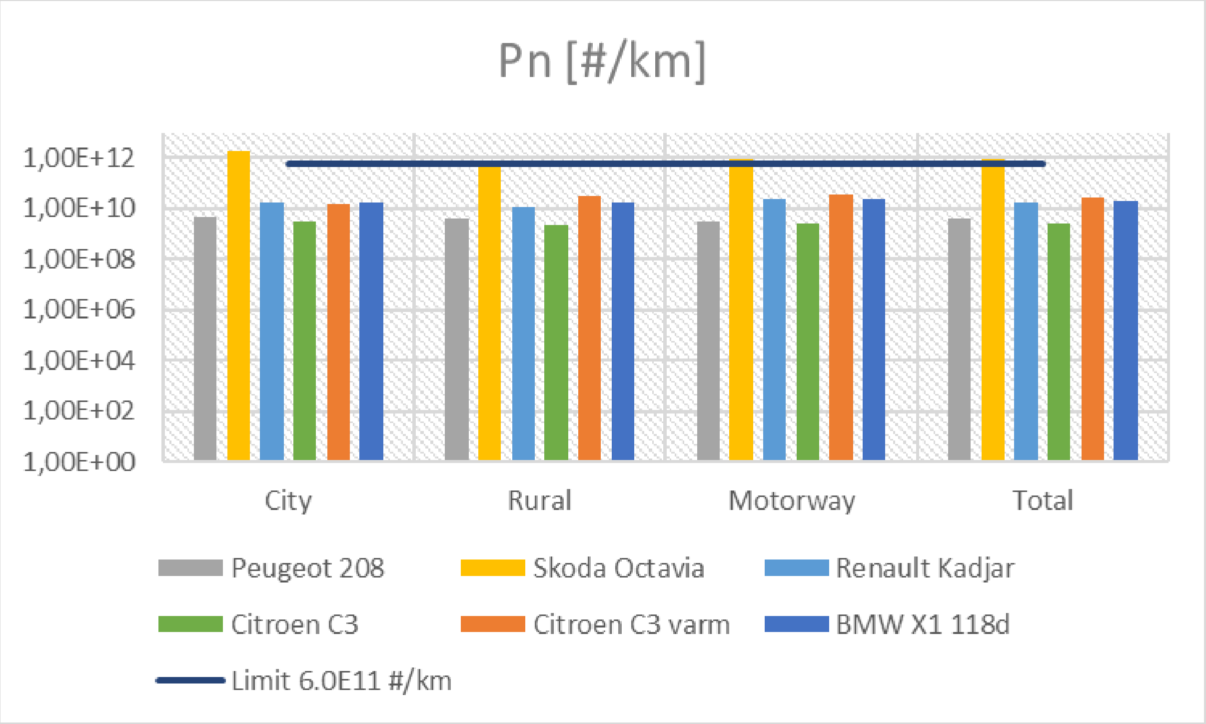

Figure 7 Particulate number emissions were well under the limit for diesels and just over the limit for gasoline

The particulate number emissions are measured with highly sensitive equipment. If the exhaust gas were as clean as ambient air the reading would be about 1.00E+10 #/km. This means that any value below 1.00E+10 #/km must be considered practically zero.

For all the diesel cars tested in this project we see a particulate number emission of practically zero. The gasoline car had particulate emissions just above the EURO 6 limit. However, it must be noted that the car was only a EURO 5b.

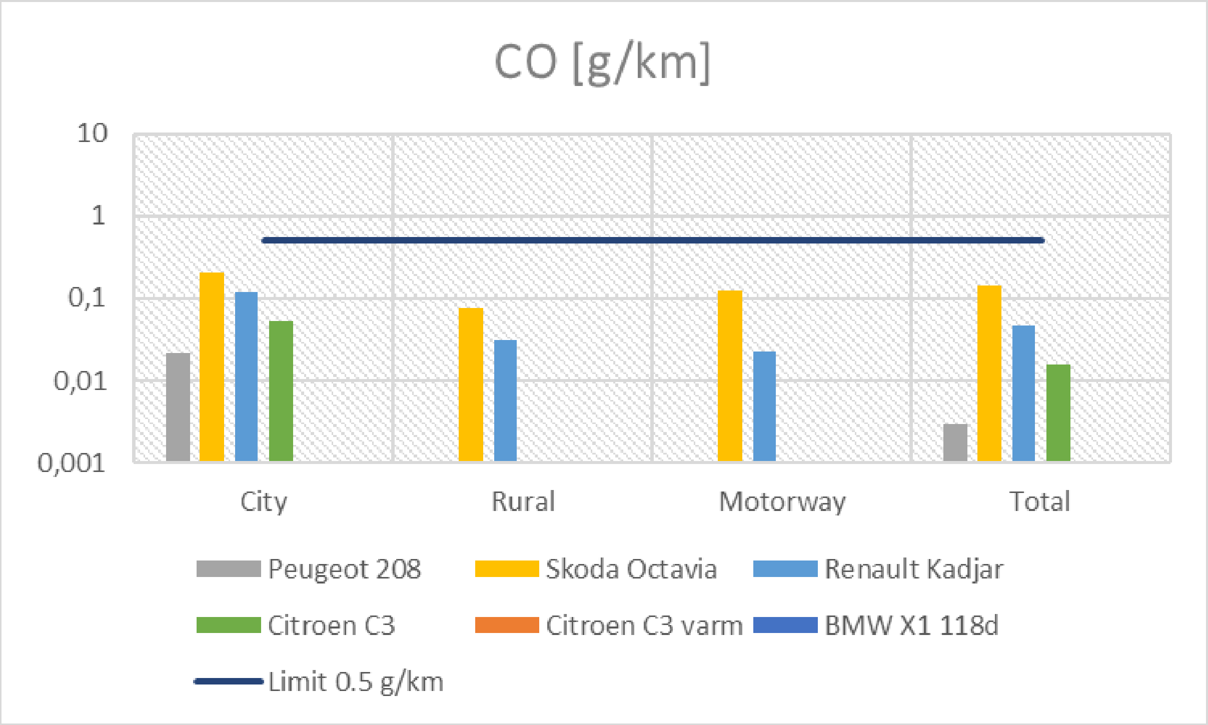

Figure 8 Carbon monoxide emissions were well under the limit. In some cases, CO could not be detected at all.

