

Analysis of vehicle emission measurements on the new WLTC, the NEDC and the CADC

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Abstract

Several studies have shown that the type-approval data is not representative for real-world usage. Consequently, the emissions and fuel consumption of the vehicles are underestimated. Aiming at a more dynamic and worldwide harmonised test cycle, the new Worldwide Light-duty Test Cycle is being developed. To analyse the new cycle, we have studied emission results of a test programme of 6 vehicles on the test cycles WLTC (Worldwide Light-duty Test Cycle), NEDC (New European Driving Cycle) and CADC (Common Artemis Driving Cycles). This paper presents the results of that analysis using two different approaches. The analysis shows that the new driving cycle needs to exhibit realistic warm-up procedures to demonstrate that aftertreatment systems will operate effectively in real service; the first trip of the test cycle could have an important contribution to the total emissions depending on the length of the trip; and that there are some areas in the acceleration vs. vehicle speed map of the new WLTC that are not completely filled, especially between 70 and 110 km/h. For certain vehicles, this has a significant effect on total emissions when comparing this to the CADC.

Keywords

vehicle emissions; type-approval test cycle; NEDC; CADC; WLTC

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Introduction

Past investigations have shown that the current type-approval test cycles are not representative for real-world vehicle usage. The NEDC (New European Driving Cycle, used for emission testing and certification in Europe) has often been criticized for being too smooth and underloaded for typical vehicle operation, as it covers only a small area of the engine operating range [1-3]. As a result, manufacturers are able to optimize emissions performance for specific operating points [4]. Oxides of Nitrogen (NO_x) emissions of modern light-duty diesel vehicles can be up to 4 times higher than type approval data [5, 6] and fuel consumption can vary up to 20% [7]. Therefore, a new cycle is being developed in the UNECE framework (Worldwideharmonised Light vehicle Test Procedure, WLTP), aiming at a more dynamic and worldwide harmonised test cycle. In 2011, a first version of the candidate Worldwide Light-duty Test Cycle (WLTC) was evaluated for driveability. Following this first validation phase, the cycle was amended and a “version 5” was established for the purpose of a validation of the whole test procedure (“Validation Phase 2”). The motivations for the new test cycle are: (1) pollutants emissions closer to real world emissions and (2) more realistic measurement of CO₂ emissions from vehicles. Demuyne et al. [8] found that for the first objective appropriate transient conditions and maximum speeds together with a cold start would be required. Similar developments have already been carried out for motorcycles (WMTC) [9] and heavy-duty vehicles (WHDC) [10].

As part of the validation of the newly developed Worldwide Light-duty Test Cycle, AECC (The Association for Emissions Control by Catalyst) conducted an extensive test program in an independent lab to compare exhaust emissions performance achieved on the WLTC with the current European regulatory New European Drive Cycle (NEDC) and with the cold-start Common Artemis Driving Cycle (CADC) [11] that incorporates more transient operating modes derived from real-world driving and that is used as the basis of emissions factors for modelling of emissions. This test program was done with 6 vehicles selected to cover a wide

range of future systems representing the European market (Table 1): three Euro 5 Gasoline Direct Injection cars, two Euro 6 Diesel cars – one equipped with a Lean NO_x-Trap and a Diesel Particulate Filter (DPF), and the other one equipped with a combination of DPF and Selective Catalytic Reduction (SCR) - and a Euro 5 non-plug-in gasoline hybrid car. All vehicles had a minimum mileage between 8500 and 25000 km. It should be noted that vehicles 1 and 2 were run on a temporary version of WLTC. In this temporary version, the main acceleration of the high-speed phase (from 20 to 93 km/h) was somewhat less aggressive.

A comparison of the three cycles has already been made for this test program [12]. In this study, it was found that the test-to-test repeatability was of the same level for each of the three test cycles and that emissions obtained on the NEDC and WLTC were quite similar. Only the CADC emissions results highlighted some higher NO_x emissions from diesel vehicles and somewhat higher NH₃ emissions from gasoline cars. As noted earlier, results from real-world testing with Portable Emissions Measurement Systems (PEMS) have also shown higher NO_x results than those obtained on the certification test, so this may indicate that CADC incorporates operating conditions closer to real-world driving than NEDC or even WLTC. There was, however, little difference for other emissions, including CO₂.

The new vehicle inertia and road load determination procedure was used for all test cycles rather than the existing Type-Approval procedure. Comparison with Type Approval figures indicated that when it comes to measuring more realistic CO₂ emissions, although the two cycles have differences in dynamics, idle share and proportion of cold start, the improvement brought by WLTC tends to be more influenced by the new inertia and road load parameters than by the NEDC or WLTC driving cycles themselves.

This finding is substantiated by the analysis of Weiss et al. [1] which suggests that parts of the difference in the CO₂ emissions between on-road driving and type-approval testing with the

NEDC do not arise from these deviating driving dynamics but from type-approval settings (e.g., tolerance for reported CO₂ values, coast down times, soak temperatures, training of drivers) and specific vehicle calibrations. Just introducing a new driving cycle will likely be insufficient for ensuring that the CO₂ emissions at type approval accurately reflect the average on-road emissions of passenger cars in Europe, but it appears that the complete set of procedures associated with WLTP may have some influence.

This paper is an extension of the research published by Demuynck et al. [8] where the focus is not on the total emissions but on the second-by-second emission measurements to investigate which parts of the test cycles are causing the highest emissions. The aim of this paper is to evaluate the new WLTC by comparing the second-by-second emission results of the new WLTC, the NEDC and the CADC.

Experimental and Analytical methods

Three test cycles were evaluated at 25°C on a chassis dynamometer for each vehicle: the current European regulatory NEDC, the new WLTC including a cold-start test comprising low, medium, high and ‘extra-high’ speed phases followed by 30-min soak and a hot-start repeat of the low and medium-speed phases (as proposed for WLTP at the time of testing; the hot-start repeat has now been dropped), and the CADC. The emissions for the CADC, which is often used as a hot-start test, were sampled from cold-start to analyse the effect of the cold start on the more dynamic cycle.

The final version of the world-harmonised cycle incorporates variations for vehicles with lower power-to-mass ratio and maximum speed (v_{\max}). The cycle used for this test program is that applicable to the typical European vehicles tested, with power to unladen mass ratio of > 34 W/kg and $v_{\max} \geq 120$ km/h (Class 3b).

Tailpipe regulated gaseous emissions (THC, CH₄, CO, NO_x, CO₂) and PM mass and number were measured per phase, according to the Euro 5&6 Regulation for all vehicles, including

the PMP procedures for PM mass and number. THC, CO, NO_x, NO, CO₂ and PM number were also measured second-by-second. In this study, the focus will only be on NO_x, CO and THC emissions.

As mentioned in the introduction, all test cycles were driven with the same vehicle test mass, not respecting the actual Type-Approval procedure for the NEDC cycle, but using the test mass defined in the draft WLTP gtr. This option was chosen rather than using the test mass specified for NEDC in the Euro 5/6 Type-Approval procedure so as to establish a direct comparison of the effect on vehicles emissions of the different test cycles. The inertia introduced by the WLTP procedure corresponded in this case to an increase of 5 to 14% compared to the current Type-Approval values.

The second-by-second emissions in mg/s are properly aligned according to the trace of the CO₂ emissions before they are converted into mg/km by dividing by the distance that is travelled within one second at the vehicle speed of that second. The continuous data of the regulated emissions are compared to the CVS data to see how good the agreement is. Only data with a difference below 20% in the total cycle value between the continuous and CVS data were used in this study.

The analytical methods for the data analysis are the same as in Reference [8]. The methods are repeated here for the sake of clarity. For the first method, the cycles are divided into different short trips between two idling periods. For each trip, the RPA (relative positive acceleration, in m/s²), average vehicle speed and emissions in mg/km are calculated. The RPA can also be 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 [13].

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

With:

- a_i : acceleration at time step i , only if $a_i > 0$, [m/s^2]
- v_i : vehicle speed at time step i , [m/s]
- Δt : time increment ($=1$), [s]
- s : total trip distance, [m]

All the RPA and average vehicle speed combinations of the trips occurring in NEDC, CADC and WLTC 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 to indicate the different contribution of the trips. These graphs demonstrate that CADC is the most demanding because of a higher RPA especially in the urban part which contains a lot of short trips. They also show that WLTC is slightly more demanding than NEDC. WLTC has 4 trips between 10-30 km/h with higher RPA than NEDC. The new WLTC also tests a wider range of conditions than NEDC and it has a trip with an average speed above 90 km/h in contrast to the NEDC cycle.

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.

For the second method, an entire map of the emissions for acceleration vs. vehicle speed is used. In literature, this is often used to compare traffic data to test cycles [7, 14]. All the combinations of acceleration and vehicle speeds in NEDC, WLTC and CADC are plotted in

Figure 3. The second-by-second emissions in mg/s 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 will represent near zero emissions and red will represent 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 (the area covering most of the acceleration and vehicle speeds as can be seen in Figure 3) since outside this zone too few data points are available for a representative contour plot.

The graphs in Figure 3 show that NEDC only has some constant accelerations and decelerations. In contrast, CADC clearly covers a wider band of combinations. For the WLTC, there are zones left out at low speeds and at speeds around 70-110 km/h. The maximum speed in the WLTC is slightly higher than the NEDC cycle, around 130 km/h but lower than the CADC. The new WLTC covers more short trips which occur in real world conditions than the NEDC cycle, as it is based on real-world data. The cycle should also cover sufficient combinations of acceleration and vehicle speed so as to minimise the possibility that the emissions of a vehicle are unexpectedly high for certain zones because they are not present in the test cycle. The acceleration vs. vehicle speed map of the test cycle should be filled as completely as possible. There must obviously be some compromise in the final cycle so as to accommodate the driving patterns of different global regions and to maintain a realistic test duration. This could be better for the WLTC cycle, though, because Figure 3b shows that there are significant regions without appropriate acceleration and vehicle speed combinations.

