Insights for post-Euro 6, based on analysis of Euro 6d-TEMP PEMS data

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Abstract

Real-Driving Emissions (RDE) requirements were introduced in the European emission legislation to address the gap between lab and real-world emissions. The procedure focuses on on-road testing with a Portable Emissions Measurement System (PEMS) and defines a Not-to-Exceed limit for NOx and PN emissions. This paper analyses a database of publicly available PEMS data of mostly Euro 6d-TEMP vehicles. Emissions data of 7 gasoline and 13 diesel vehicles are investigated. Different routes are included per vehicle to explore the emissions over a range of driving conditions. A standard analysis approach is to look at the average emissions per kilometre over the total test, but it has to become difficult to derive trends as overall emissions have reduced significantly compared to the pre-RDE era. This investigation therefore looks at smaller trips within the RDE tests. The intention is to explore remaining emission events to derive insights for Euro 7. The results firstly confirm a significant reduction in real-world emissions with the introduction of RDE requirements, both for PN and NOx emissions. Secondly, the paper shows cold-start emissions are important for both gasoline and diesel vehicles. Once the emissions control technologies are at normal operation temperature, emissions are well controlled for most cases. Finally, it is shown that relatively high emission events are still happening and that this is not only limited during to the cold-start phase. As overall emission levels are indeed reducing, the relative contribution of the remaining emission events becomes significant. Effective legislation must ensure that the remaining emission peaks are properly controlled by designing the testing protocol to apply appropriate averaging of emissions over the emissions test, or part of it.

1. Introduction

Real-Driving Emissions (RDE) requirements were introduced in the European emission legislation to address the gap between lab and real-world emissions. The requirements are applied in 2 steps with Euro 6d-TEMP and Euro 6d type approvals. The procedure focuses on on-road testing with a Portable Emissions Measurement System (PEMS) and defines a Not-to-Exceed limit for NOx and PN emissions. No compliance requirement is defined for the other regulated pollutants CO and THC, these are covered by the WLTC test in the lab. Data from type approval and independent third-party testing confirms Euro6d-TEMP and Euro 6d vehicles have low on-road NOx and PN emissions. Most significant progress is made for gasoline PN and diesel NOx. The positive trend from pre-RDE towards Euro 6d is shown in Figure 1, based on type-approval data in OEM RDE databases [1-2]. Pre-RDE emissions are based on emission factors [3] for gasoline PN and Euro 6b/c data in the OEM databases for diesel NOx.

