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Recommendations for the new WLTP cycle based on an analysis of vehicle emission measurements on NEDC and CADC

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Abstract

Past investigations have shown that the current type-approval test cycles are not representative for real-world vehicle usage. Consequently, the emissions and fuel consumption of the vehicles are underestimated. Therefore, a new cycle is being developed in the UNECE framework (World-harmonised Light-duty Test Procedure, WLTP), aiming at a more dynamic and worldwide harmonised test cycle. To provide recommendations for the new cycle, we have analysed the noxious emission results of a test programme of 7 vehicles on the test cycles NEDC (New European Driving Cycle) and CADC (Common Artemis Driving Cycles). This paper presents the results of that analysis to show the zones of the cycle that are causing the highest emissions, using two different approaches. Both approaches show that the zones with the highest emissions of modern vehicles differ from vehicle to vehicle. Consequently, a representative test cycle has to contain as many combinations of vehicle speed and acceleration that occur in real-world traffic as possible to prevent that a vehicle does not perform well for certain combinations because they are not included in the test cycle. Furthermore,

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the paper demonstrates that it is important to include a cold start to ensure rapid warm up of the catalysts.

Keywords

vehicle emissions; type-approval test cycle; Worldwide Harmonized Light-duty Test Procedures (WLTP)

Introduction

The emissions and fuel consumption of light-duty vehicles have to be tested on cycles in order to be type-approved. This type-approval data is used to inform the customer and used to serve as an input for models that predict the share of transportation in energy usage and emission production. Several studies have shown, however, that the type-approval data is not representative for real-world usage, because the current EU test cycles were not derived from real world in-use data and they are not dynamic enough. Oxides of Nitrogen (NOx) emissions of modern light-duty diesel vehicles can be up to 4 times higher than type approval data (Joumard et al., 2000; Weiss et al., 2011) and fuel consumption can be underestimated up to 20% (Pelkmans and Debal, 2006). Consequently, prediction models like the Handbook of Emission Factors (INFRAS, 2010) or COPERT (European Environment Agency, 2011) do not use type-approval data anymore to calculate emissions of road transport. Therefore, efforts have been made to develop more representative cycles, based on real-world traffic data, e.g. the CADC (Common Artemis Driving Cycles) (André, 2004). In addition there is a desire to develop a more dynamic world harmonised type-approval cycle that could be accepted by legislative authorities around the world. This is being developed in the UNECE framework, labelled WLTP (World harmonised Light-Duty Test Procedure). Similar developments have already been carried out for motorcycles (WMTC) (UNECE, 2005a) and heavy-duty vehicles (WHDC) (UNECE, 2006). The new cycle should provide a better representation of transient conditions than the current one so as to ensure proper control of real-life driving patterns and should provide sufficiently high speeds to properly represent European driving conditions, again so as to ensure proper emissions control under normal European driving conditions.

In the context of WLTP, a test programme was developed by the Association for Emissions Control by Catalyst (AECC) to examine the emissions of a selection of 'state of the art' light-duty vehicles with emissions technologies designed to meet recent to future emissions on the current European test cycle (NEDC) used for Type Approval and the more dynamic CADC. Normally only total cycle emission values are analysed, which do not allow an investigation of the zones in the cycle that result in high emissions. Therefore, this paper analyses the second-by-second emission results of FTIR measurements (Fourier Transform InfraRed spectroscopy) to investigate which parts of the test cycles are causing the highest emissions.

Experimental Method

The test programme was conducted at a recognised type-approval lab.

Table 1 gives an overview of the tested vehicles of which 2 were gasoline vehicles (1 and 2) and 5 were diesel vehicles. Three diesel vehicles (5-7) were fitted with advanced technology for control of both oxides of nitrogen (NOx) and particulate matter (PM) emissions. The purpose of the paper is to demonstrate the advantages of the proposed analytical methods and to give general recommendations for the development of the new type-approval test cycle. It is not the purpose of the paper to investigate differences between engine or aftertreatment technologies, so limited information about the vehicles is given in Table 1. Vehicle 3 was certified for Euro 3 and vehicles 1,2 and 4 for Euro 4. Vehicles 5-7 are demonstration vehicles with an advanced emissions control system and calibration targeted at Euro 6.

Table 1: Overview of tested vehicles

vehicle nr.	Engine type	Emissions control
1	SI	Catalyst + deNOx
2	SI	Three-way catalyst
3	CI	Oxidation catalyst
4	CI	Catalyst + particulate filter
5	CI	Advanced diesel demonstration system
6	CI	Advanced diesel demonstration system
7	CI	Advanced diesel demonstration system

During the tests, regulated (CO, NOx, THC) emissions were measured according to European type approval standards (labelled CVS data, Constant Volume Sampling) on NEDC and CADC and also on the WMTC for vehicle 7. Additionally, both regulated and unregulated (CH_4, NO, NO_2, N_2O, NH_3) emissions were measured with FTIR technology (Fourier Transform InfraRed spectroscopy) before (engine-out) and after (tailpipe) the aftertreatment technology. The advantage of these measurements is that it results in second-by-second data that gives insight in the emission production within the test cycles.

The first part of the NEDC (the ECE urban cycle) is repeated four times after a cold start, so the effect of the cold start on the emissions can be analysed by comparing the results of these four ECE parts. The CADC normally does not contain a cold start, but for some vehicles the CADC was also run after a cold start to be able to analyse the effect of the cold start on the more dynamic cycle.

The FTIR data of the regulated emissions were first compared to the CVS data by calculating total cycle emission values in mg/km to see how good the agreement is. The differences were the smallest for the NOx emissions, for which all the FTIR results were within 20% of the CVS results. The CO data showed a larger deviation, because of lower absolute emission values. Therefore, only CO data of vehicles with a difference in the total cycle value between the FTIR and CVS data below 50% were analysed (vehicles 2-3 and 5-7). The FTIR THC data was not analysed at all, because all data showed a difference larger than 50%. This can be explained by the fact that FTIR only measures a limited amount of hydrocarbons in contrast to the FID (Flame Ionisation Detection) used in the CVS method. This paper will focus on the NOx and CO emissions, the unregulated emissions will not be analysed.