In this study, we also looked at which accelerations vs. vehicle speed are most present in the WLTC and CADC. Therefore we divided the acceleration vs. vehicle speed area in smaller parts of 10 km/h and 0.4 m/s^2 , after which we counted every acceleration vs. vehicle speed for

each second of the cycle within the same area of 10 km/h and 0.4 m/s². As a result, a contour plot of the acceleration vs. vehicle speed data can be made. In Figure 4, this plot is shown for the new WLTC and for the CADC.

For the WLTC, most accelerations are between 0 and 0.4 m/s² at a vehicle speed between 50 and 60 km/h. There are few points between 100 and 110 km/h while for the CADC cycle, there is an active area in this range. For the CADC, more accelerations are at high speed (between 120 and 130 km/h and between 0 and 0.4 km/h). The CADC can be used for comparison with other cycles because most accelerations vs. vehicle speeds are present in the CADC. In this study, the CADC will be used to check whether vehicles can be optimised up for the WLTC while emitting much more on the CADC and so potentially in real driving conditions.

Results

Results will be shown for NO_x, CO and THC emissions. First, the bubble chart analysis will be presented and finally, the contour plots will be analysed. All the results presented here are based on the tailpipe emissions of the vehicles.

Bubble chart analysis

The NO_x, CO and THC emissions of diesel vehicle 1 are plotted for the WLTC trips in Figure 5 with the reference bubble at the left bottom corner being 300 mg/km, 300 mg/km and 100 mg/km respectively for NO_x, CO and THC. It should be noted that the WLTC has 4 phases: low, middle, high and extra high. Figure 5 presents the emissions for the four phases starting with a cold start. In Figure 6 only the low and middle phase is included starting with a hot start. The reference bubbles are the same for the hot and cold start cycles, making it possible to compare the figures.

If we compare the NO_x emissions of vehicle 1, we see that the highest emissions for the short trips of the low phase are in a different trip for the hot and the cold start. In Figure 5 a the third trip of the low phase has the highest NO_x emissions per km while for the hot start (Figure 6 a), the fourth trip has the highest NO_x emissions per km. For CO and THC emissions, it is also difficult to see a trend between cold and hot start. The trips with the highest emissions are different for the cycles with a hot and cold start. Vehicle 1 has an advanced aftertreatment system with a Lean NO_x-Trap and a Diesel Particulate Filter. Because of the presence of this advanced aftertreatment system, there would be a larger freedom in the calibration of the engine, possibly resulting in differences between cycles with a cold and a hot start. Consequently, for some modern vehicles, it is probably not possible to generally predict the performance of any given system/calibration combination based solely on speed/RPA data [8]. When comparing the CO emissions of diesel vehicle 4 for the WLTC with cold and hot start, see Figure 7, it is clear that there is a big decrease for the hot start (reference bubble for the cold start is 1500 mg/km, for the hot start 10 mg/km). The length of the test cycle also influences the effect of the cold start. Taking gasoline vehicle 2, for example, the cumulative CO emissions during the first 30s of an NEDC test (1854 mg) amounted to some 79% of the total CO emitted during the test, whereas for the longer WLTC test the 1820 mg emitted during the same time period represented only 19% of the total test emissions, due to the longer test. It can be concluded that the new WLTC needs to exhibit realistic warm-up procedures to demonstrate that aftertreatment systems will operate effectively in real service but also that the length of the test should not dilute the effect of the important cold-start.

In Figure 8 the CO emissions are shown for gasoline vehicle 2 (with a 3-way catalyst; TWC) for the WLTC, NEDC and CADC. The aftertreatment system of this vehicle is less complex than the aftertreatment of diesel vehicle 1. As a result, for every cycle, the first trip has the

highest emissions. This indicates that, for certain vehicles, the first trip could have an important contribution to the total emissions depending on the length of the trip. The reference bubbles are 1500 mg/km for the WLTC, 10 000 mg/km for the NEDC and 1500 mg/km for the CADC. The reference bubble for NEDC has a very high value because the emissions in the first trip of the NEDC are relatively high relative to the length of the first trip. The first trip of the NEDC is 0.053 km compared to 0.61 km for the WLTC and 0.40 km for the CADC. The length of the first trip of the NEDC is only 0.48% of the total length of the cycle but it contributes for 44.29% to the total CO emissions. The first trips of the WLTC and CADC are longer but because the WLTC and CADC have long trips at high speed, the first trips are only 2.65% of the total length for the WLTC and 0.78% of the total length for the CADC. Nevertheless, the first trip of WLTC and CADC are contributing for 33.74% and 8.65% respectively to the total CO emissions. The same conclusions can be drawn for the NO_x emissions and the THC emissions of gasoline vehicle 2. As a result, sufficient attention should be given to the first trip of the WLTC cycle in trying to get close to real driving. For example, the average speed of the first cycle of the NEDC is considerably lower than in the WLTC or CADC. This could simulate driving in an urban environment with a lot of traffic jams. Eventually, this should be compared to real driving (PEMS) data. When the first trip is at a speed that is too low, this could result in an overestimation of the real world driving emissions. On the other hand, when the speed is too high, this could result in an underestimation.

In Figure 9 to Figure 11 the NO_x and CO emissions are shown for lean DI gasoline vehicle 3 which is equipped with a TWC and a Lean NO_x-Trap. For the CO emissions it can be seen that the more demanding trips at lower speeds in the CADC can be significant, see Figure 11. For the NO_x emissions, both the WLTC and the CADC have a trip at high speed with high NO_x emissions while no such a trip is included in the NEDC. This suggests that the vehicle is

not specifically calibrated to control NO_x in these high speed trips because it was not necessary for the NEDC, thus resulting in high emissions. When the NO_x emissions of vehicle 4 are compared for the WLTC and the CADC, (see Figure 12) this could again be interpreted as a calibration issue for these trips: the NO_x total emission for the low speed phase of the WLTC has an average of 296.4 mg/km while for the CADC this is 517 mg/km for the urban part. In Figure 12 b, it can be seen that for the CADC there is also a high speed trip (with an average of 103.4 km/h) with high emissions which is not visible in the WLTC in Figure 12 a. The cause for this appears to be that there are accelerations which are present in the high speed trips of the CADC but not in the WLTC. This can be seen in Figure 3 and certainly in Figure 4 where it is clear that there are less accelerations around 100 km/h in the WLTC. As a result, the total NO_x emission for the WLTC is 83.1 mg/km whereas for the CADC, it is 514.5 mg/km. Therefore, it is important to have enough high speed trips and enough trips for which the load is high enough. In order to typify real European driving patterns, it is important to include representative high load short trips.

Contour plot analysis

The contour plot analysis should allow a better comparison between the emissions of different test cycles. When using the CADC, the contour plot gives a map of the emissions of the vehicles for most of the combinations of acceleration and vehicle speed. Demuyneck et al. [8] pointed out that 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 to ensure that real driving conditions are matched. In Figure 3 b, it can be seen that for the new WLTC, there are some areas in the acceleration vs. vehicle speed map that are not completely filled, especially between 70 and 110 km/h. The test on the CADC can be used to see if there are important contributions of emissions in these areas. In Figure 13 to Figure 16, the acceleration vs. vehicle speed maps are shown for the CADC for vehicle speeds between 70 and 110 km/h.

The NO_x emissions are shown for vehicle 3 and 4 and the CO emissions are shown for vehicle 3 and 5 because the emissions at high speeds were relatively high for these vehicles. On the figures, the areas with high emissions that are not included in the new WLTC are circled. The presence of a significant region without appropriate acceleration and vehicle speed combinations, such as occurs in the WLTC, should be avoided.

As can be seen in the legend in Figure 16, the CO emissions for vehicle 5 are very high in the area that is not included in the WLTC cycle. This has a significant effect on total emissions for the two cycles. The new WLTC has an average CO emission of 127.7 mg/km while the CADC has an average CO emission of 500 mg/km for vehicle 5. These high CO emissions can also be seen on the RPA vs. average vehicle speed plot of vehicle 5. In Figure 17, this is shown for the WLTC and for the CADC, where it is clear that the CO emissions for the CADC are higher for the high speed trips. It should be noted, though, that the Euro 5 CO limit for PI vehicles is 1000 mg/km.

Conclusion

The aim of this paper is to evaluate the new WLTC by comparing the second-by-second emission results of the new WLTC, the NEDC and the CADC. AECC (The Association for Emissions Control by Catalyst) conducted an extensive test program with 6 vehicles selected to cover a wide range of future systems representing the European market. All vehicles had a minimum mileage between 8500 and 25000 km.

This paper presents the results using two different approaches. For the first analytical method, the emissions that are produced during each trip, between two idling periods, are visualised by bubbles on a graph with RPA (relative positive acceleration) versus vehicle speed, where the magnitude of the bubbles correspond to the emission value of the trip in mg/km. For the second method the second-by-second emissions in mg/s are visualised on the acceleration vs. vehicle speed map with a contour plot.