CO measurements confirmed the general perception that CO is not a problem for diesels. Due to the high amount of excess air in the diesel engine, CO combusts almost entirely on its own. The gasoline car emits CO mainly when the engine and catalyst are cold. However, the average emission is still way below 0,5 g/km. In earlier days, before catalysts were introduced, CO emissions for gasoline cars could reach up to 50 g/km.

8. Track results

The aggressiveness of driving can be measured by the factor v*a, speed times acceleration. An aggressive driver uses both brakes and accelerator at high speeds and thus uses much more engine and braking power. The SORDS cycle (see Figure 3) represents an aggressive, but not entirely unrealistic, driving style.

Figure 9 through Figure 18 illustrates the difference between SORDS and RDE.

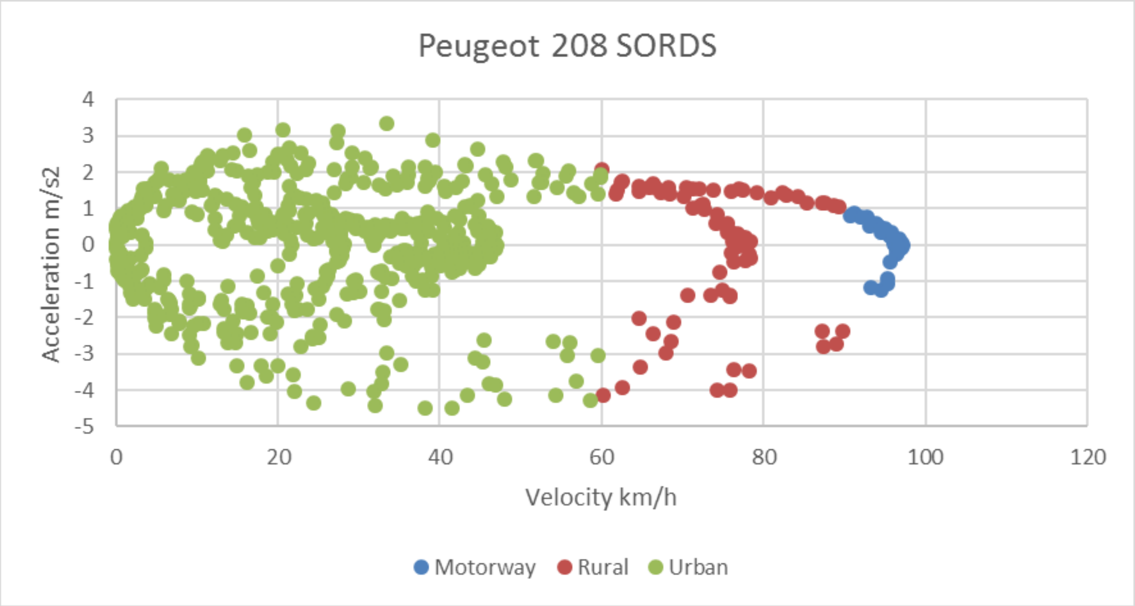

Figure 9 SORDS cycle has high acceleration rates in both positive and negative direction