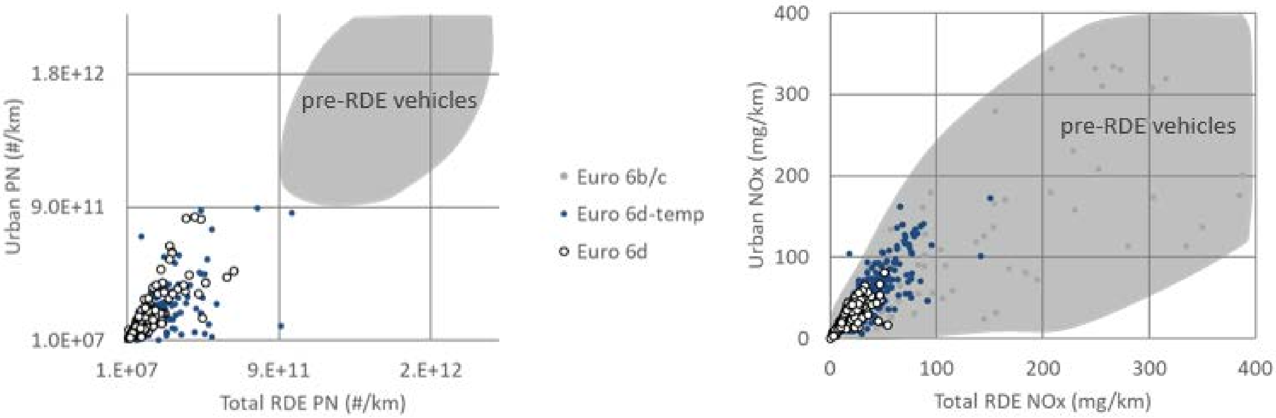

Figure 1 – Reduction in gasoline PN and diesel NOx emissions towards Euro 6d

Emissions control technologies have evolved significantly towards vehicle RDE compliance, see some examples in Figure 2. For gasoline vehicles with direct injection, Gasoline Particulate Filters (GPF) are introduced to reduce PN emissions in addition to the existing Three-Way Catalysts (TWC) for conversion of gaseous emissions. For diesel vehicles, a combination of deNOx technologies is integrated into the exhaust in addition to the Diesel Particulate Filter (DPF). This can be a Diesel Oxidation Catalyst (DOC) or Lean NOx Trap (LNT) in combination with one or more Selective Catalytic Reduction (SCR) volumes.

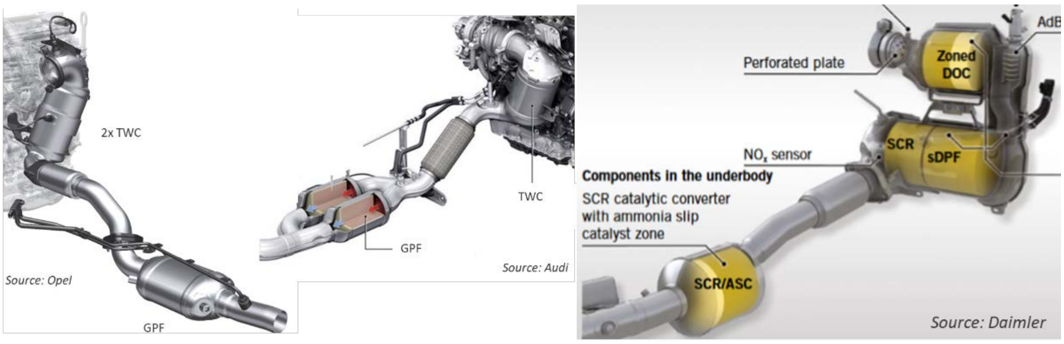

Figure 2 – Example of Euro 6d(-TEMP) emission control systems for gasoline (left) and diesel (right)

The development process for a new Euro 7 emissions regulation for cars, vans, trucks and buses is ongoing. It continues to consider the stringency and testing measures to ensure low vehicle emissions. A European Commission proposal for Euro 7 is expected by the end of 2021. This paper analyses a PEMS database of mostly Euro 6d-TEMP vehicles. The intention is to investigate overall emissions performance of a range of gasoline and diesel vehicles and to identify remaining emission events. The data will be analysed to derive insights for the Euro 7 considerations. It is to be noted that the analysis presented in this paper does not allow to draw any conclusions about emissions compliance of the specific vehicles compared to their respective Euro 6 type approval requirements.

2. Research methodology

In this paper, RDE test results of several vehicles are investigated. The database consists of benchmark data obtained by AECC (vehicle 1), publicly available data from the global RDE database [4] and JRC publications [5-6]. Table 1 gives an overview of the vehicle specifications: fuel type, type-approval stage and engine and emission control technology. Vehicles 1-7 are gasoline, vehicles 8-20 are diesel.