Analytical Methods

Two different approaches were used to analyse which parts of the cycle are causing the highest emissions. For the first approach, the cycles were divided into different short trips between two idling periods. For each trip, the RPA (relative positive acceleration, in m/s^2), average vehicle speed and emissions in mg/km were calculated. The RPA can also been interpreted as the specific acceleration work of the trip (in kW.s/kg.km). The RPA is a value that characterises the load of the trip and it is often used as a factor to compare different test cycles, being calculated with equation 1. This RPA is also being put forward as an important factor to characterise vehicle trips in the analysis of traffic data in the WLTP process (UNECE, 2005b).

$$RPA = \frac{\sum_{i=1}^{n} a_i \cdot v_i \cdot \Delta t}{s} \qquad (1)$$

With:

- a_i: acceleration at time step i, only if $a_i>0$, [m/s²]
- v_i: vehicle speed at time step i, [m/s]
- Δt: time increment (=1), [s]
- s: total trip distance, [m]

As a reference, all the RPA and average vehicle speed combinations of the trips occurring in NEDC, CADC and WMTC are plotted in Figure 1. A bubble chart is used in Figure 2, where the size of the bubble represents the distance of the trip in km to indicate the different contribution of the trips. The graphs demonstrates that CADC is more demanding for the engine because of a higher RPA, especially in the urban part which contains a lot of short trips. CADC also tests a wider range of conditions than NEDC. WMTC covers a higher load than NEDC, but contains less trips with a high demand at low speeds compared to CADC. It does have one trip with a high RPA value which is comparable to CADC.

The emissions that are produced during each trip will be visualised on a graph with RPA versus vehicle speed, like in Figure 2, where the magnitude of the bubbles this time will correspond to the emission value of the trip in mg/km (bubble chart). A reference symbol will be added at the left bottom corner of each graph so that the emissions of different vehicles can be compared.

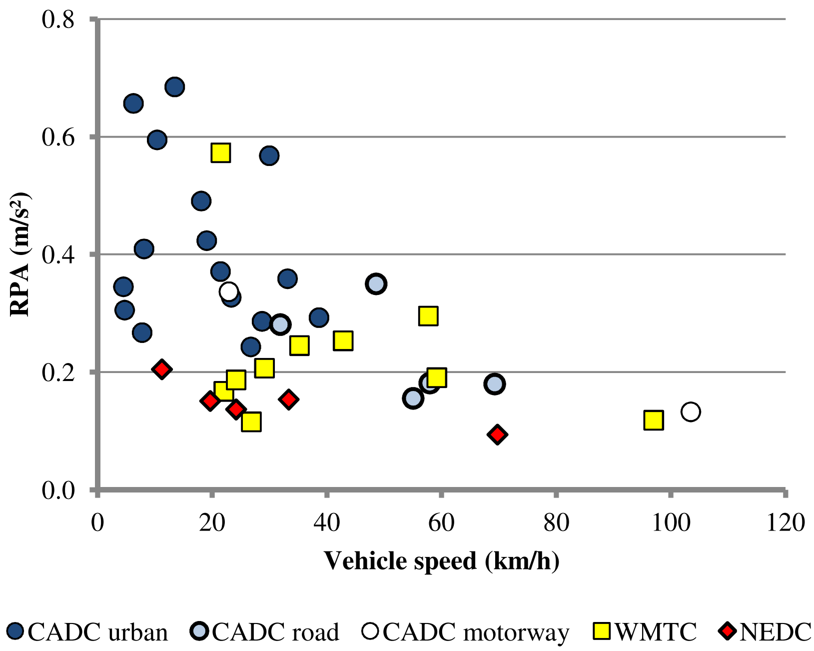


Figure 1: RPA vs. vehicle speed for NEDC, CADC and WMTC

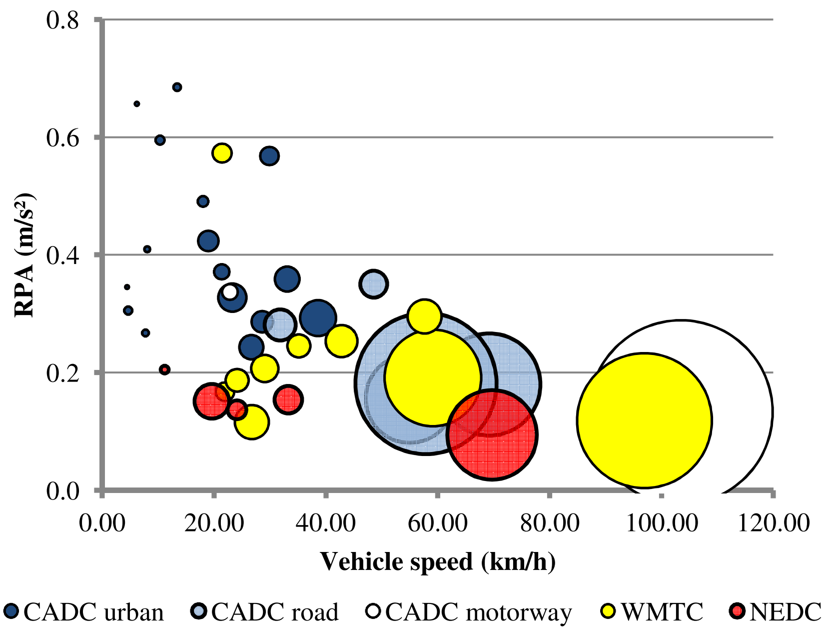


Figure 2: Bubble chart of the time share of the trips for NEDC, CADC and WMTC

There are only a limited amount of trips in the test cycles, so the first method only allows visualisation of certain zones within the cycle. In literature, Traffic data is often compared to test cycles by plotting instantaneous acceleration versus vehicle speed (Pelkmans and Debal, 2006; Goyns, 2008). Therefore, for the second approach, an entire map of the emissions for acceleration vs. vehicle speed was used. To visualise the approach, all the combinations of acceleration and vehicle speeds in NEDC and CADC are plotted In Figure 3. The graph shows that NEDC only has some constant accelerations and decelerations. In contrast, CADC clearly covers a wider band of combinations. The map of WMTC is plotted in Figure 4, demonstrating that it covers about the same combinations of accelerations and vehicle speeds as CADC. However, there is a zone left out at low vehicle speeds and the maximum speed is limited to 120 km/h.

The second-by-second emissions in mg measured by the FTIR are properly aligned according to the trace of the CO_2 emissions (accurate within 1-2s) before they are converted in mg/km by dividing by the distance that is travelled within one second at the vehicle speed of that second. These values will be visualised on the acceleration vs. vehicle speed map with a contour plot, where the level of the emissions is characterised by a certain colour. Blue represents near zero emissions (or no data, for the blank zone in WMTC) and red represents high emissions. The range of emissions covered in the graphs will be shown in the legend. The contour plots are created for the red zone in Figure 3 and Figure 4, since outside this zone too little data points are available for a representative contour plot.