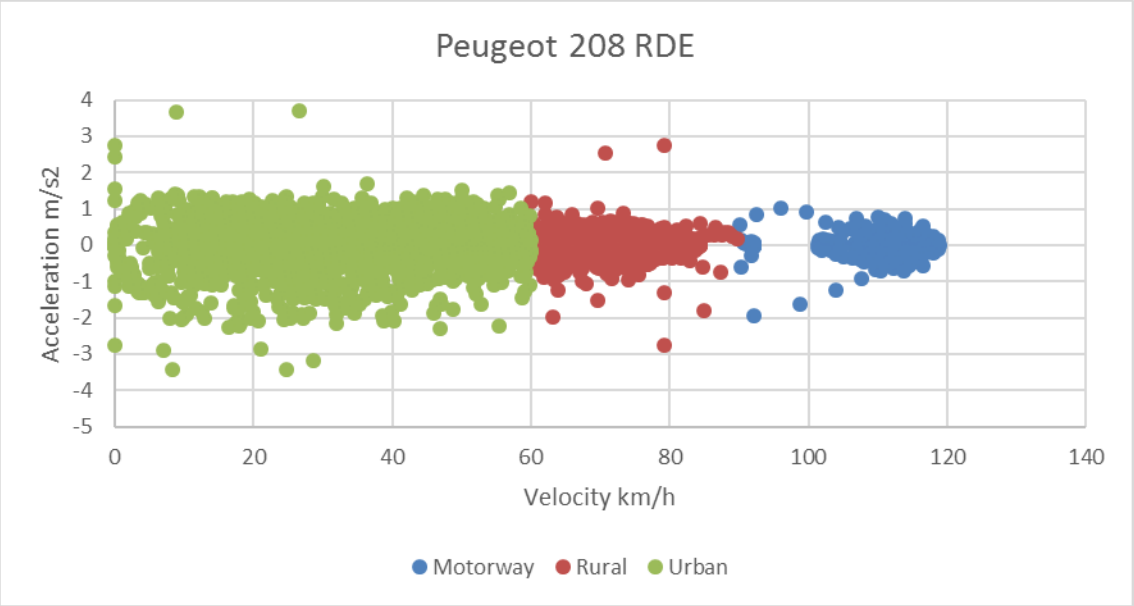

Figure 10 RDE cycle has modest acceleration and deceleration rates

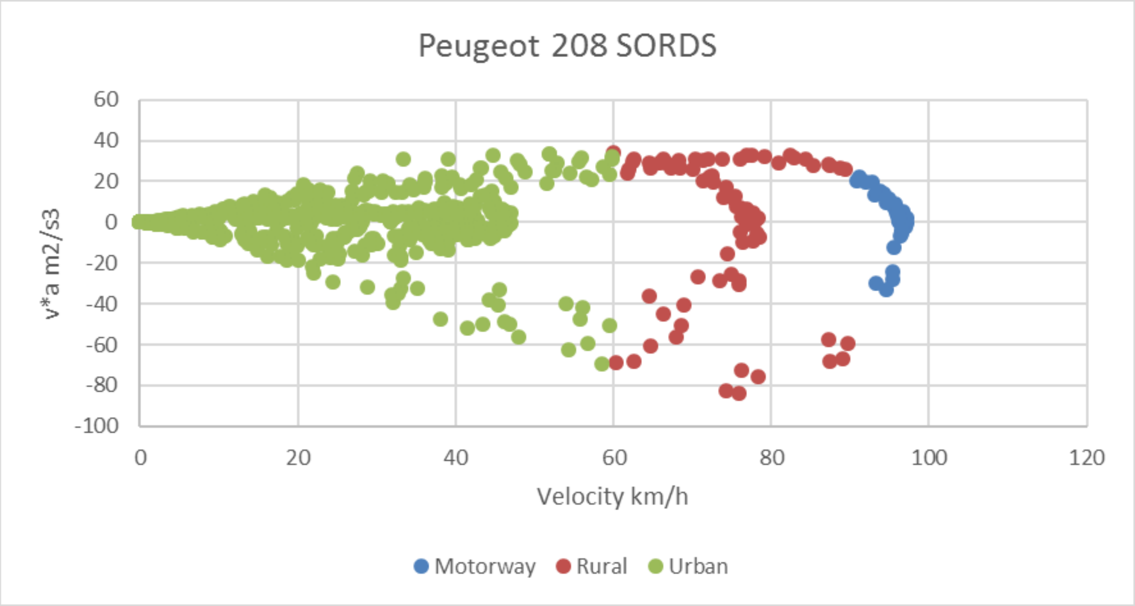

Figure 11 SORDS test show high levels of aggressiveness in terms of both positive and negative v*a

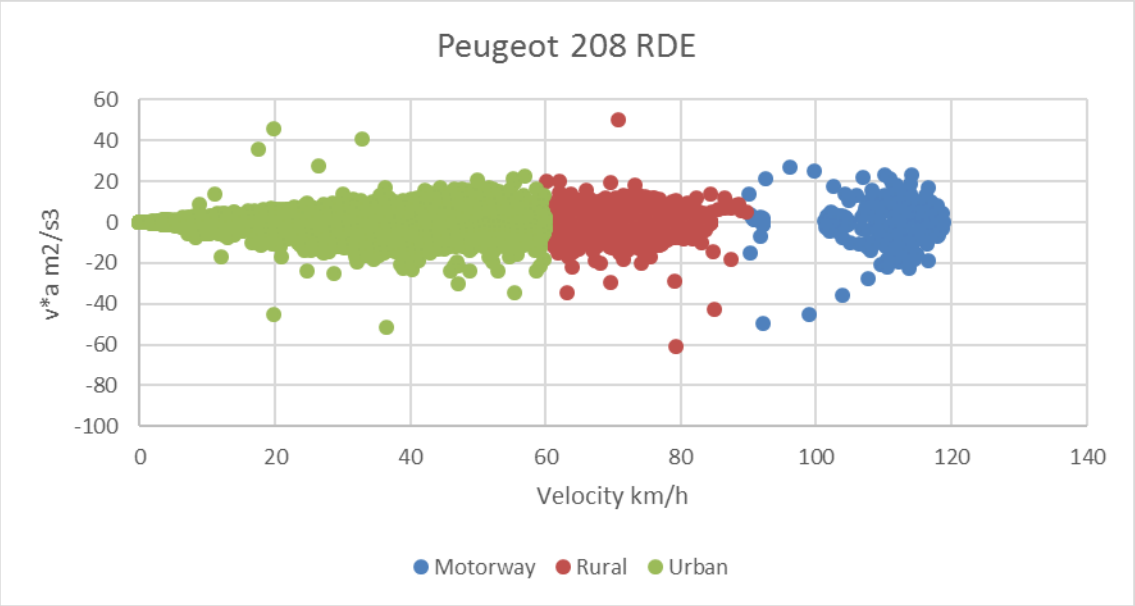

Figure 12 RDE test shows much less aggressiveness despite higher speeds

CO_2 mass flow depends strongly on v*a (Figure 13-Figure 14). This is not surprising since the RDE specific VELINE formula states that engine power is approximately proportional to CO_2 mass flow.