Table 1 – Overview of PEMS database

VehicleID	**Fuel_type**	**Type Approval**	**Technology**
Vehicle 1	gasoline	Euro 6d-TEMP	GDI, TWC, GPF, 48V mild-hybrid
Vehicle 2	gasoline	Euro 6d-TEMP	GDI, TWC, GPF
Vehicle 3	gasoline	Euro 6d-TEMP	PFI, TWC
Vehicle 4	gasoline	Euro 6c	GDI, TWC
Vehicle 5	gasoline	Euro 6b	GDI, TWC, GPF
Vehicle 6	gasoline	Euro 6d-TEMP	PFI, TWC
Vehicle 7	gasoline	Euro 6d-TEMP	GDI, TWC, GPF
Vehicle 8	diesel	Euro 6c	DOC, EGR, DPF, SCR
Vehicle 9	diesel	Euro 6d-TEMP	DOC, EGR, DPF, SCR
Vehicle 10	diesel	Euro 6d-TEMP	DOC, EGR, DPF, LNT, SCR
Vehicle 11	diesel	Euro 6d-TEMP	DOC, EGR, LNT, DPF, LNT, pSCR
Vehicle 12	diesel	Euro 6d-TEMP	SCR, EGR, DPF
Vehicle 13	diesel	Euro 6d-TEMP	SCR, LNT, DPF
Vehicle 14	diesel	Euro 6d-TEMP	LNT, EGR, DPF
Vehicle 15	diesel	Euro 6d-TEMP	SCR, EGR, DPF
Vehicle 16	diesel	Euro 6c	SCR, EGR, DPF
Vehicle 17	diesel	Euro 6d-TEMP	SCR, EGR, DPF
Vehicle 18	diesel	Euro 6d-TEMP	SCR, EGR, DPF
Vehicle 19	diesel	Euro 6d-TEMP	SCR, EGR, DPF
Vehicle 20	diesel	Euro 6d-TEMP	SCR, EGR, DPF

A standard regulatory analysis approach is to look at the average emissions per kilometre over the total test. As overall vehicle emissions have reduced significantly compared to the pre-RDE era, it is difficult to derive trends when only looking at the total RDE test result. The RDE procedure introduced separate requirements for the urban part of the test because of specific attention to urban air quality. The investigation in this paper further looks at shorter trips anywhere within the RDE tests to screen for possible emission events.

The available PEMS data of these vehicles was measured according to the RDE procedure defined in Regulation (EU) 2017/1151. For this paper, the raw emission data is used, without applying some of the specific RDE data post-processing, to have a clear view on the emissions as measured at the tailpipe.

3. Results and discussions

In a first step, the overall emissions performance of the vehicles is investigated. The data analysis focuses on those trips that are within current RDE boundary conditions for $vxa_{pos.}$ As defined in the RDE procedure in Regulation (EU) 2017/1151, there is a limit for the 95th percentile of this parameter, which is the product of vehicle speed per positive acceleration greater than 0,1 m/s^2. It is an indication for the driving dynamics. In a second step, a more detailed analysis will be done for possible remaining emission events: the initial cold-start and any outlier result.

3.1. Overall emissions performance

Figure 3 shows an overview of the NOx and PN emissions of the different vehicles in the database. The emissions in mg/km or #/km of the urban (left) , rural (middle) and motorway (right) part of the RDE trips are plotted vs. the average vehicle speed. An orange circle is used for the gasoline vehicles, an open blue one for the diesel vehicles. Outlier results are highlighted with a red marker for specific vehicle numbers. These will be discussed in more detail in the paper.

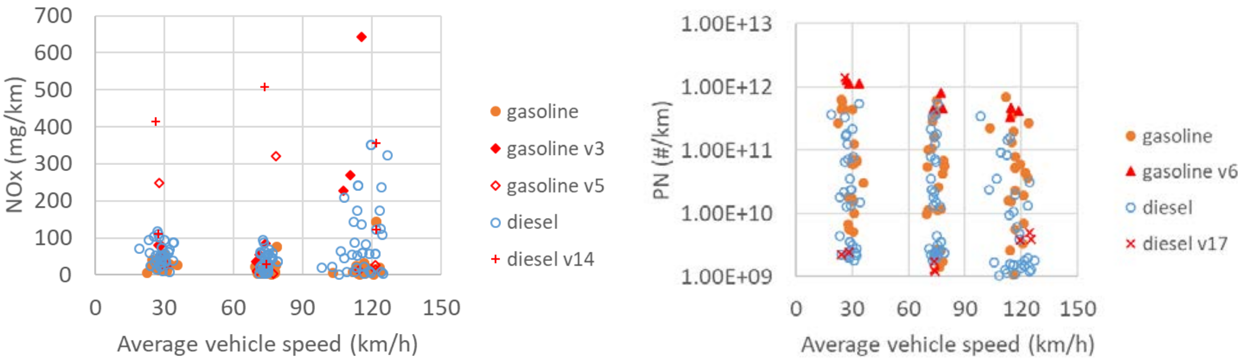

Figure 3 - NOx and PN emissions vs. average vehicle speed of the urban/rural/motorway part of the PEMS tests