The following conclusions can be drawn:

- To ensure that the introduction of WLTC puts proper emphasis on the important area of cold start emissions, it is important that as well as exhibiting realistic warm-up procedures to demonstrate that aftertreatment systems will operate effectively in real service, it needs to be understood that the effect of the extended test length compared to the NEDC may be to dilute the impact of the cold start emissions on the overall test result.
- For certain vehicles, the first trip of the test cycle could have an important contribution to the total emissions depending on the length of the trip. This could result in a misrepresentation of the real world driving emissions. Eventually, this trip should be compared to real driving (PEMS) data.
- For the new WLTC, there are some areas in the acceleration vs. vehicle speed map that are not completely filled, especially between 70 and 110 km/h. For certain vehicles, this has a significant effect on total emissions when comparing this to the CADC. 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 if this makes the driving cycle closer to real driving conditions. Therefore, comparison with real driving (PEMS) data is needed. As the new cycle is composed of ‘short trips’ (idle to idle) from the database of driving measurements, it may be possible to fill this gap without significantly changing the cycle length.

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Table 1: Specifications of selected vehicles.

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Engine type	Diesel	GDI stoichio	GDI lean	Diesel	GDI stoichio	Petrol hybrid
Engine displacement [l]	3,0	1,7	3,5	3,0	1,2	1,8
Rated engine power [kW]	190	147	225	190	78	73
Emission standard	Euro 6	Euro 5	Euro 5	Euro 6	Euro 5	Euro 5
Aftertreatment system	DPF+LN T	TWC	TWC + LNT	DPF + SCR	TWC	TWC
Transmission	Auto	Manual	Auto	Auto	Auto	CVT
Mileage [km]	25000	10000	15000	16000	8500	21000
Weighed mass [kg]	2017	1671	1692	2150	1174	1406
Test mass [kg]	2165	1810	1856	2310	1323	1551

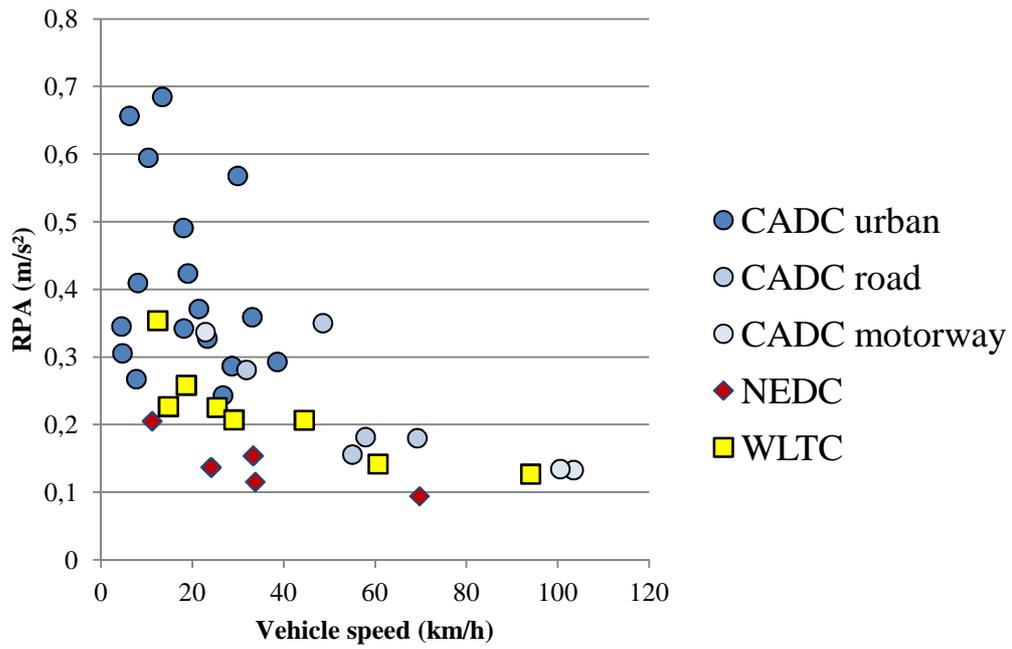


Figure 1: RPA vs. vehicle speed for NEDC, CADC and WLTC

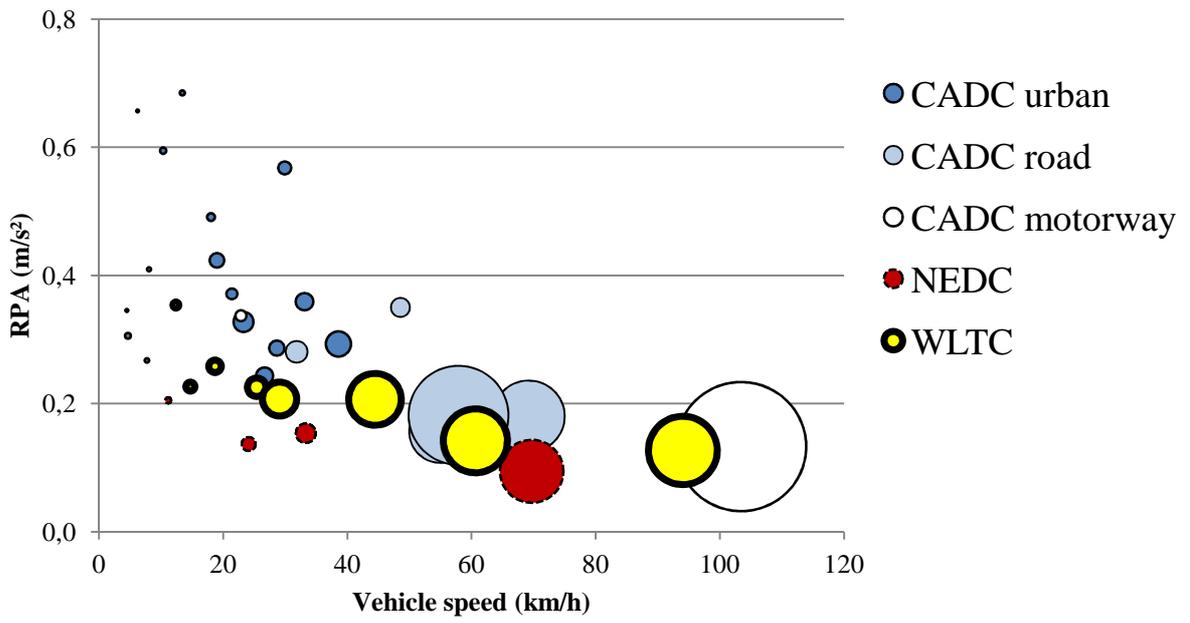
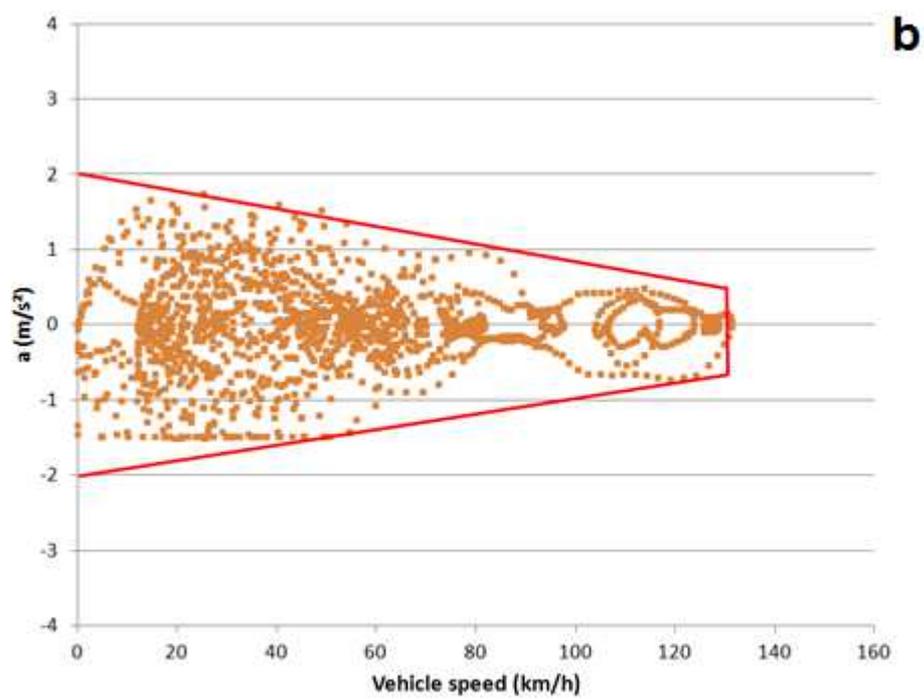
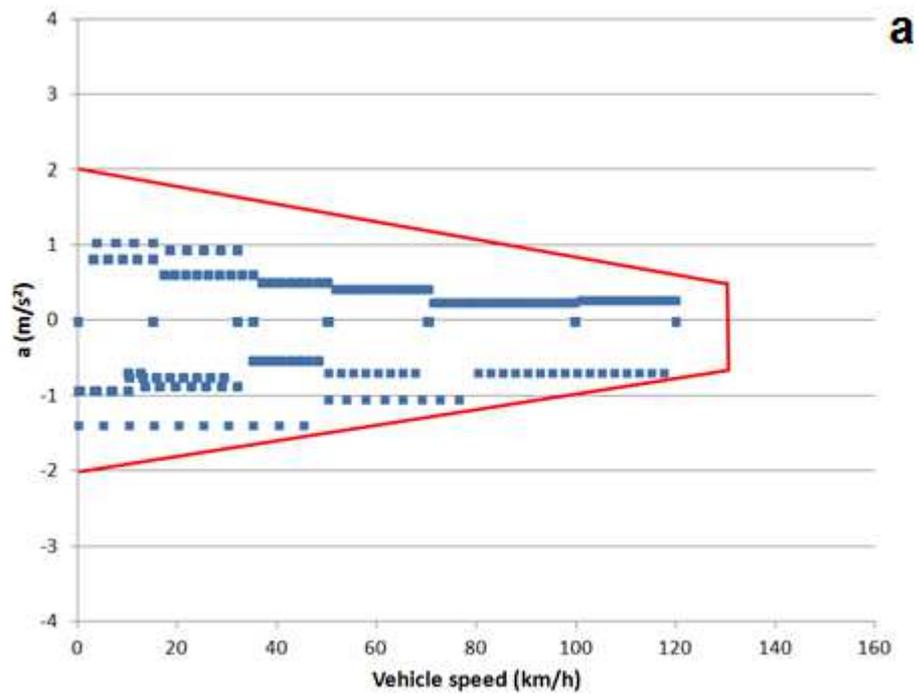