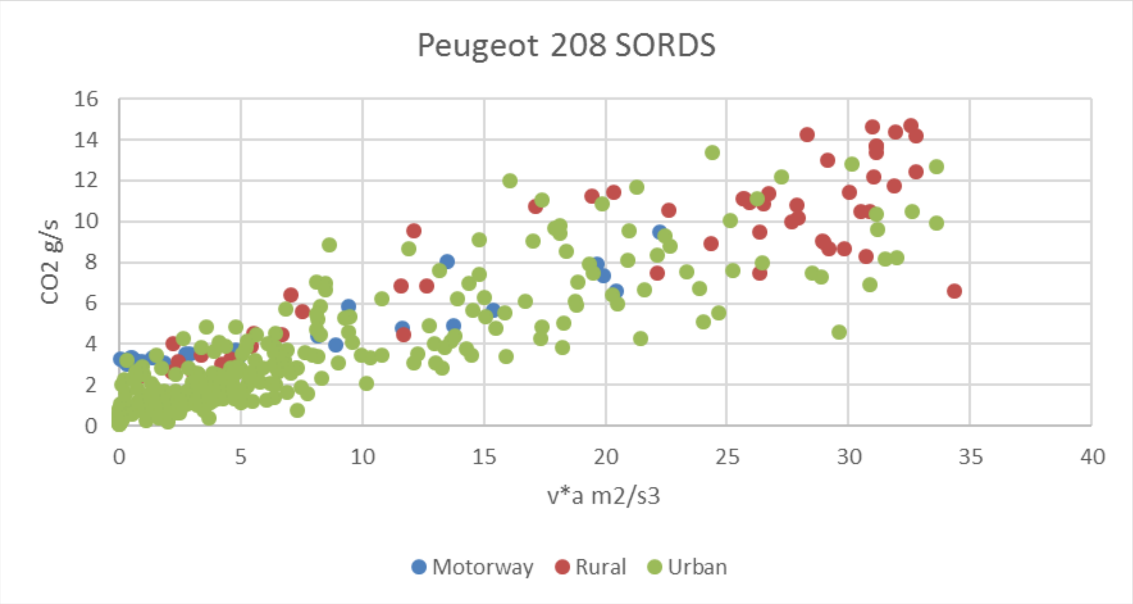

Figure 13 SORT requires high engine power thus a high CO_2 mass flow

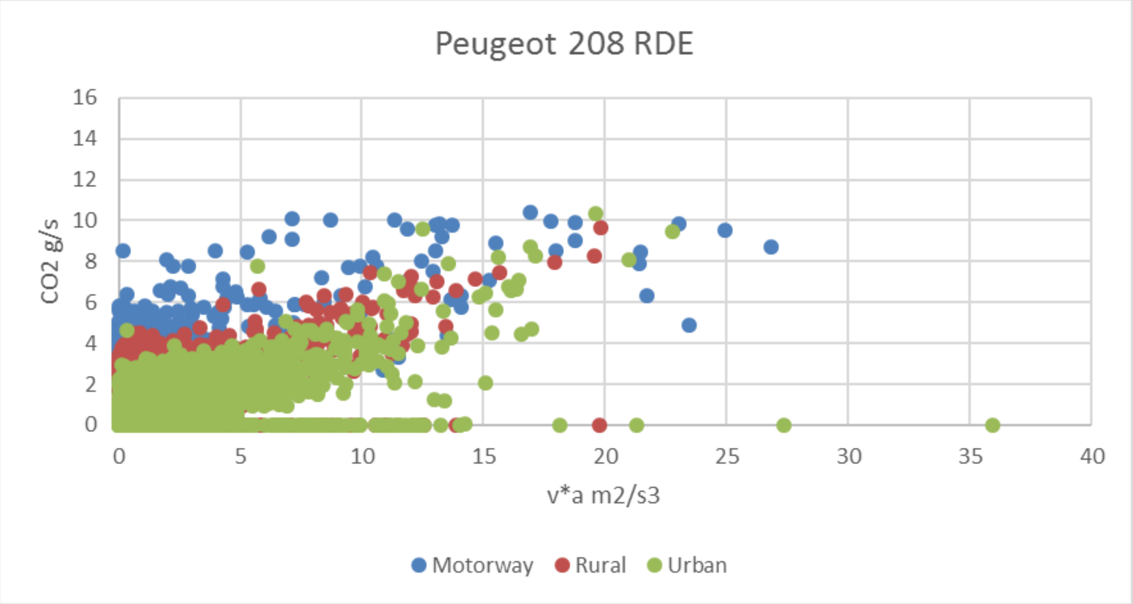

Figure 14 RDE requires less engine power thus less CO_2 mass flow

There seems to be a clear correlation between v*a and NOx mass flow (Figure 15-Figure 16).