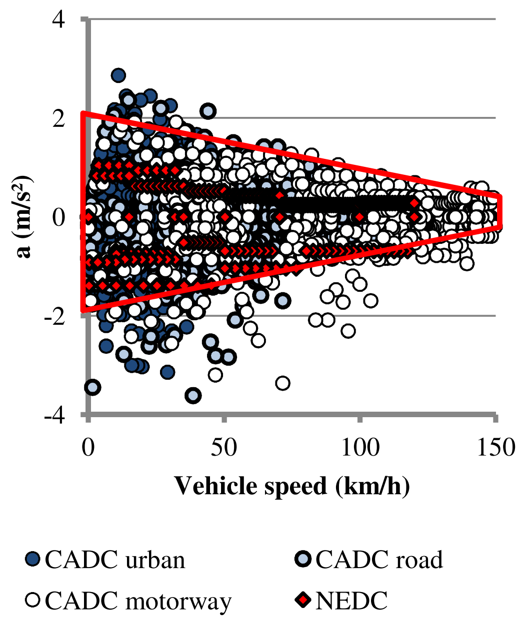


Figure 3: acceleration vs. vehicle speed for NEDC and CADC

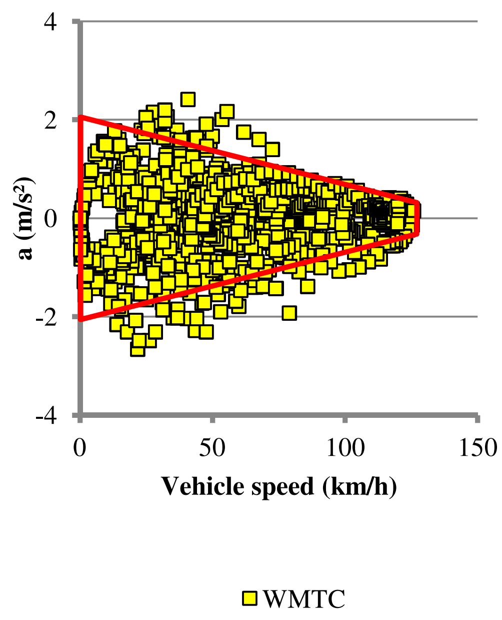


Figure 4: acceleration vs. vehicle speed for WMTC

Results

First, the bubble chart analysis will be presented for the NOx and CO emissions. This analysis will then be used to demonstrate the effect of the cold start on the emissions. Finally, the contour plot analysis will be presented for the NOx emissions.

<u>Bubble chart analysis</u>

NOx emissions

The NOx emissions of diesel vehicles 3 and 4 are plotted in Figure 5 and Figure 6, with the reference bubble at the left bottom corner being 500 mg/km. The NEDC trips are plotted in red and the results of trips with the same RPA and vehicle speed are averaged (because the ECE part is repeated four times).The urban CADC trips are plotted in dark blue, the road trips in a lighter blue and the motorway trips in the lightest blue. These two graphs demonstrate that these vehicles have the largest NOx emissions for the highest RPA values and vehicle speeds. There is no difference between the engine-out and tailpipe NOx emissions (not shown here), because there are no dedicated NOx aftertreatment technologies on these two diesel vehicles.

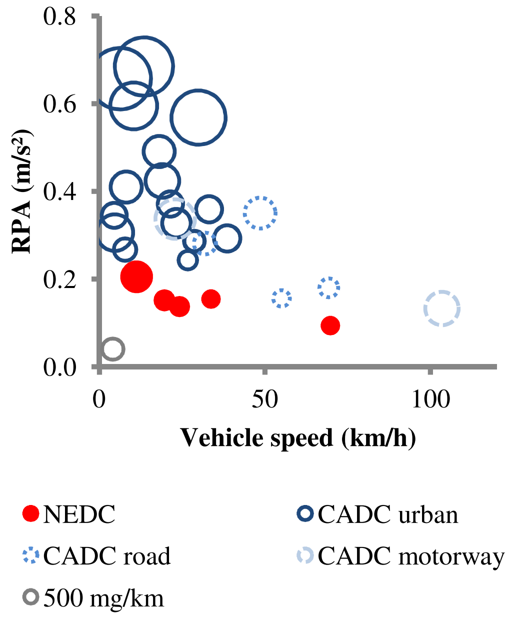


Figure 5: Bubble chart of tailpipe NOx emissions of vehicle 3

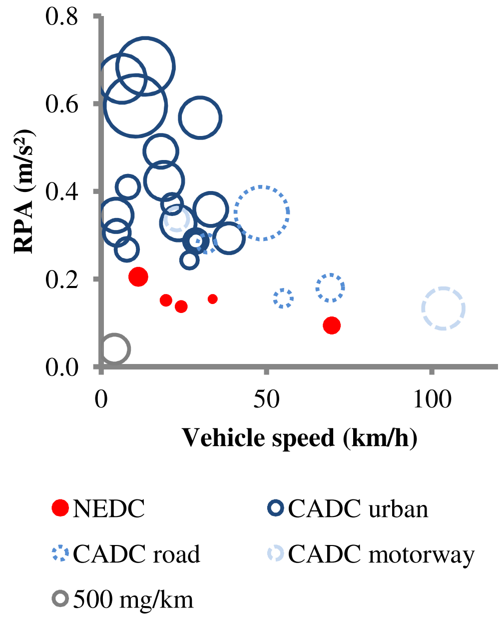


Figure 6: Bubble chart of tailpipe NOx emissions of vehicle 4

The tailpipe emissions of the first two advanced technology demonstration vehicles (5 and 6) are plotted in Figure 7 and Figure 8. In contrast to the previous vehicles, the tailpipe emissions of these vehicles do not show a clear trend for the NOx emissions. The zones with the highest emissions are randomly spread over the graph and differ from vehicle to vehicle. The highest emissions of vehicle 5 are generated by trips with an RPA between 0.2 and 0.4 m/s² and vehicle speed between 0 and 50 km/h. The emissions of vehicle 6 are the highest for trips with an RPA between 0.4 and 0.6 m/s² and for the trip with an RPA and vehicle speed of around 0.3 m/s² and 35 km/h, respectively. The engine-out emissions of these vehicles are plotted in

Figure 9 and Figure 10 to demonstrate that in general, before the catalyst, the same trend is visible as for the vehicles 3 & 4. There, the emissions increase with a higher RPA (for low vehicle speed) and vehicle speed (for low RPA), although more exceptions are visible than for vehicles 3 & 4 (e.g. the trip with an RPA of 0.5 m/s^2 and speed of 25 km/h for vehicle 6). The advanced technology diesel vehicles do have a dedicated NOx aftertreatment system, so the analysis shows that it has an influence on the zones with high and low emissions. Because of the presence of the catalyst, there is a larger freedom in the calibration of the engine, so even the engine-out emissions are more randomly spread compared to - vehicles 3 and 4. Consequently, for modern vehicles, in the absence of a 'real driving emissions test', it is probably not possible to generally predict the performance of any given system/calibration combination based solely on speed/RPA data.