It can be seen that the emissions of the vehicles are generally very low for both NOx and PN. The overall emissions of the diesel and gasoline vehicles are similar. For the motorway part, the graph indicates that the diesel NOx emissions tend to be higher. Further reductions are possible through a combination of reduction in engine-out emissions and appropriate sizing of the emission control system, as demonstrated for a C-segment vehicle [6]. It is to be noted that the RDE legislation foresees a compliance requirement for the total test as well as for the urban part. There is no specific requirement for the motorway part. On the other hand, a majority of the motorway diesel PN emissions in Figure 3 are the lowest of the range observed.

NOx outliers observed are gasoline vehicle 3 and 5 and diesel vehicle 14. These vehicles have test results that are within the range of other vehicles, but higher values are measured during specific parts of a certain test. For PN, diesel vehicle 17 will be analysed in more detail. 2 tests show PN results at the lowest range, whereas there is one test which shows an urban value at the higher end. Gasoline vehicle 6, a PFI with TWC, shows overall higher PN results for all tests.

3.2. Initial cold-start emissions

For both gasoline and diesel vehicles, the catalytic converters need to reach their operational temperature after an engine start. The operation temperature depends on the specific emission control technology. This leads to an initial cold-start peak of emissions. In the next sections, we will investigate the impact of the cold-start for gasoline and diesel vehicles.

3.2.1. Gasoline vehicles

The emissions for most of the RDE tests of the gasoline vehicles are very low, as explained in section 3.1. The main remaining emission event is expected to be the initial cold-start, which, relative to its duration, has an important impact on the emissions of the RDE test. This is certainly true for shorter trips, e.g. the urban part which includes the cold-start. The effect is less visible in the total RDE test result as it is averaged out over around 80-100 km. Once the emission control system is up to temperature, emissions are kept at a very low level, except for some remaining emission events which will be discussed in section 3.3.

In Figure 4, one can see the impact of the cold-start on the complete RDE tests of all the gasoline vehicles used in this study (except the outlier results). The horizontal axis represents the fraction (in distance) of the complete RDE test (if a test is 80 km, 1% = 0.8 km). On the vertical axis, the fraction of the NOx emissions emitted for the complete RDE test up to the distance on the horizontal axis is shown. If the emissions would be constant per distance over the whole test, a straight line through the origin would occur on the figure, but this is clearly not the case.

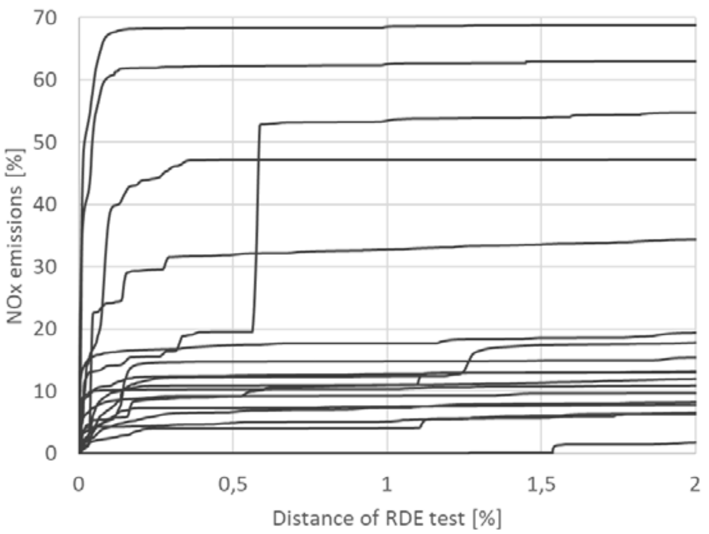

Figure 4 – Impact of cold start on NOx: Fraction of NOx emissions as a function of the fraction of distance for RDE test of gasoline vehicles.