Figure 2: Bubble chart of the distance of the trips for NEDC, CADC and WLTC



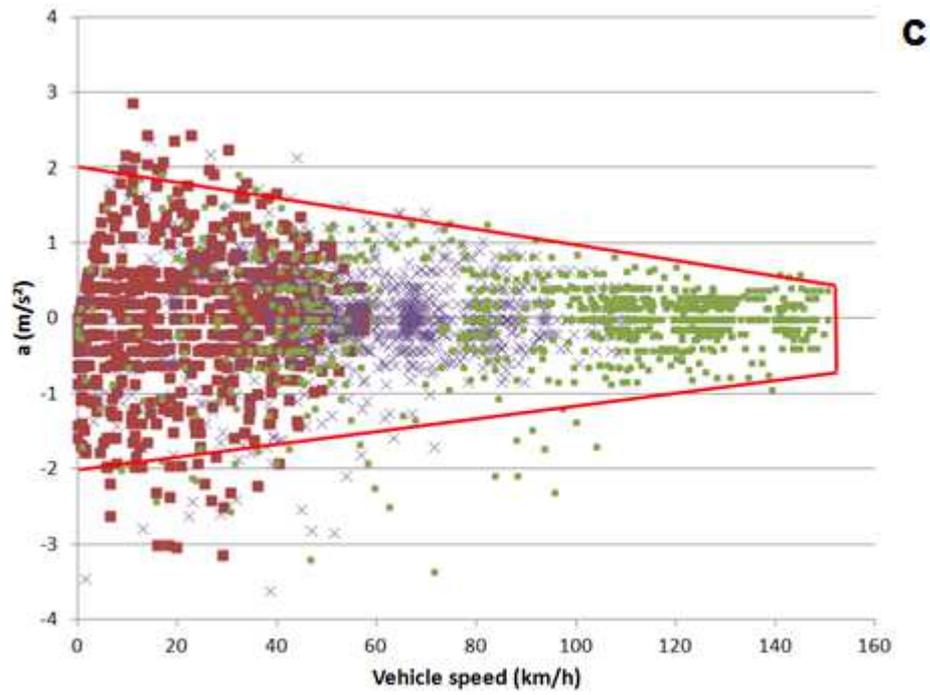


Figure 3: Acceleration vs. vehicle speed for NEDC (a), WLTC (b) and CADC (c)

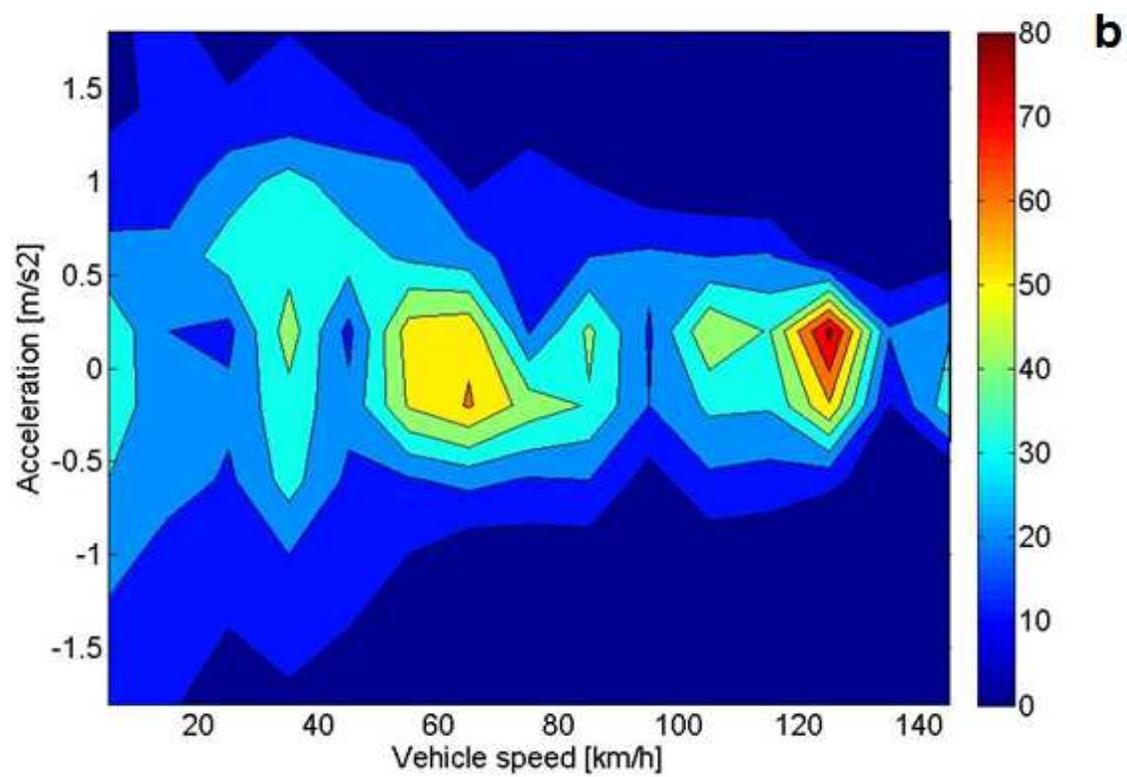
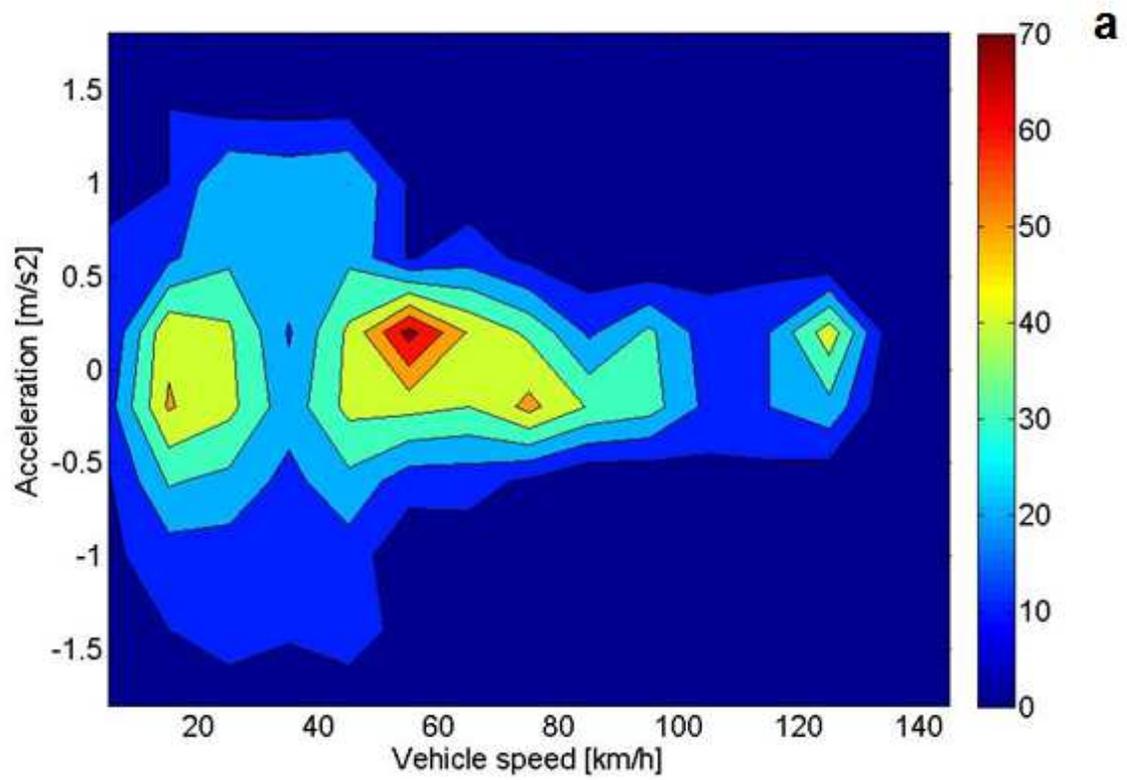


Figure 4: contourplot of acceleration vs. vehicle speed for WLTC (a) and CADC (b)