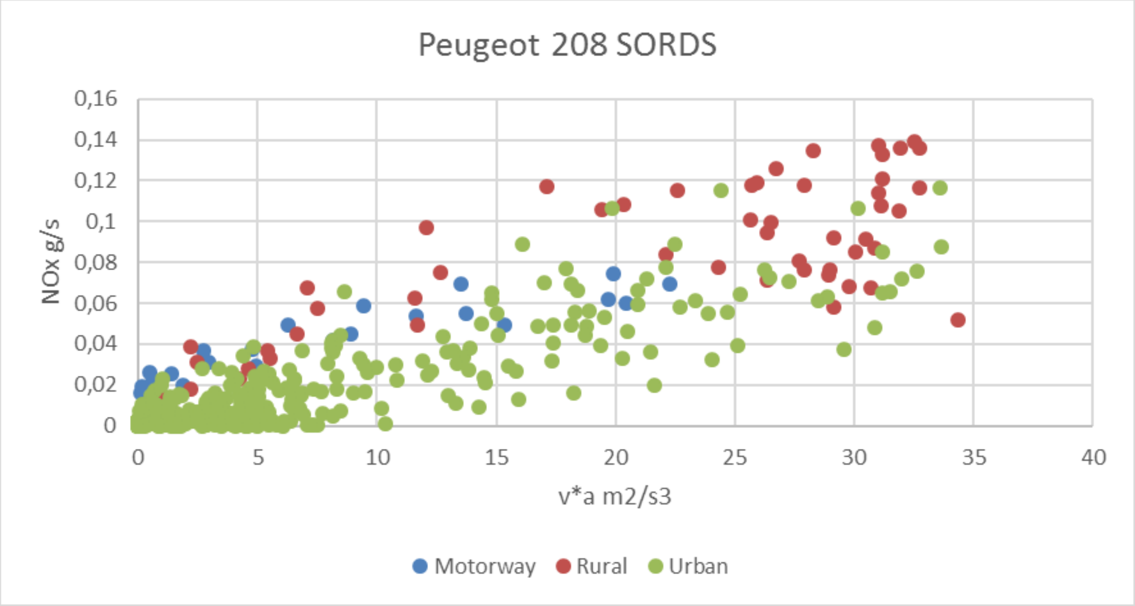

Figure 15 The aggressiveness of SORT results in higher NOx mass flows

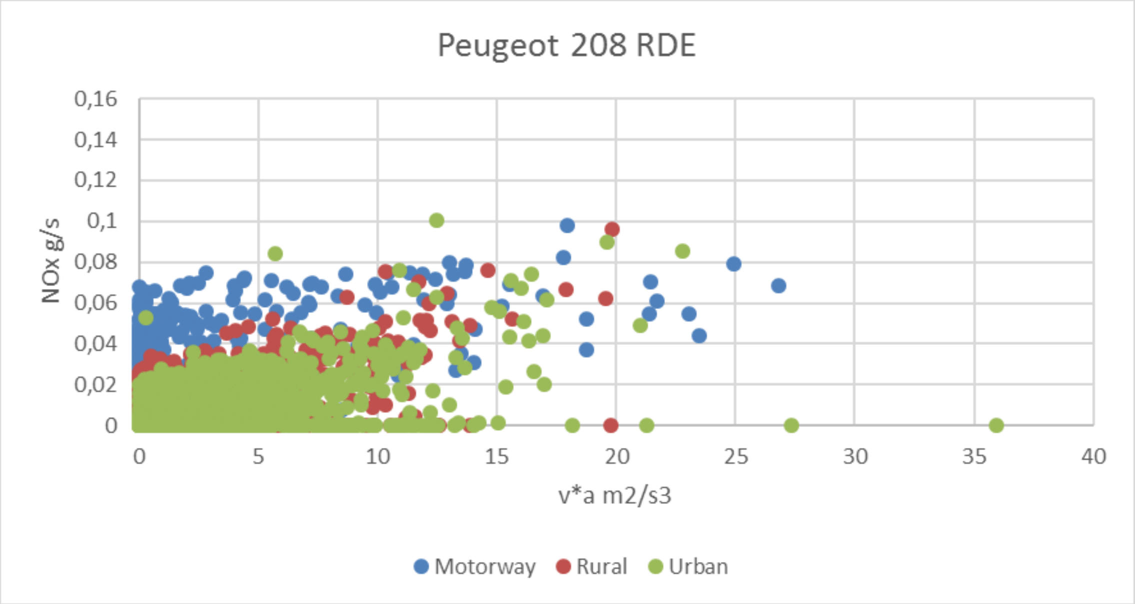

Figure 16 The lesser aggressiveness of RDE results in lower NOx mass flows

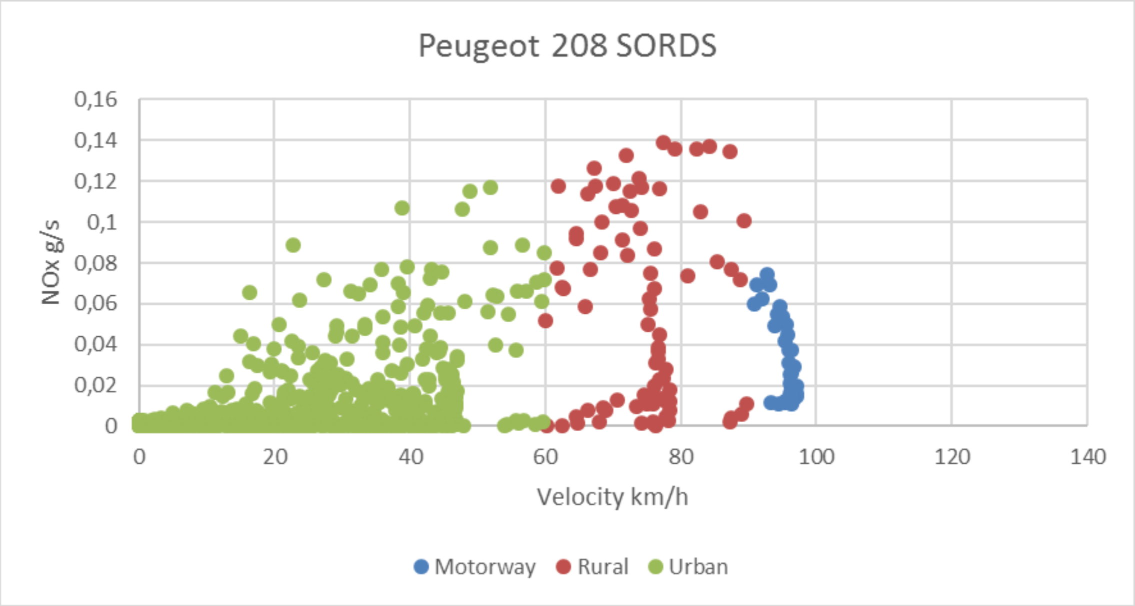

Figure 17 NOx mass flow in SORDS was speed dependent but did not capture a realistic motorway average due to the 100 km/h speed limitation

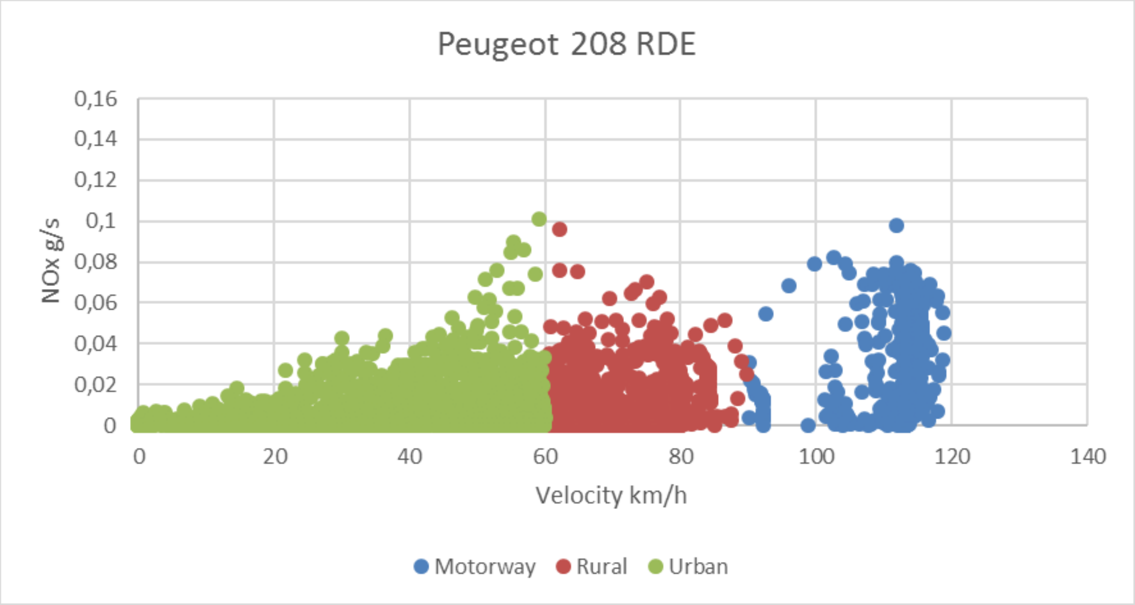

Figure 18 NOx mass flow in RDE was clearly speed dependent and captured a realistic motorway average

The SORDS track test did not give good average results. However, it gave insight in the more extreme situations of high acceleration and engine load.

9. Effect of data filtering

In RDE Act. 3 there are two methods of data filtering of which the manufacturer may choose one.

The methods are known as 'EMROAD' and 'CLEAR'.

The purpose of data filtering is to eliminate abnormal load points, such as very high engine loads or very high fuel consumption. The filtered data should then correspond better to the laboratory test WLTP. The actual process of data filtering is mathematically complex and will not be described in detail here.