In the figure, only two percent of the complete distance of the RDE tests is shown. It can be seen that for some gasoline vehicles, more than 60% of all the NOx emissions are already emitted in less than 0.5% of the distance of the test. This can mean two things: either a lot of NOx is being emitted during the cold-start of those vehicles or the emission control system of those vehicles works very effectively once it is up to temperature, and very little NOx is being emitted for the rest of the test. As it was already mentioned in section 3.1 that the emissions of these vehicles are, in general, very low over the complete RDE test, we can conclude that the latter is the dominant effect. Further emission reduction would need to come from the very initial seconds of the tests. For shorter trips, this impact would even be higher and it also means that the reported value in mg/km strongly depends on the minimum trip definition. On the other hand, Figure 4 also shows a majority of the vehicles emits less than 20% of the total emissions during the initial cold-start phase. This means that the effectiveness of the emission control system still can be improved even once it is up to temperature.

3.2.2. Diesel vehicles

For diesel vehicles, as emissions are drastically reduced compared to pre-RDE vehicles, it is to be expected that the cold-start is also becoming more important. Especially if the emission control system of the diesel vehicles is working properly and the diesel vehicle has overall low emissions, the cold-start can have a significant contribution to the emissions which are still being emitted.

In Figure 5, a similar plot as for the gasoline vehicles (Figure 3) has been made for the tests of the diesel vehicles. The impact of the cold start on the emissions seems less strong compared to the gasoline vehicles. As diesel vehicles rely on a combination of deNOx technologies, the cold-start effect is less pronounced as for gasoline, which relates to the light-off of the first TWC. But it is still significant for some of the best performing vehicles. The average NOx emission of these vehicles for the complete RDE tests is 35.3 mg/km so these emissions are already at a low level, comparable to the gasoline vehicles. The same conclusions can be drawn as for the gasoline vehicles: to lower the emissions to extremely low values, the cold start can be further improved and for the vehicles for which the impact of the cold start was relatively limited, the effectiveness of the emission control system should also be further improved.

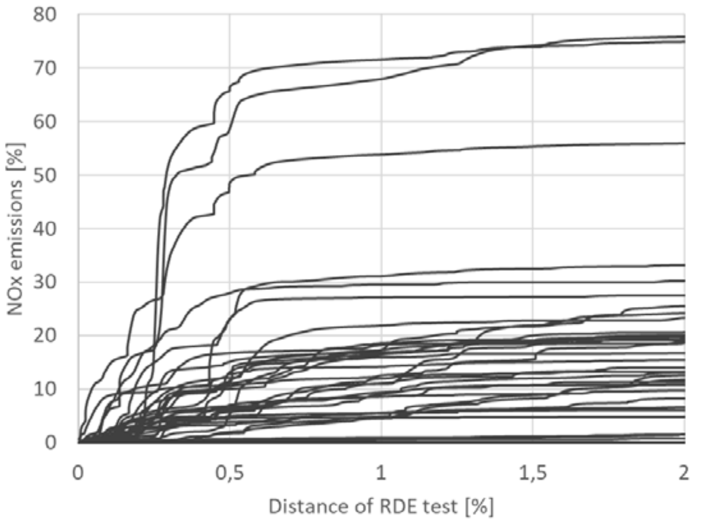

Figure 5 - Impact of cold start on NOx: Fraction of NOx emissions as a function of the fraction of distance for RDE test of diesel vehicles.

3.3. Other emission events

In the next sections, we will look into remaining emission events during some of the RDE tests for both the gasoline and diesel vehicles. We will cover the vehicles that were highlighted in section 3.1 as outliers (vehicle 3, 5, 14 and 17), in addition, vehicles where a clear “event” was seen for a short period during the test despite overall low emission results will also be studied.

It needs to be noted upfront that not enough parameters were available to investigate the root cause for these emission events, but it will be clear that these can significantly impact the reported value of a certain vehicle. More detailed data about ambient conditions, exhaust temperature at different locations, etc. are needed to look into the root cause of these events and how to avoid them.

3.3.1. Gasoline vehicles

For the gasoline vehicles, only 4 of the 22 tests resulted in NOx emissions that were higher than the lab limit of 60 mg/km. The tests of vehicle 3 and 5 were already mentioned in section 3.1. For vehicle 3, all three tests had higher NOx emissions (122-267 mg/km for total RDE) and for vehicle 5, there was only 1 test (206 mg/km for total RDE) with high NOx emissions.