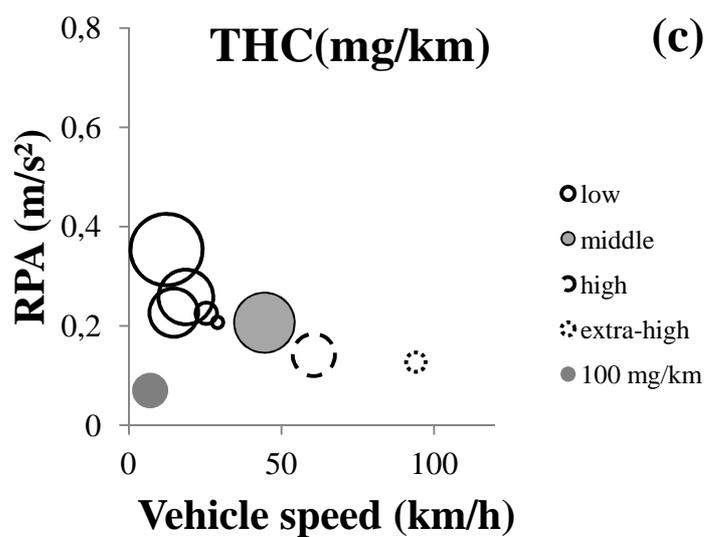
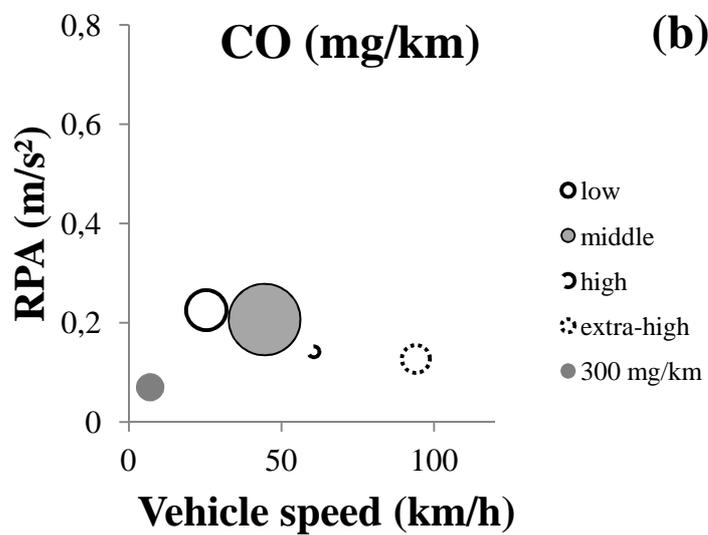
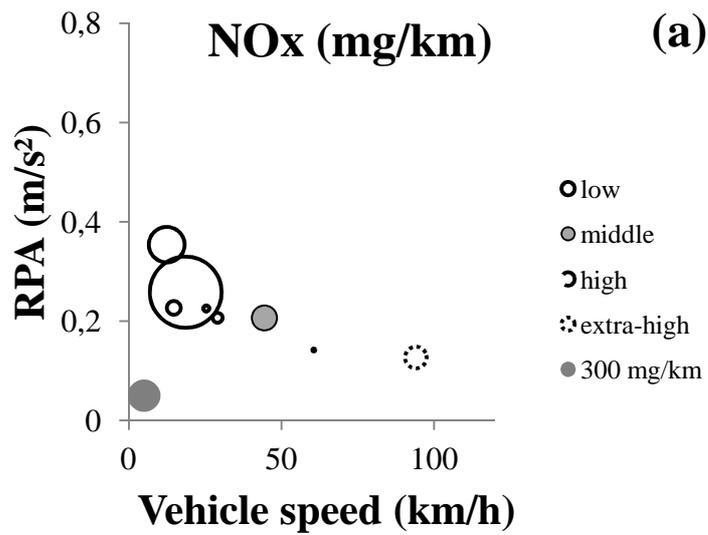


Figure 5: Bubble chart of tailpipe NO_x emissions (a), CO emissions (b) and THC emissions (c) of vehicle 1 (cold-start WLTC)

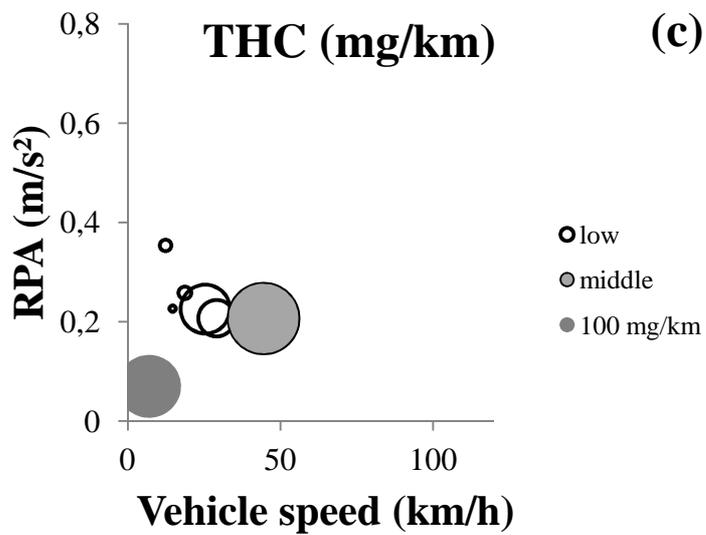
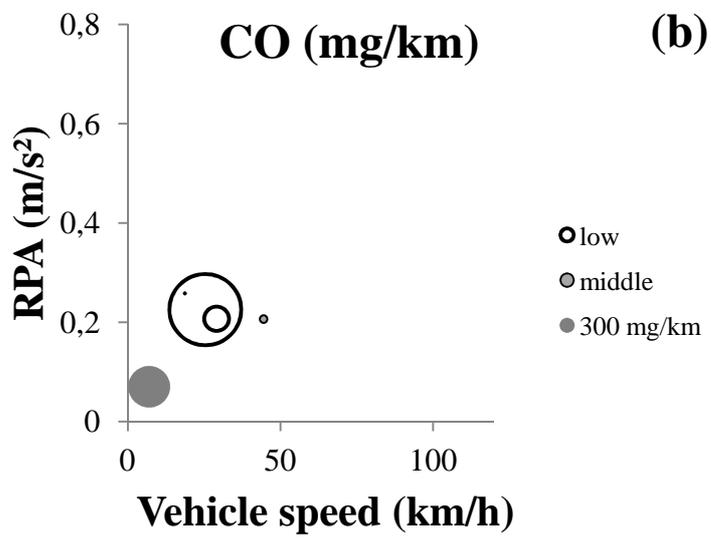
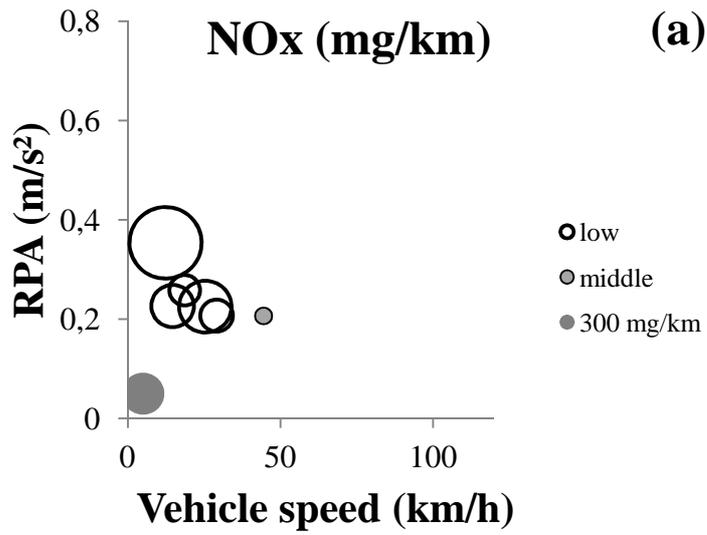


Figure 6: Bubble chart of tailpipe NOx emissions (a), CO emissions (b) and THC emissions (c) of vehicle 1 with a hot start (phase 1 and 2 of WLTC)

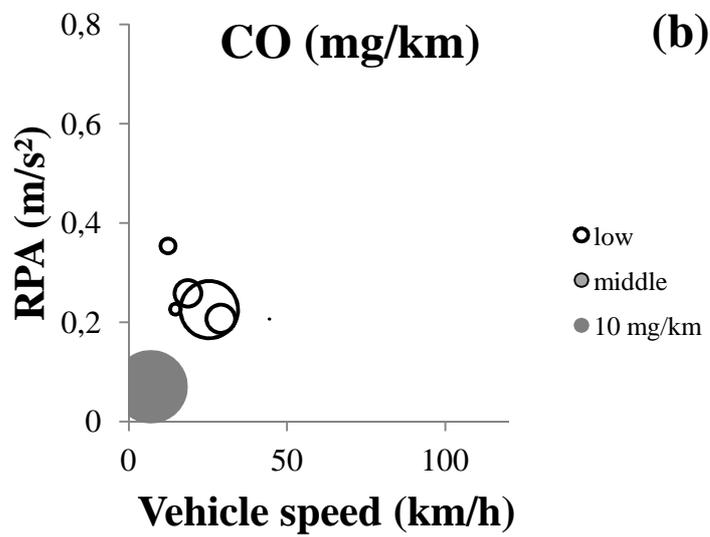
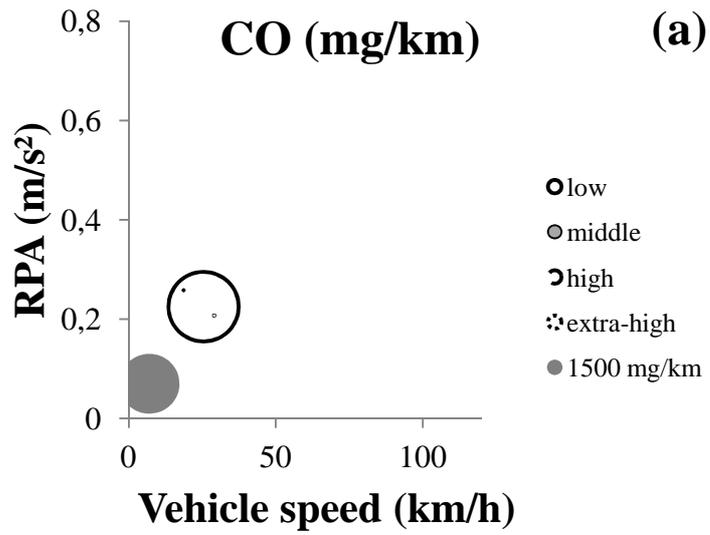