For the purpose of investigating the impact on the data both methods were applied to the data shown in the Chapter 7.

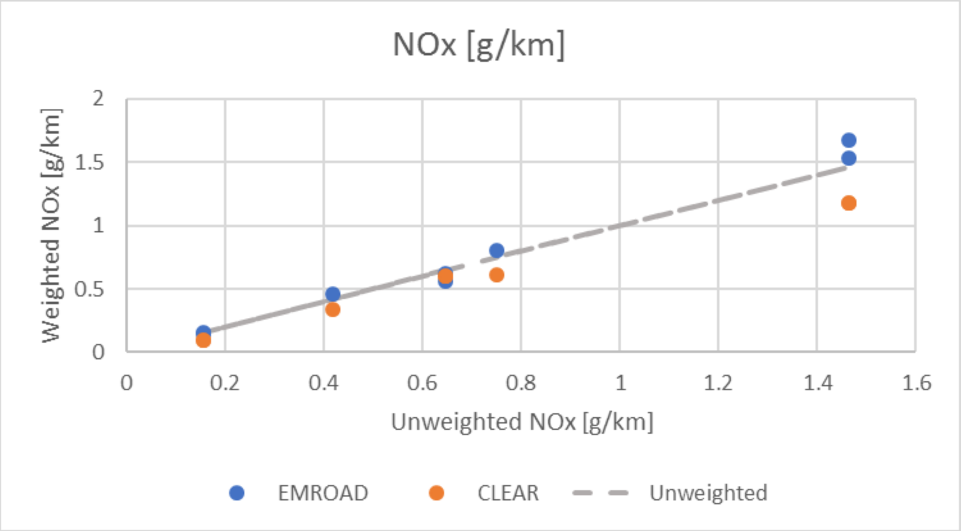

Figure 19 CLEAR reduced the higher NOx emissions whereas EMRAOD reduced them

The data filters had limited impact on the overall conclusions, and they did not seem to agree on the need for corrections. Sometimes EMROAD and CLEAR would pull in each different direction.

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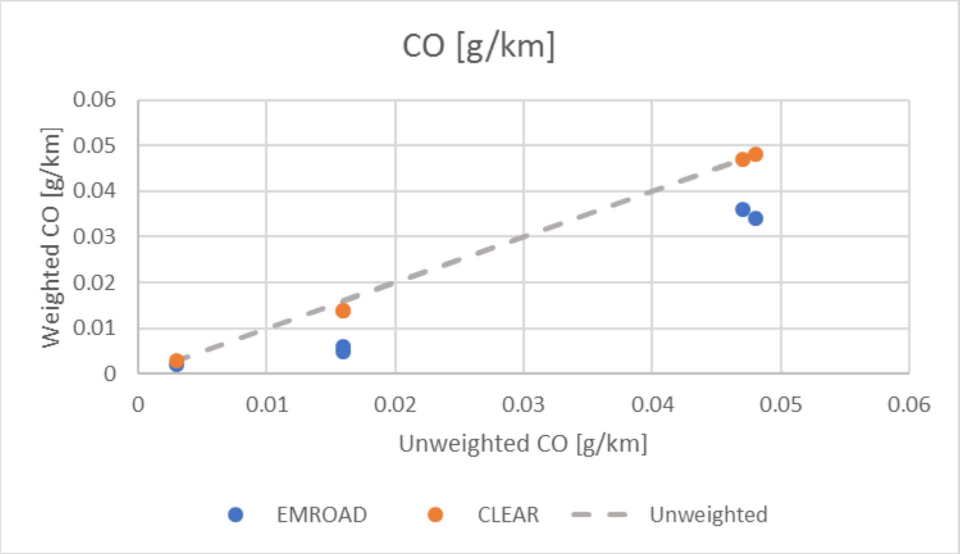