All three tests of vehicle 3 show more or less the same behaviour. High emissions are mainly observed for the motorway part of the test. In Figure 6, the average NOx emissions in mg/km for every kilometre of one RDE test of vehicle 3 are shown. Dividing the test in smaller trips of 1 km is used to screen for possible emission events instead of only looking into the overall emission result. It is to be noted that this has a significant effect on the mg/km value for these short sections. On the right axis of the Figure, the average speed for each trip of 1 km can be seen. It is clear that the high NOx emissions are located in the motorway part of the RDE test. The emissions calculated in this way are much higher on the motorway than for the initial cold-start, which is expected to be the main remaining emission event. A similar behaviour is seen for each test of vehicle 3.

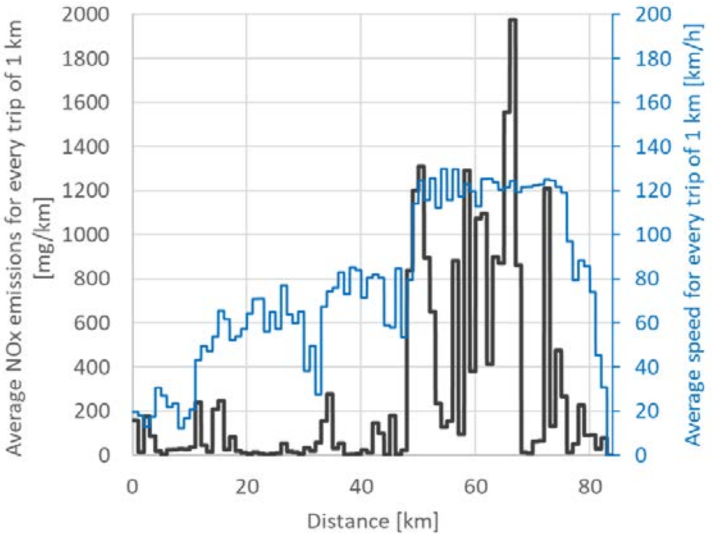

Figure 6 – Average NOx emissions for every trip of 1km [mg/km] (left axis)
Average speed for every trip of 1 km [km/h] (right axis)

Up to km 45, the NOx emissions for vehicle 3 are not abnormal. The average NOx emissions over the three tests up to km 45 is 64.7 mg/km. This is still relatively high compared to the other vehicles, but within the RDE Not to Exceed limit for Euro 6d-TEMP. One of the reasons of the relatively high NOx emissions in the urban and rural part of vehicle 3 and the very high NOx emissions in the highway part of vehicle 3 might be that vehicle 3 is a small PFI car with 61 kW of engine power. Because of the limited power of the engine of this vehicle, this means that the load of this engine is always relatively high, combined with higher engine rpm at highway speeds. As CO emissions remained controlled, this could indicate that the total emission control system volume is not able to control the peak engine-out NOx under these conditions. However, not enough parameters were available from the RDE tests to further examine this.

For vehicle 5, one test has considerably higher NOx emissions than the other RDE tests. When the cumulative NOx emissions are plotted as a function of distance for two very similar tests of vehicle 5 in Figure 7, it is very clear that for one test, after km 20 (more or less the beginning of the rural part), there is a sudden jump in NOx emissions. The rest of that particular test seems to be similar to the other test. No clear hypothesis could be found for this sudden increase in NOx emissions. Not enough parameters were available from the RDE tests to exactly explain this emission event. But it demonstrates that it is important to further eliminate single emission events as these could drastically impact the local air quality.