Figure 7: Bubble chart of tailpipe CO emissions of vehicle 4 (WLTC (a) and phase 1 and 2 of WLTC with hot start (b))

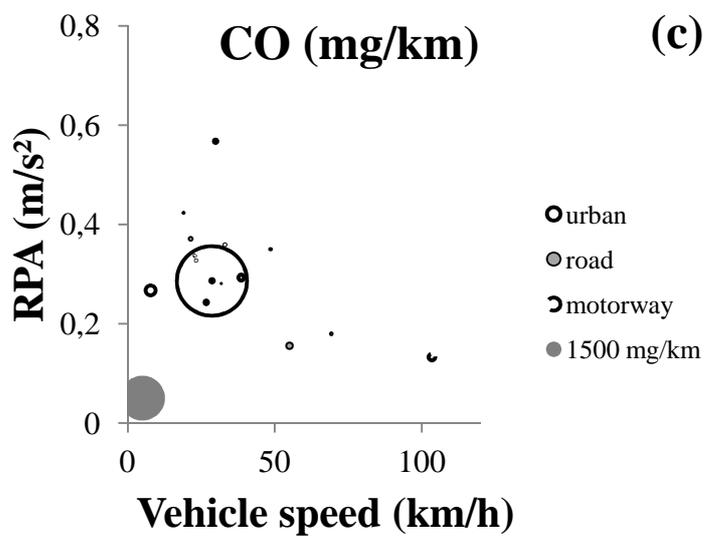
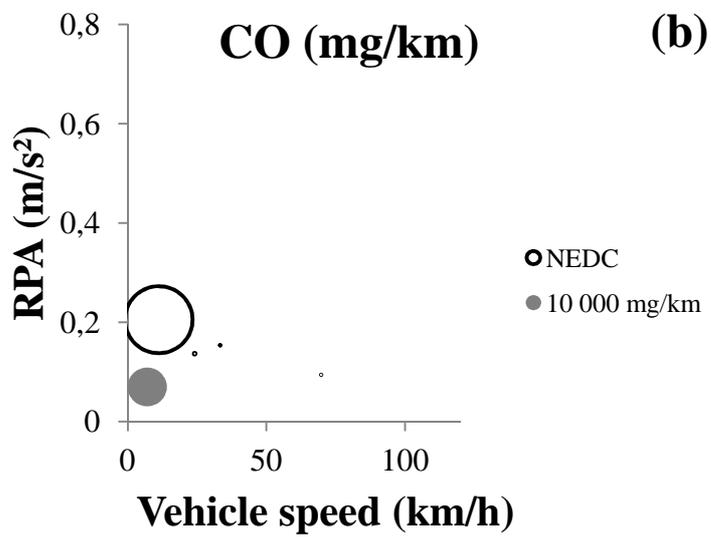
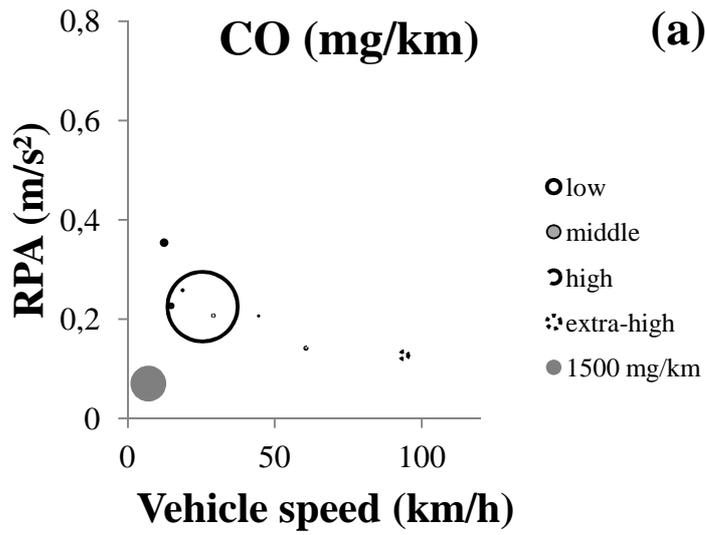


Figure 8: Bubble chart of tailpipe CO emissions of vehicle 2 (WLTC (a), NEDC (b) and CADC (c)).

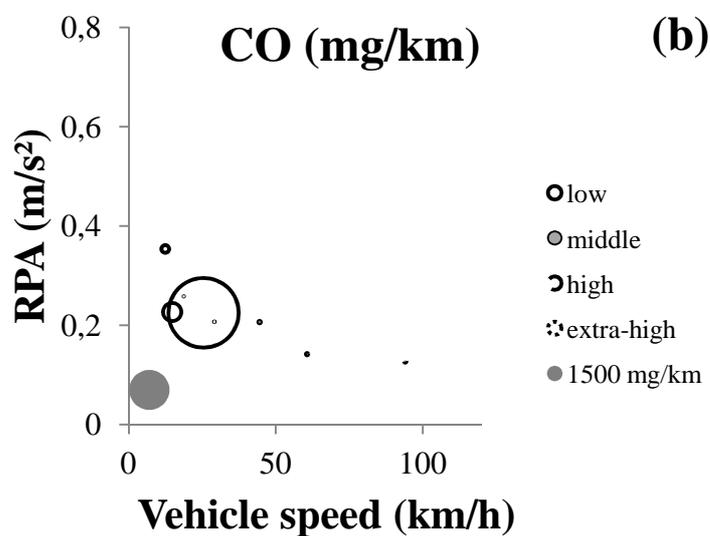
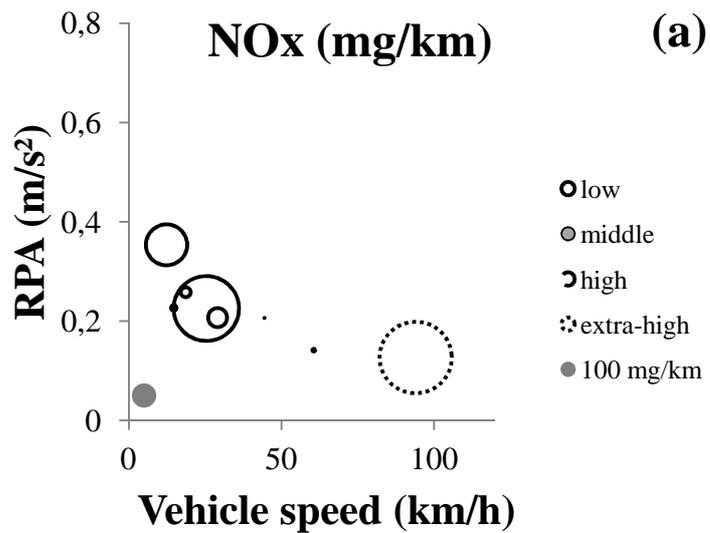


Figure 9: Bubble chart of tailpipe NO_x emissions (a) and CO emissions (b) of vehicle 3 (WLTC)

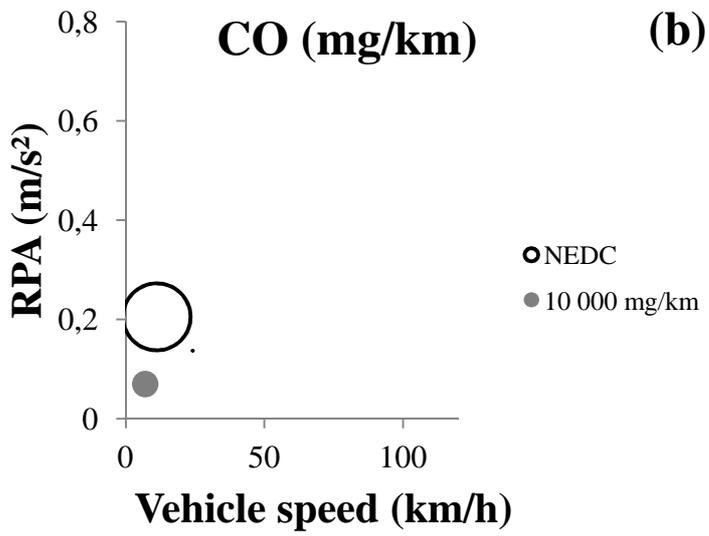
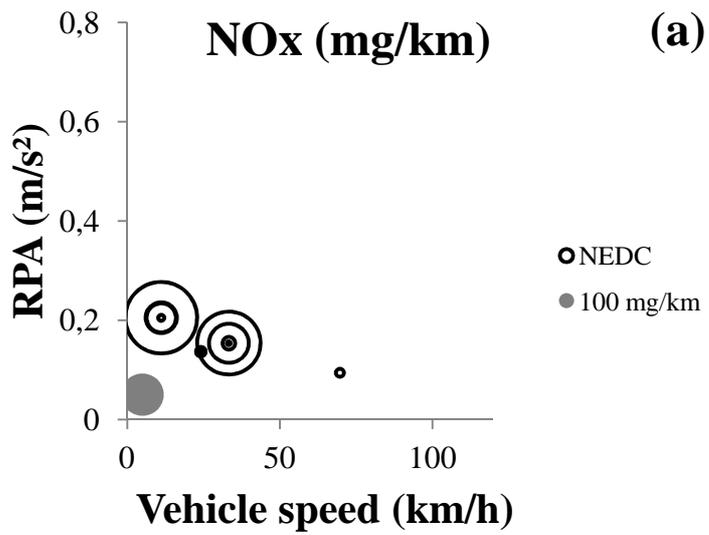