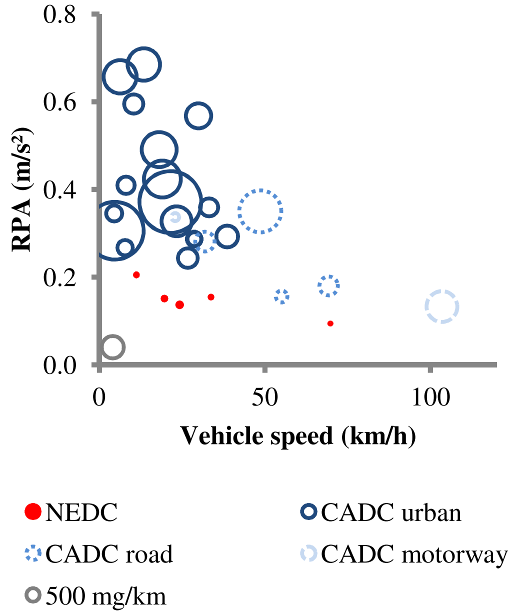


Figure 7: Bubble chart of tailpipe NOx emissions of vehicle 5

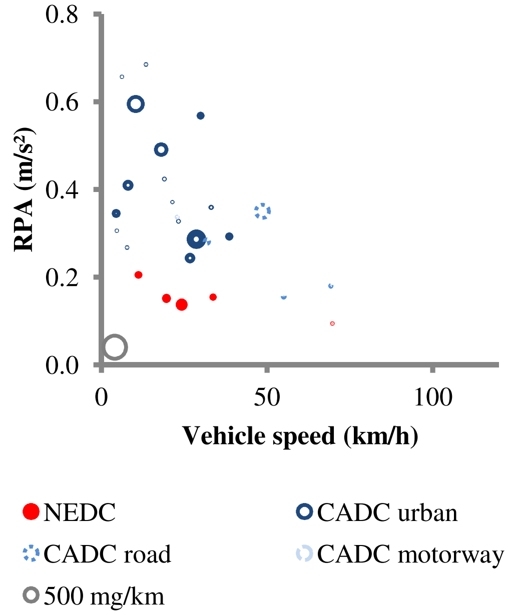


Figure 8: Bubble chart of tailpipe NOx emissions of vehicle 6

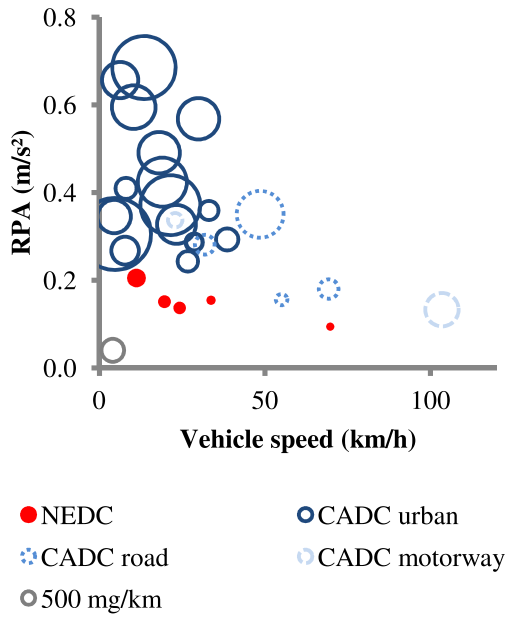


Figure 9: Bubble chart of engine-out NOx emissions of vehicle 5

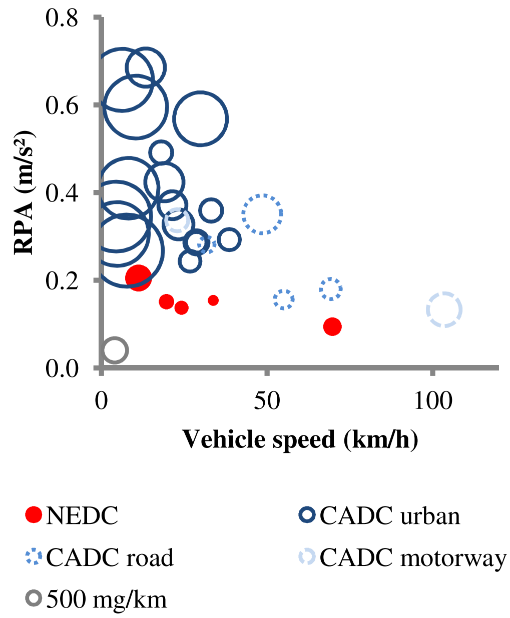


Figure 10: Bubble chart of engine-out NOx emissions of vehicle 6

Vehicle 7 was also tested on WMTC and the emissions of these trips are plotted together with those of CADC and NEDC in Figure 11. Again, the zones with highest NOx emissions are randomly spread around the graph.

Additionally, Figure 11 demonstrates that, although some trips have about the same RPA and average vehicle speed, they still can generate different emissions (e.g. the WMTC trip with the highest RPA (0.573) and the surrounding CADC urban trips). Therefore, the RPA and average vehicle speed of a trip do not fully characterize the emissions the vehicle will emit. Emissions of a vehicle depend on the operational point in the engine map of torque vs. engine speed, so the emissions of two different trips with the same RPA and average speed can differ due to the selected gear. This analysis shows the importance of the requirements for gear selection, which are currently under discussion in the group developing the World-harmonised Light-duty Test Procedure (WLTP). Current prescriptions for manual gearboxes used vehicle speed as the basis for gearshift points. WLTP is considering this as one option, but also an alternative of unique shiftpoints for each vehicle based on the vehicle configuration (partly based on engine speed and better accounting for 5 or 6-speed gearboxes) and a third option of using a vehicle's gearshift indicator.