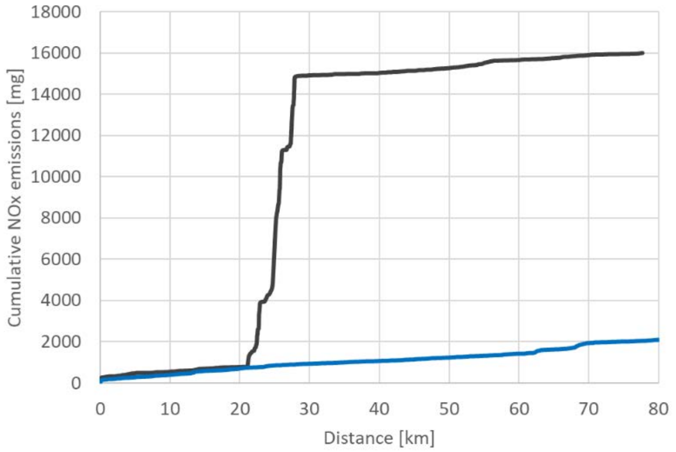

Figure 7 - Cumulative NOx emissions of vehicle 5

3.3.2. Diesel vehicles

For the diesel vehicles, vehicle 14 was mentioned in section 3.1 as an outlier. A closer look at the emission traces of this vehicle show there is a variation between the three tests available. The NOx emissions of the three tests can be seen in Figure 8. Total test results range from 86 up to 421 mg/km. It is clear that every test has completely different NOx emissions but it seems that it cannot only be attributed to a single unexpected emission event in this case. All three tests seem to have a couple of emission events during the test which cause an increase in the cumulative emissions. It is not caused by a continuously higher level of emissions. As a consequence, the initial cold-start is not the main remaining emission event of this vehicle. In different tests, this is occurring at a similar distance, but not to the same extent. It is to be noted that this vehicle relies on EGR and LNT only. The data indicates the emission control system hits some limitations under specific driving conditions. LNT can however well support SCR under urban driving conditions as demonstrated in [7]. Not enough parameters were unfortunately available, e.g. exhaust temperature or NOx emissions at different sampling points, to investigate the cause of this behavior in more detail.

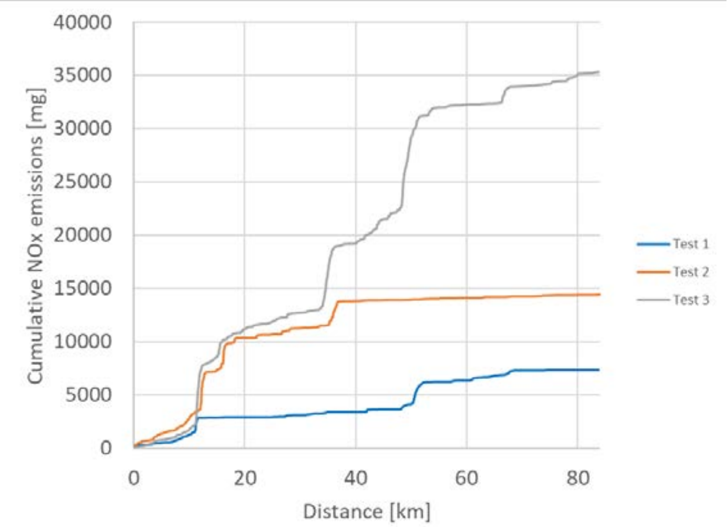

Figure 8 - Cumulative NOx emissions of vehicle 14

For the diesel vehicles, vehicle 18 is another interesting case because one of the three tests has higher NOx (134 mg/km vs. 21-22 mg/km) and PN (2e11 #/km vs. 2e8-2e10 #/km) emissions compared to the other two. For the first test, the high NOx emissions are due to a high emission event in the motorway part. This is clear from Figure 9. In Figure 10, the PN emissions have been plotted where a similar behavior can be seen.