Figure 10: Bubble chart of tailpipe NO_x emissions (a) and CO emissions (b) of vehicle 3 (NEDC)

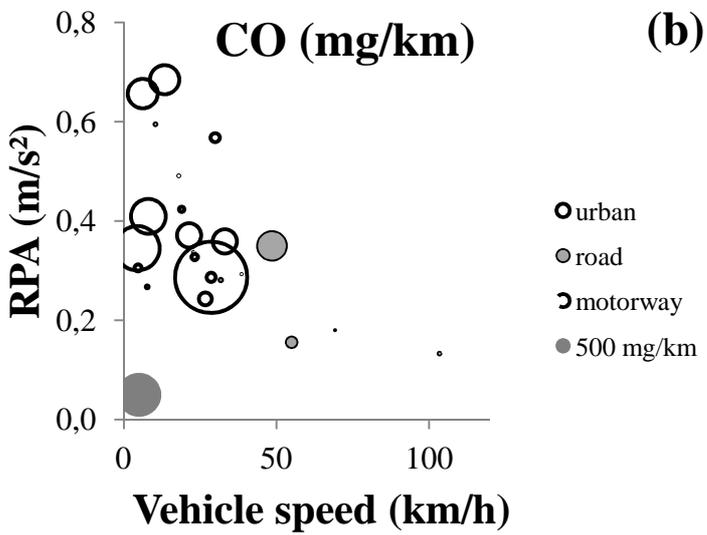
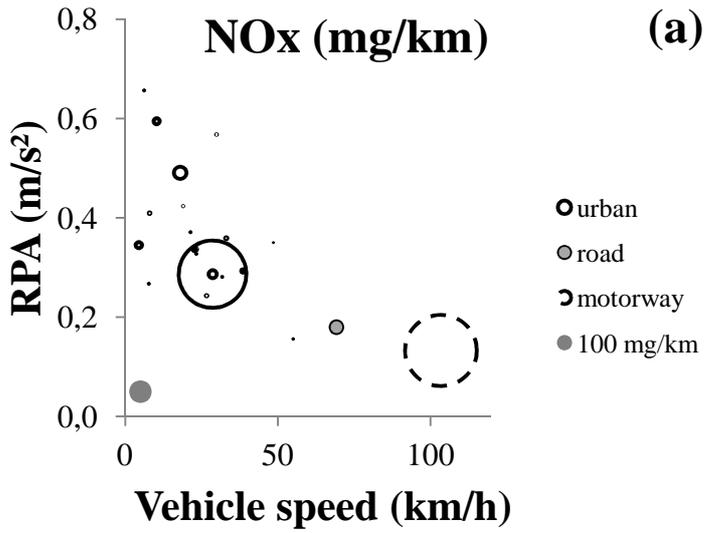


Figure 11: Bubble chart of tailpipe NO_x emissions (a) and CO emissions (b) of vehicle 3 (CADC)

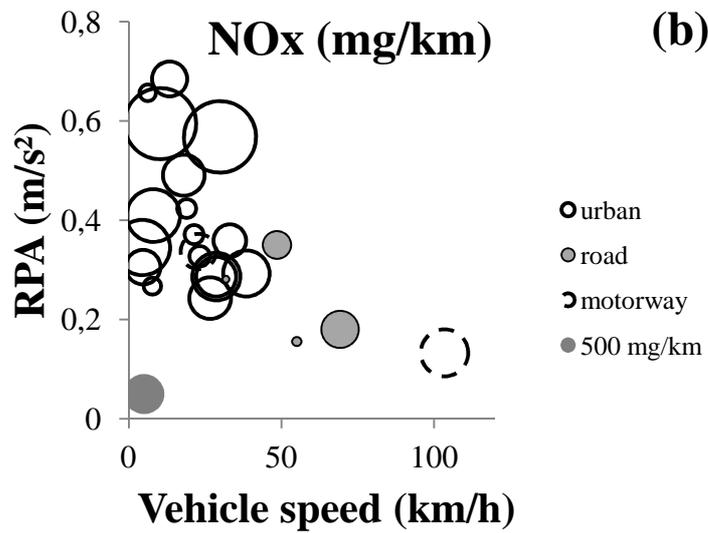
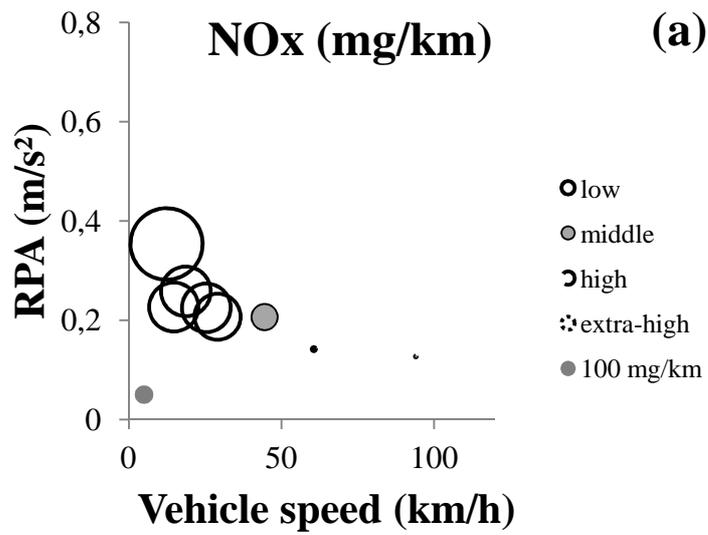


Figure 12: Bubble chart of tailpipe NO_x emissions of vehicle 4 (WLTC (a) and CADC (b)).

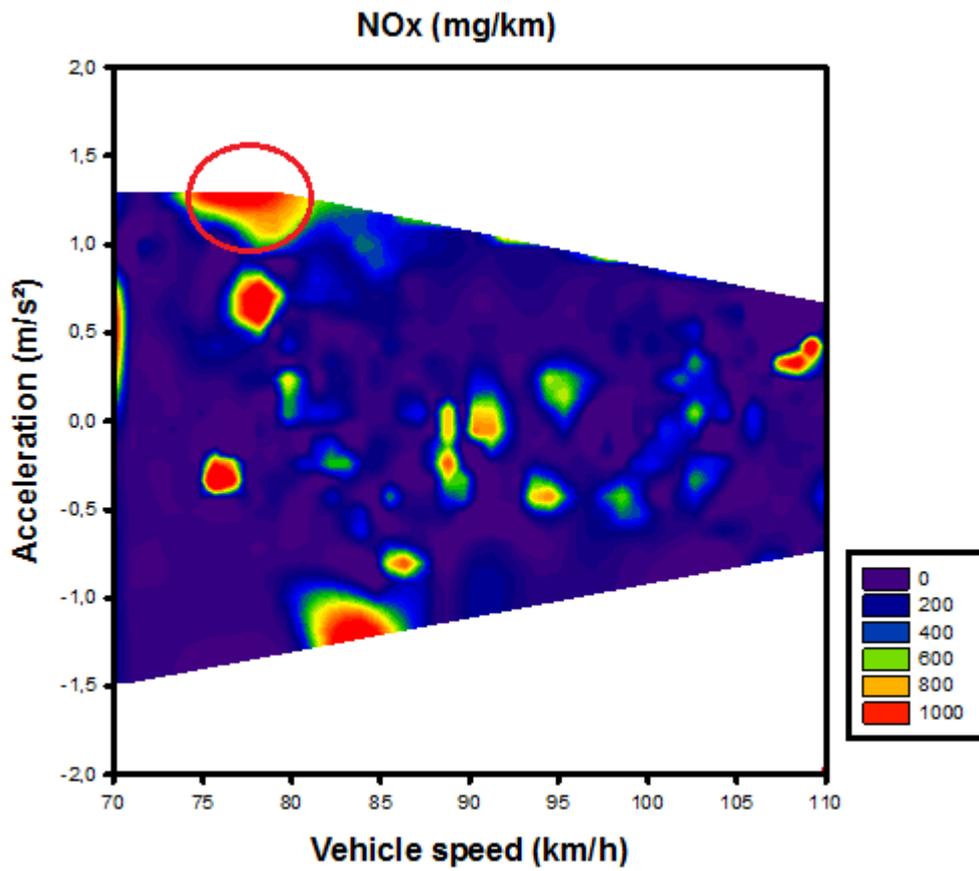


Figure 13: Contour plot of tailpipe NOx emissions in mg/km of vehicle 3 (CADC)