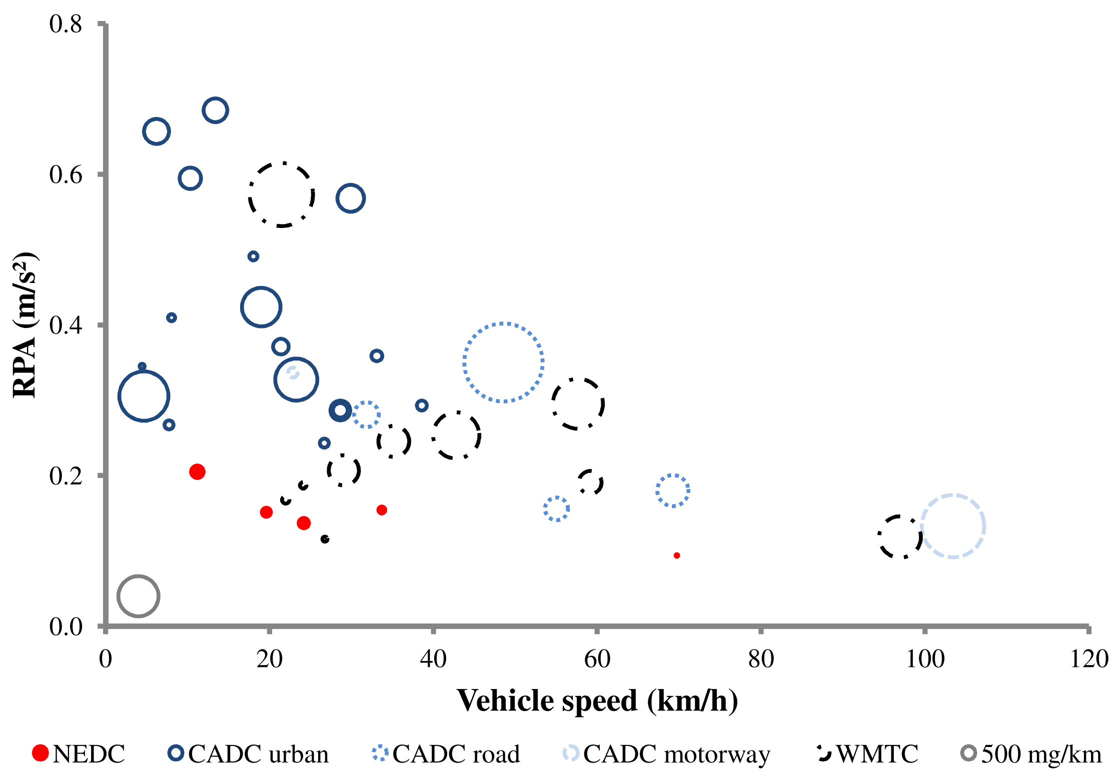


Figure 11: Bubble chart of tailpipe NOx emissions of vehicle 7

The gasoline vehicles do have dedicated NOx aftertreatment systems and the effect of that on the zones with high and low emissions is shown in Figure 12 and Figure 13. The reference bubble in these graphs is 100 mg/km. The engine-out plots of both vehicles show about the same trend (not plotted here). In contrast there are significant differences between the tailpipe emissions. Those of vehicle 1 mainly seem to occur at very high vehicle speeds (CADC motorway), whereas they occur at low speeds for vehicle 2. This difference will be demonstrated more clearly with the NOx contour plots below (Figure 26 to Figure 29).

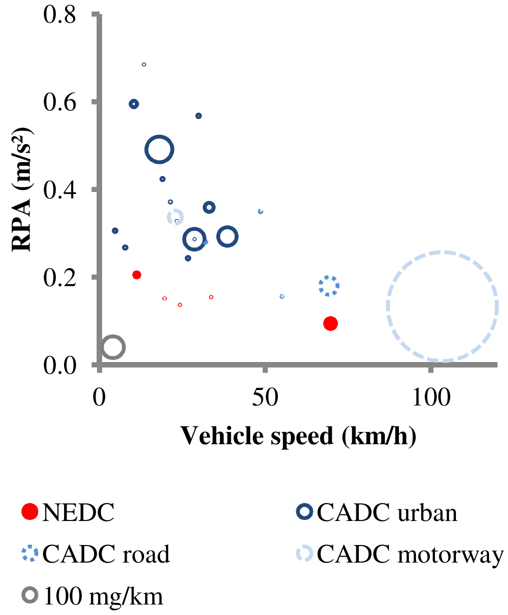


Figure 12: Bubble chart of tailpipe NOx emissions of vehicle 1

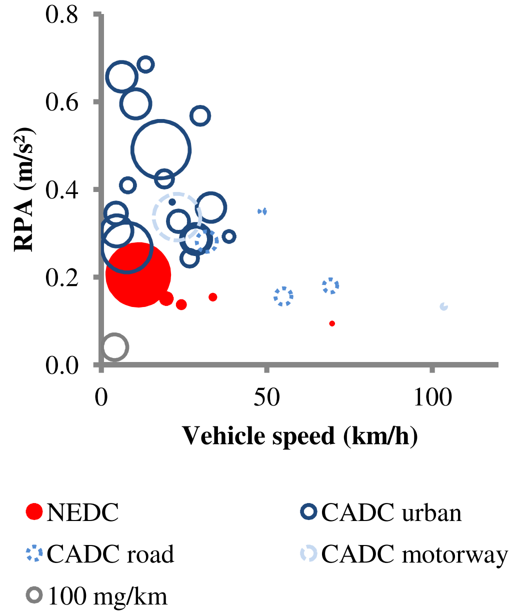


Figure 13: Bubble chart of tailpipe NOx emissions of vehicle 2

CO emissions

The engine-out CO emissions of all the vehicles are mainly located at low vehicle speeds, as demonstrated for vehicle 3 in Figure 14. All the vehicles have a dedicated CO aftertreatment which is capable to remove most of the emissions, as shown in Figure 15 with a graph of the tailpipe emissions of the same vehicle. The reference bubble in both graphs is 1000 mg/km. Tailpipe emissions are only high in the cold phase of the cycles because of the light-off temperature of the catalyst, which will be better visualised in the next section.