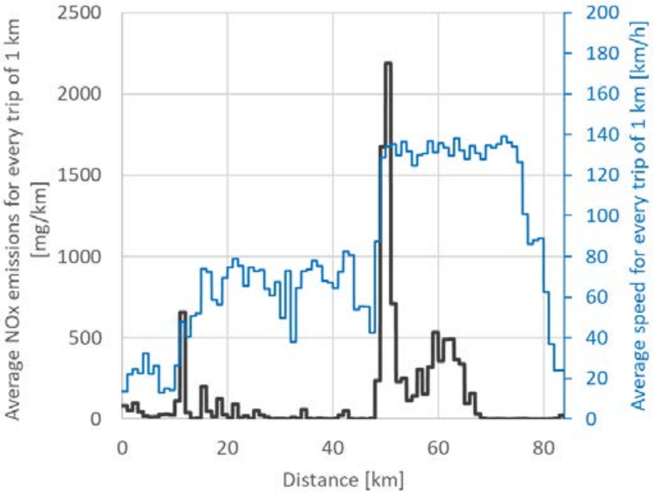

Figure 9 – Vehicle 18: Average NOx emissions for every trip of 1km [#/km]
Average speed for every trip of 1km [km/h]]

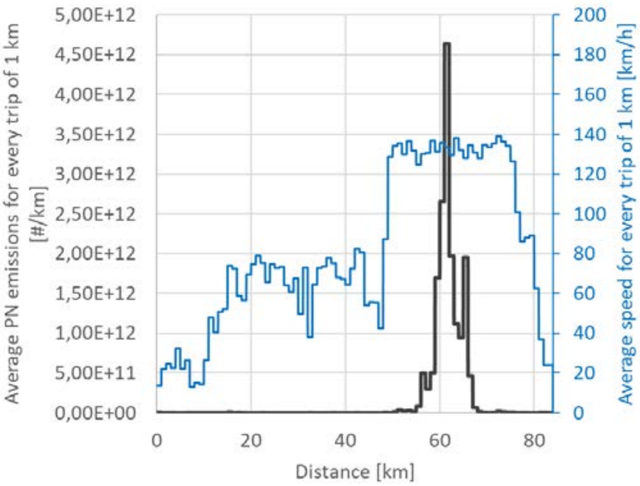

Figure 10 – Vehicle 18: Average PN emissions for every trip of 1km [#/km]
Average speed for every trip of 1km [km/h]

As can be seen on the two Figures for NOx and PN, first the NOx emissions are peaking and after a few kilometres, the PN emissions start to peak as well. As there are few parameters from the engine and emission control system, nothing can be concluded with certainty, but this seems to be linked to a regeneration event of the filter. The increase in NOx emissions could indicate the start of the DPF regeneration, the increase in PN the end. PN increase towards the end of the regeneration event is due to the complete burn-off of the soot cake layer which actually supports particle filtration. It is to be noted that the emissions (2e11 #/km) also remain within the Euro 6d-TEMP Not to Exceed limit for this particular test. There are some other tests in the database that could indicate DPF regeneration occurred. All the measured emissions remain within the Not to Exceed limit and unfortunately not enough parameters were available from the RDE tests to further investigate these emission events.

4. Conclusion

RDE regulation ensured that the on-road NOx and PN emissions of gasoline and diesel vehicles significantly reduced. The data shown in this paper confirmed that Euro 6d-TEMP gasoline and diesel vehicles overall have very low emissions. The purpose of the analysis reported, was to look into remaining emission events and to derive potential insights for Euro 7. It was shown that still some outliers occur for both diesel and gasoline, which are to be tackled by Euro 7. Diesel NOx emissions tend to be higher in the motorway section, whereas it is technically feasible to have consistent NOx control with proper system volume and reductant injection strategy. Then it was shown that the initial cold-start becomes increasingly important when the overall emissions are reduced to Euro 6d-TEMP levels. Other outlier results can be linked to certain limitations of implemented emission control systems (no filter, no SCR) or certain emission events that only occur time to time (DPF regeneration). In summary, effective legislation must ensure that the remaining emission peaks are properly controlled by designing the testing protocol to apply appropriate averaging of emissions over the emissions test, or part of it. Important aspects to consider for appropriate averaging are, for example, separate evaluation for specific driving conditions (especially urban) on top of the total test average and definition of the minimum evaluation distance. The effect of the initial cold-start on report value in mg/km and #/km needs to be considered. But challenging conditions should not be overcompensated by the rest of the test.. The available dataset demonstrates such emission tests are a good way to judge overall emission performance on a total vehicle approach, but are too limited to investigate the specific root cause of observed emission events.

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