Figure 20 EMROAD significantly reduced CO whereas CLEAR was neutral

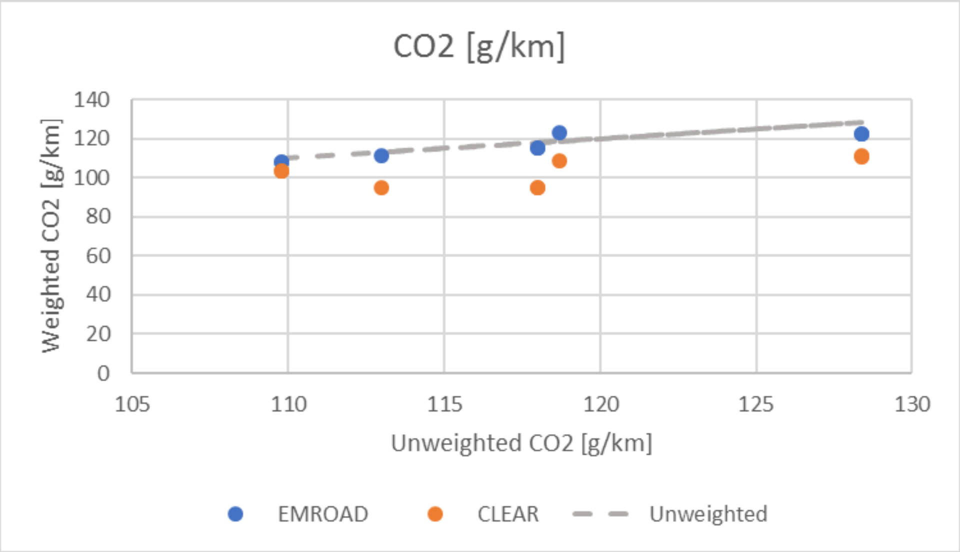

Figure 21 CLEAR reduced overall CO2 while EMROAD was neutral

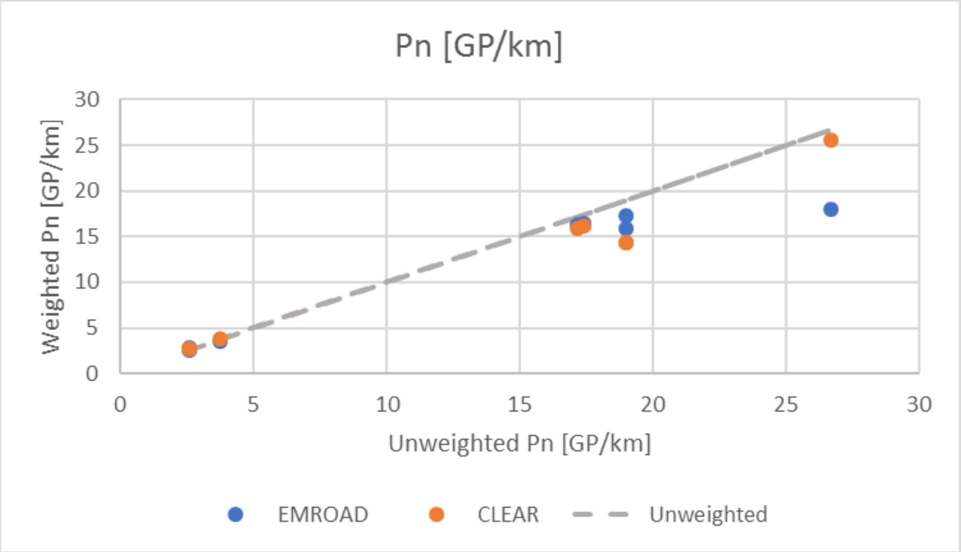

Figure 22 EMROAD reduced the higher Pn emission. CLEAR was almost neutral

Overall, the data filtering did not seem to improve the quality of data significantly. It is expected that EMROAD and CLEAR will be removed from the method with the introduction of RDE Act. 4.

10. Emissions mapping

RDE driving uses most of the engine's useful operation range, without abusing or overstressing the engine. The data can be used to map emission behavior versus engine load and speed. This is shown in Figure 23 through Figure 26.

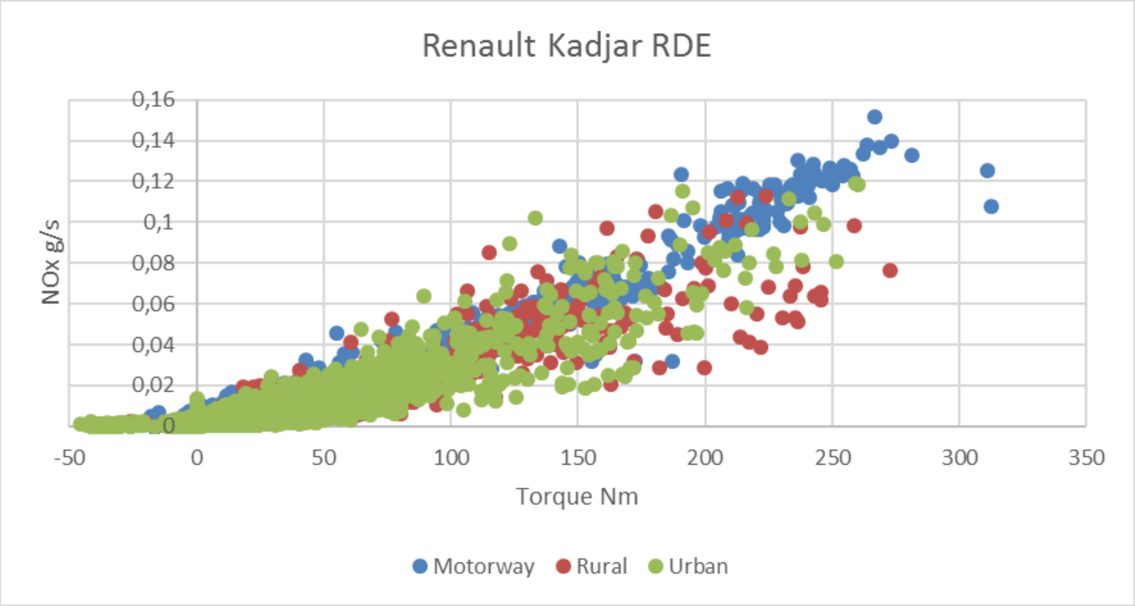

Figure 23 NOx depends exponentially on engine torque

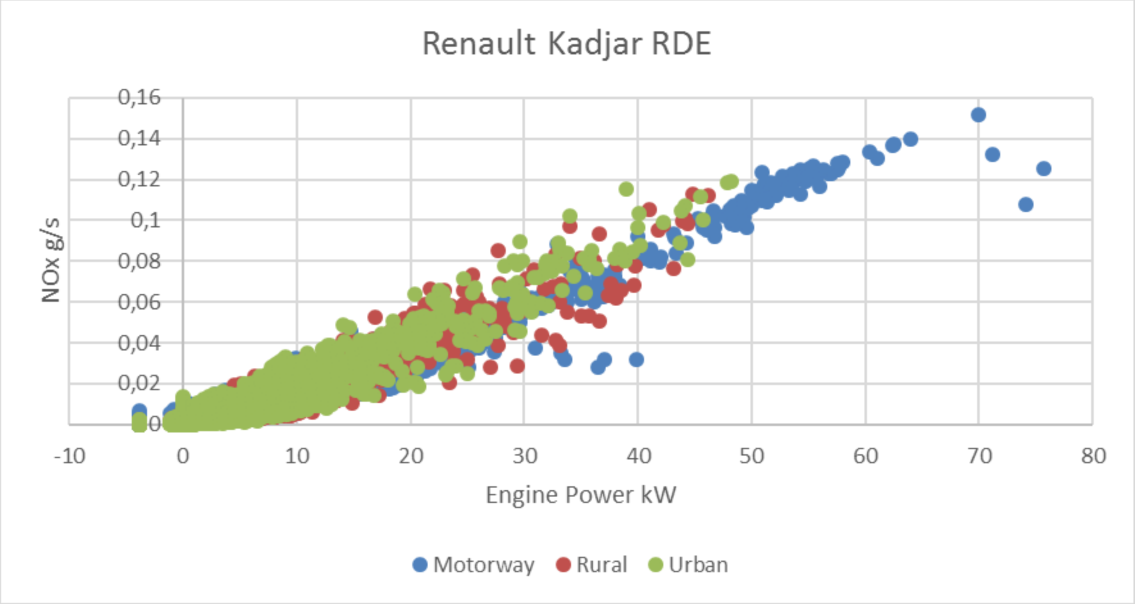

Figure 24 NOx depends almost linearly on engine power

The NOx clearly depended on engine torque and power, which is consistent with the common observation that engine NOx is developed at high combustion temperatures (thermal NOx). However, the data also seems to indicate that catalytic converters on passenger car are under dimensioned, such as the LNT catalyst on the Renault Kadjar DCi 130 shown in Figure 25.