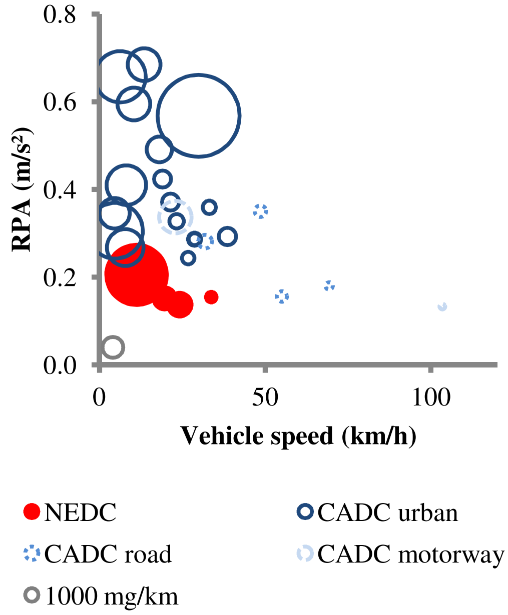


Figure 14: Bubble chart of engine-out CO emissions of vehicle 3

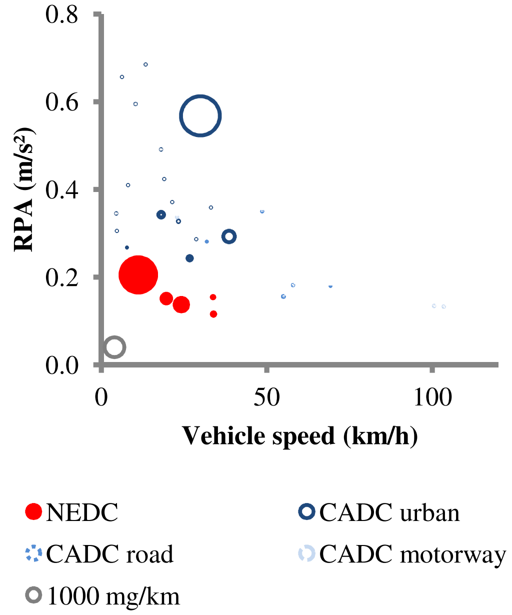


Figure 15: Bubble chart of tailpipe CO emissions of vehicle 3

Cold start effect

The effect of a cold start, due to the warming up time of the catalysts, on the NOx and CO emissions is shown for vehicle 6 in Figure 16 and Figure 17. For NOx, the emissions during the cold start phases (CADC urban cold and the first ECE part) are clearly higher than during the hot phases. The cold start effect on the NOx emissions is visible in all the trips of CADC urban. Figure 17 shows that there are only CO bubbles visible for a limited number of trips. Consequently, there are only significant emissions during the very first trips of the test cycles (ECE1 first 2 trips of CADC urban), indicating a fast heating up of the catalyst.

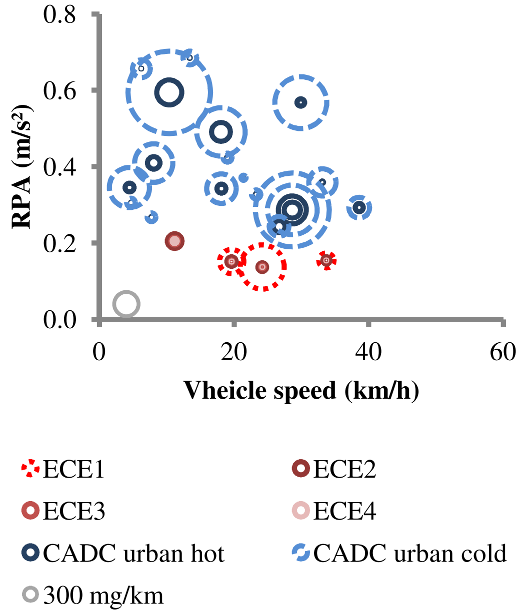


Figure 16: Bubble chart of tailpipe NOx emissions of vehicle 6 with cold start effect

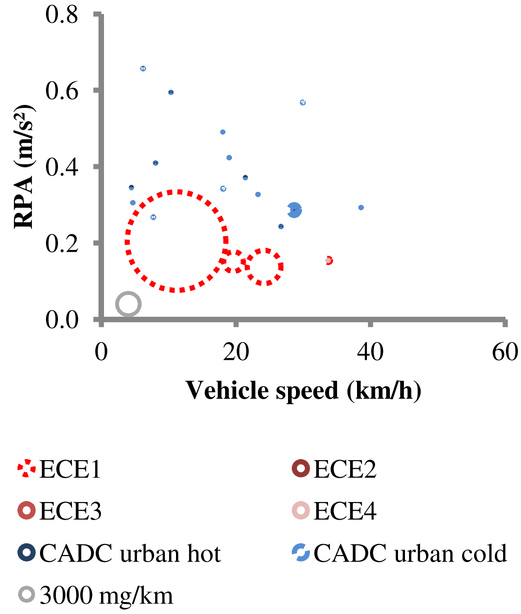


Figure 17: Bubble chart of tailpipe CO emissions of vehicle 6 with cold start effect

<u>Contour plot analysis of NOx emissions</u>

The second analysis allows an entire map of the emissions of the vehicles for all the combinations of acceleration and vehicle speed. This should allow a better comparison between the emissions of different test cycles. Since CO emissions were mainly affected by the cold start, this analysis was only conducted for the NOx emissions. As for the bubble charts, diesel vehicles 3 and 4 have comparable maps with high emissions at high speeds and high accelerations, as demonstrated in Figure 18 and Figure 19. Emissions in red are higher than 3000 mg/km. There is no difference between the engine-out (not plotted here) and tailpipe map because the absence of a dedicated NOx aftertreatment.

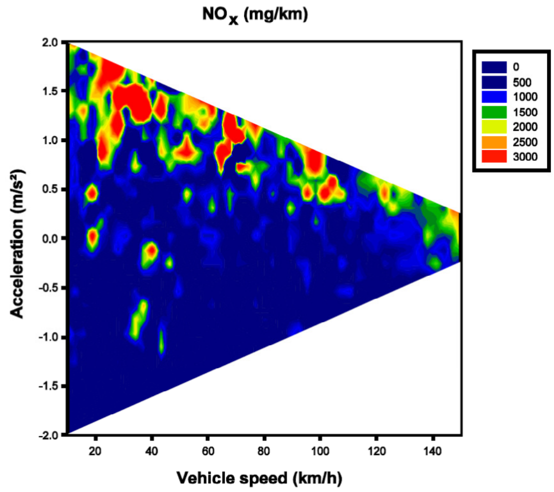


Figure 18: Contour plot of tailpipe NOx emissions in mg/km of vehicle 3

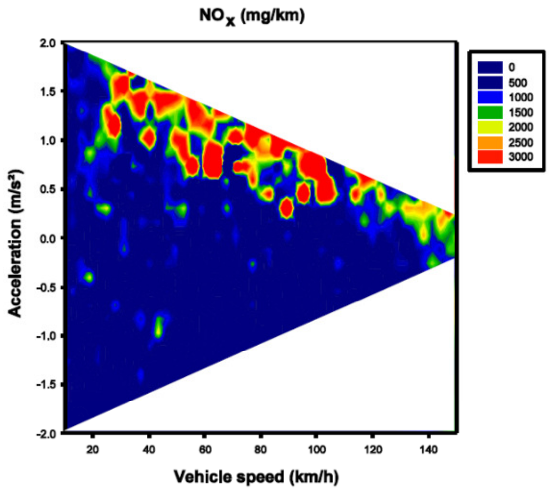


Figure 19: Contour plot of tailpipe NOx emissions in mg/km of vehicle 4

The graphs of the NOx emissions of advanced technology demonstration diesel vehicles confirm what was visible in the bubble charts. The alternative engine-emissions control systems and calibrations result in the zones with the highest emissions differing from vehicle to vehicle. This is visualised in Figure 20 to Figure 23 for vehicle 6 and 7 by comparing engine-out with tailpipe emissions. The engine-out maps are comparable, whereas the tailpipe maps differ significantly. Figure 21 shows that there are almost no zones with very high emissions in the tailpipe of vehicle 6, although there are several at engine-out level.

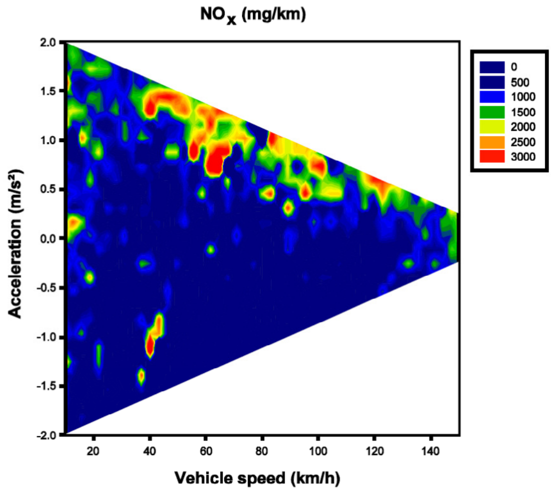


Figure 20: Contour plot of engine-out NOx emissions in mg/km of vehicle 6

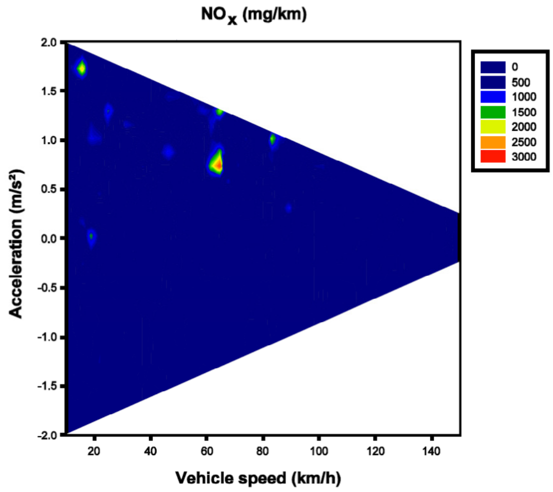


Figure 21: Contour plot of tailpipe NOx emissions in mg/km of vehicle 6

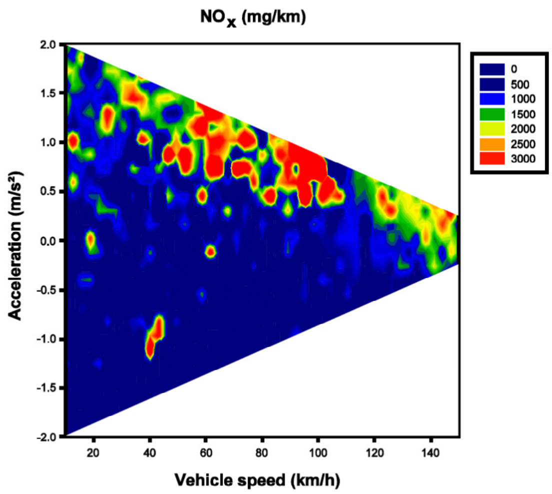


Figure 22: Contour plot of engine-out NOx emissions in mg/km of vehicle 7

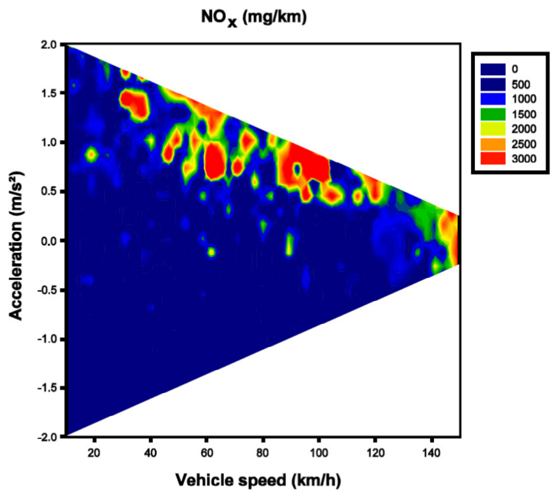


Figure 23: Contour plot of tailpipe NOx emissions in mg/km of vehicle 7

The tailpipe contour plot of vehicle 7 on CADC is plotted in Figure 24 next to that of the vehicle on WMTC in Figure 25, to see whether this analysis allows a better comparison between different test cycles. The maps are not completely the same, but it is the same zone (the highest accelerations between 40 and 120 km/h) that results in the highest emissions. It is clear that the contour plots provide a better comparison than the bubble charts.

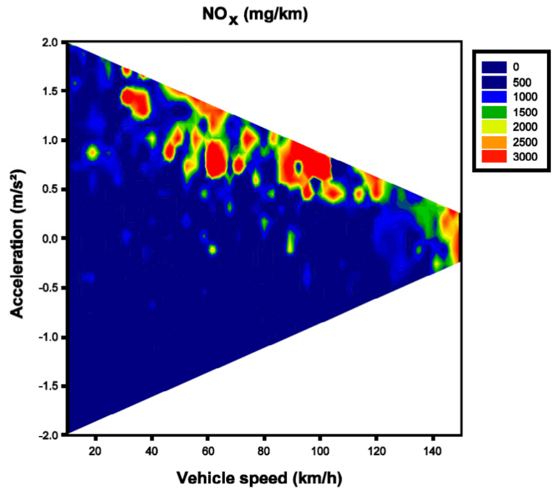


Figure 24: Contour plot of tailpipe NOx emissions in mg/km of vehicle 7 (CADC)

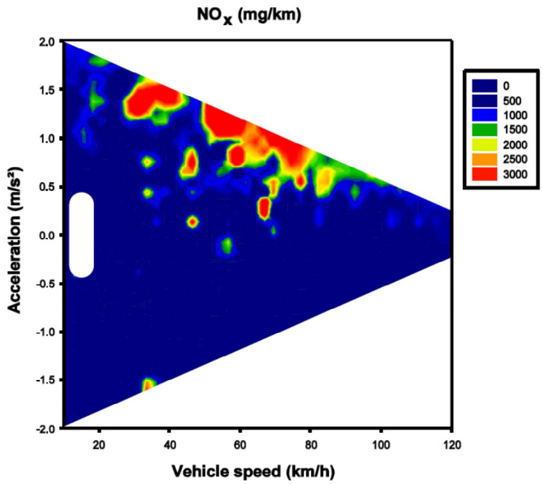
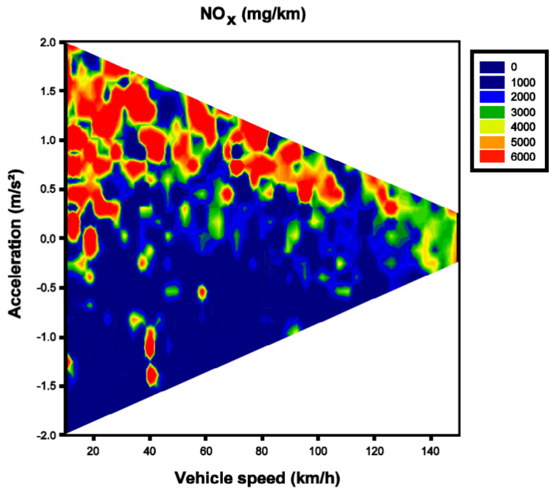