When too small catalytic converters are used, a conflict arises between optimum fuel economy and low emissions. This is commonly known as the NOx Trade-Off. Figure 26 shows this effect; fuel consumption is low when the NOx is high. This is an undesired situation and thus properly sized catalysts or combinations of catalysts shall be recommended.

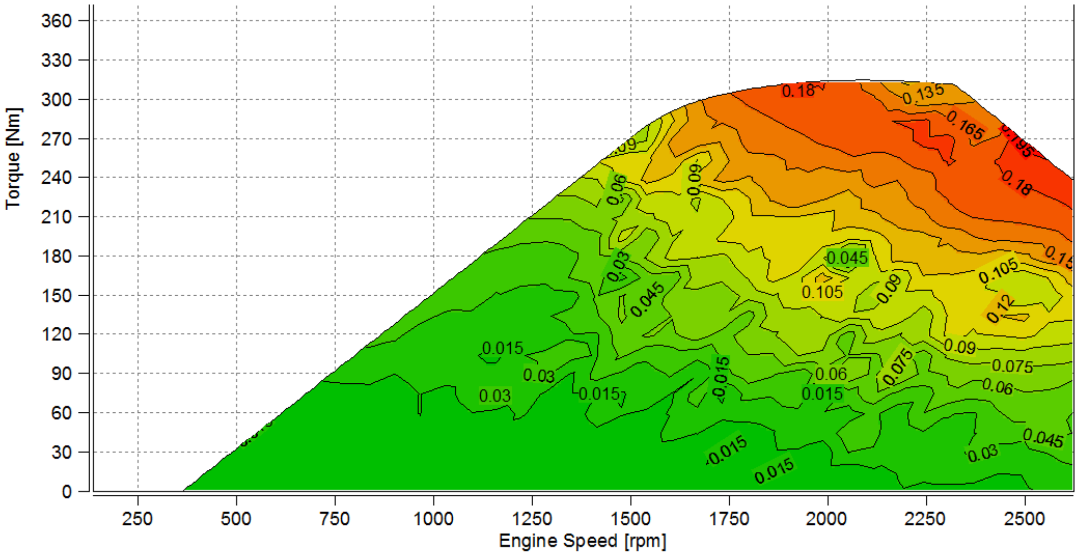

Figure 25 NOx mass flow was high in the high load region which indicates too small catalyst

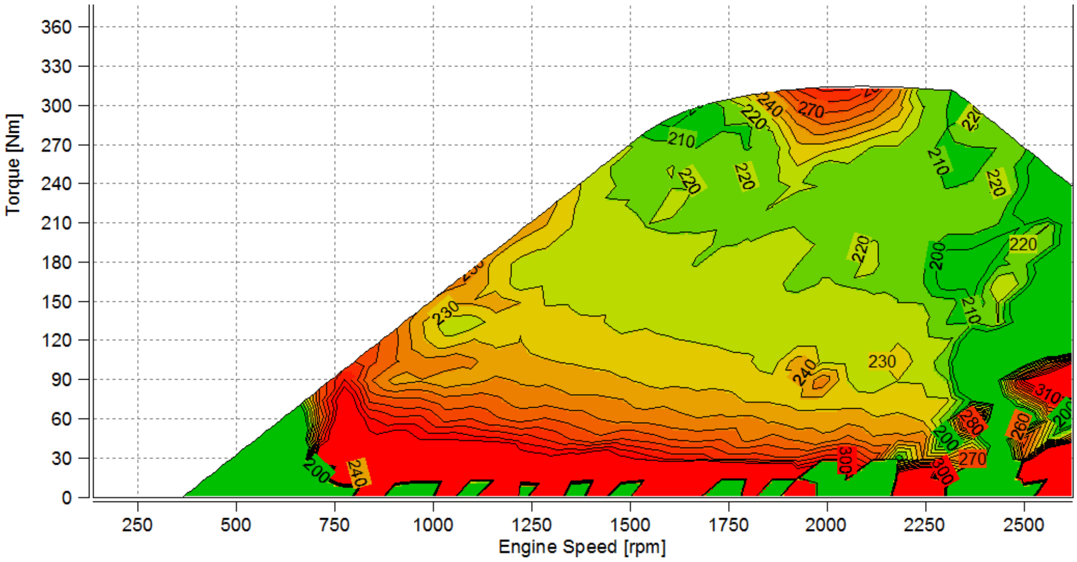

Figure 26 Optimum fuel consumption was colliding with the high-NOx regions.

11. Conclusions

In this project we have tested diesel cars of Model Year 2015-2017. They are all approved according to EURO 6b, which does not require RDE testing by the factory. Our finding were:

- EURO 6b diesels emit too much NOx – up to 18 times the limit.
- A large variation in NOx exists between car brands within the EURO 6b category.
- Temperature seriously affects the NOx emission of EURO 6b diesels.
- EURO 6b gasoline cars perform well on NOx
- EURO 6b diesel perform very well on particles, CO and CO2.
- EURO 6b gasoline cars emit more CO, CO_2 and particulate matter than EURO 6b diesels

When tested at cooler temperatures around 4°C the small EURO 6b diesel cars had alarmingly high NOx-emissions. Most were several times over the EURO 6 limit. Renault Kadjar even surpassed the limit by a factor of 18. Only the BMW X1 was close to fulfilling the EURO 6 limit for NOx. The gasoline Skoda had extremely low NOx, but higher CO_2 than the diesels, especially in city driving. The gasoline car also showed a higher particulate number emissions than the diesels, because it was the only car which was not equipped with a particulate filter.

When comparing the Citroen C3 diesel in winter driving at 4°C with summer driving at 23°C, NOx emissions in city and rural driving was roughly doubled in the cooler weather. At highway driving no such difference was observed.

With the introduction of EURO 6d-temp in 2019 it is expected that the diesel cars will perform much better on the NOx emission. This is expected as a result of the mandatory RDE testing. Some manufacturers have already released EURO 6d-temp data which look promising.

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