Figure 25: Contour plot of tailpipe NOx emissions in mg/km of vehicle 7 (WMTC)

The effect of the catalytic converter on the zones with the highest emissions is even more visible in the results of the gasoline vehicles. Vehicle 1 and 2 have a similar engine-out NOx emission pattern, as shown in Figure 26 and Figure 28, but a totally different tailpipe map as shown in Figure 27 and Figure 29. The emissions of vehicle 1 are only generated at very high vehicle speeds, whereas those of vehicle 2 are generated at low speeds. All the emissions go down from engine-out to tailpipe, although the colour might change from green to red, because the legends of the engine out and tailpipe graphs are different in order to better visualise the zones with the highest engine-out NOx emissions.



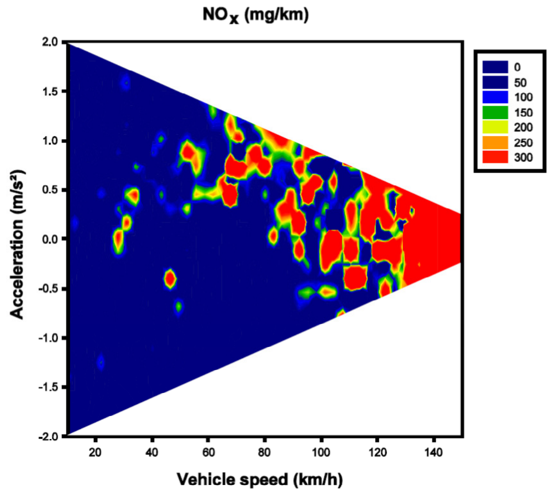
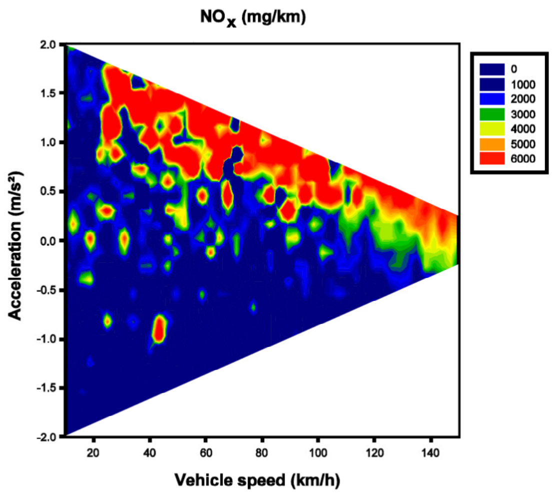


Figure 26: Contour plot of engine-out NOx emissions in mg/km of vehicle 1

Figure 27: Contour plot of tailpipe NOx emissions in mg/km of vehicle 1



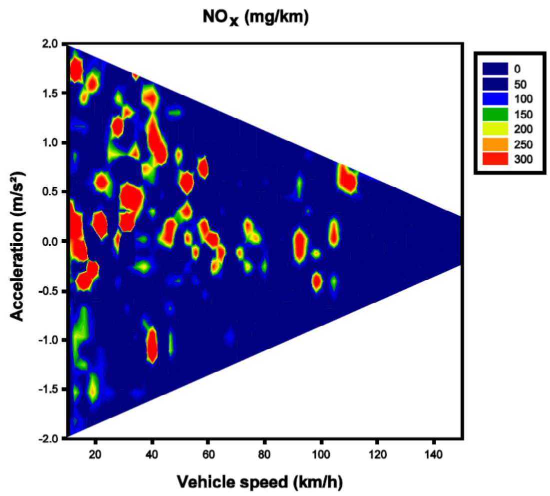


Figure 28: Contour plot of engine-out NOx emissions in mg/km of vehicle 2

Figure 29: Contour plot of tailpipe NOx emissions in mg/km of vehicle 2

Conclusion

This paper has analysed the second-by-second FTIR data of an AECC light-duty test programme. The purpose was to investigate which parts of the test cycles result in the highest emissions. The analysis was done to result in recommendations for the new WLTP cycle which is being developed in the UNECE framework, since it is key to ensure that WLTP provides a sound basis for good, real-world emissions performance. Two approaches were used to visualise the zones with the highest emissions.

First, the different trips (in between two idling periods) of the test cycles were analysed for their contribution to the emissions by calculating a trip value in mg/km. These values were plotted on bubble charts of RPA (Relative Positive Acceleration) vs. vehicle speed. The results showed that the trips with the highest emissions differed from vehicle to vehicle in case of the presence of a dedicated catalytic converter. Furthermore, it was shown that the RPA and average vehicle speed of a trip do not fully characterise the emissions of a certain vehicle, because different trips with the same RPA and average vehicle speed (within the same cycle or within another cycle) could result in significantly different emission levels. This approach was also used to demonstrate the cold start effect on the emissions. An inclusion of a cold start is very important to enforce a short warming up time of the catalyst. WLTP should exhibit realistic warm-up procedures to demonstrate that aftertreatment systems will operate effectively in real service.

Second, contour plots of NOx emissions for acceleration vs. vehicle speed were analysed which confirmed that the zones with high emissions differ from vehicle to vehicle in the case that a catalytic system was present. The advantage of this approach was that it allowed a better comparison between the results of different test cycles.

This paper has demonstrated that both approaches can give more insight in the emissions of vehicles that were measured during a test cycle. It is clear that a representative WLTP cycle has to contain as many as possible of the short trips that occur in real-world conditions together with sufficient combinations of acceleration and vehicle speed so as to minimize the possibility that the emissions of a vehicle are unexpectedly high for certain zones because they are not present in the test cycle. Certain combinations might not occur that frequently in real-world traffic, so the development of supplementary procedures such as the European Commission's initiative on Real Driving Emissions of Light-Duty Vehicles (RDE-LDV) is to be supported. The acceleration vs. vehicle speed map of the test cycle should be filled as completely as possible within the time constraints of a legislative test . The presence of a significant region without appropriate acceleration and vehicle speed combinations, such as occurs in the WMTC, should be avoided.

Therefore, the key points to ensure that WLTP is representative of real-world emissions are the inclusion of appropriate transient conditions and maximum speeds together with a cold-start with the immediately-following conditions being representative of warm-up under normal operating conditions.

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