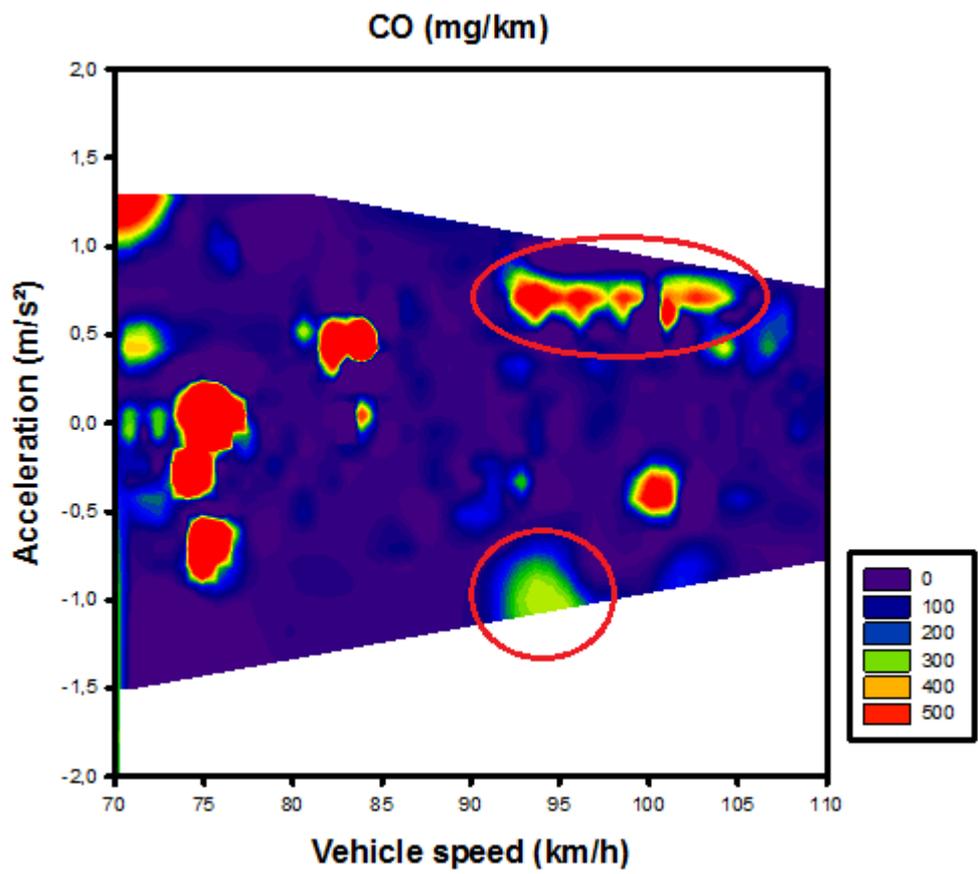


Figure 14: Contour plot of tailpipe CO emissions in mg/km of vehicle 3 (CADC)

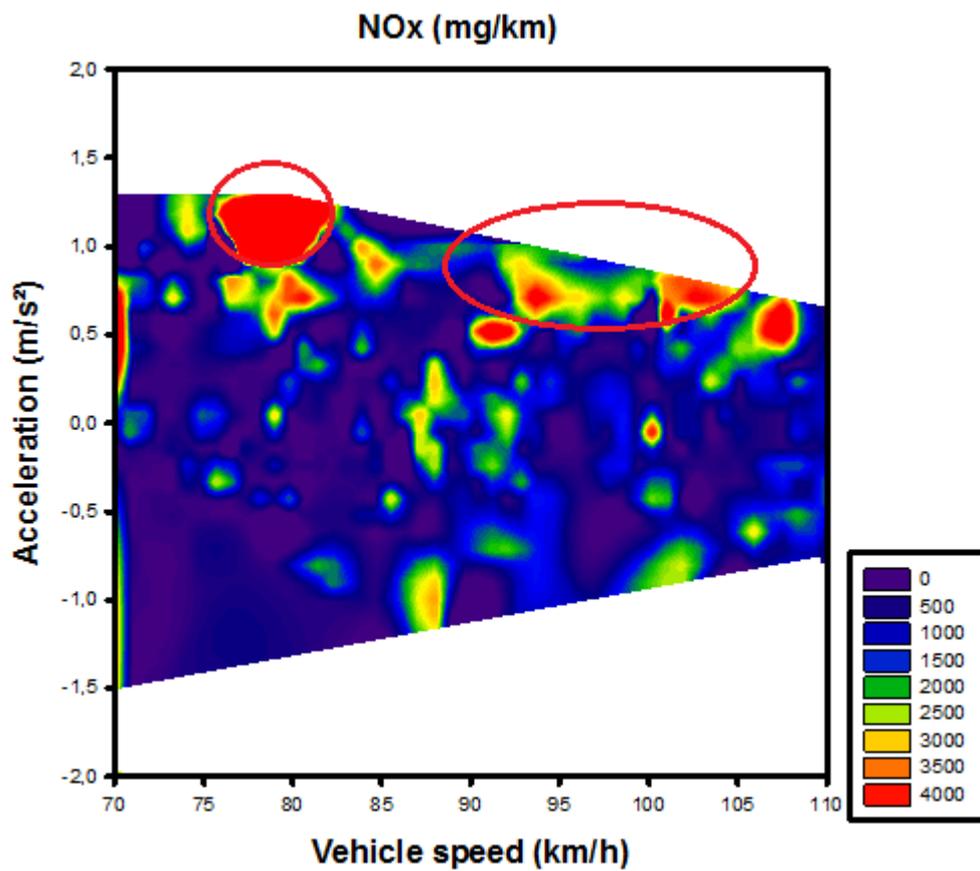


Figure 15: Contour plot of tailpipe NOx emissions in mg/km of vehicle 4 (CADC)

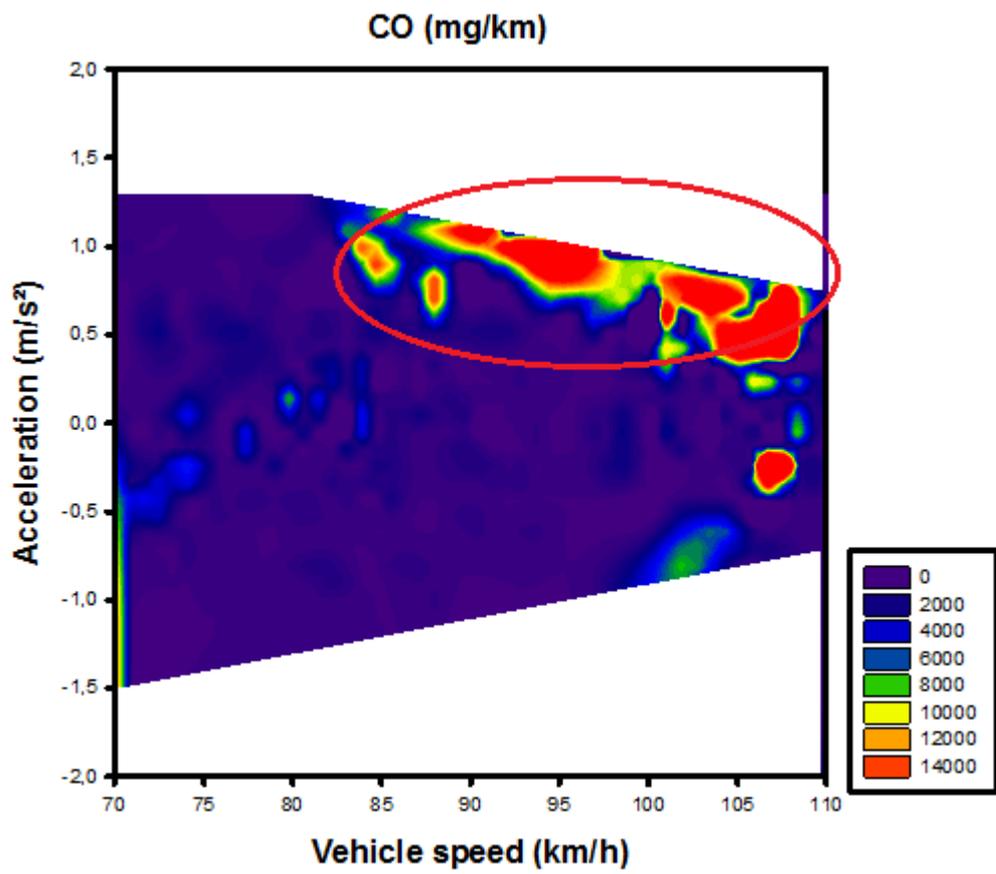


Figure 16: Contour plot of tailpipe CO emissions in mg/km of vehicle 5 (CAD/C)

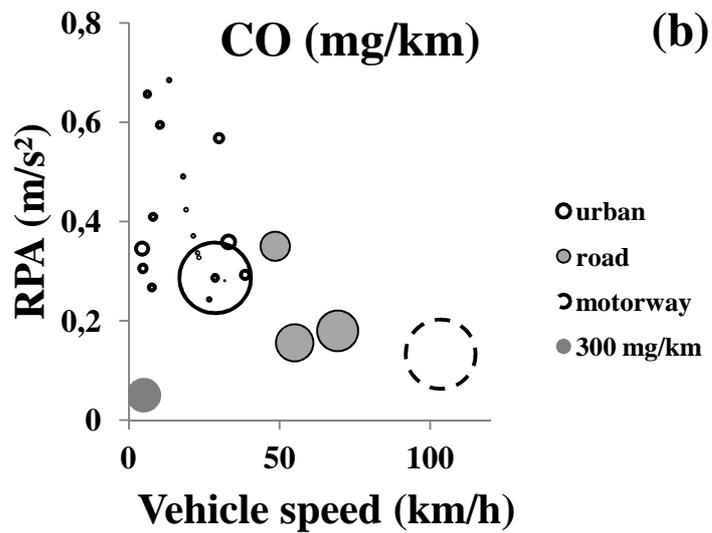
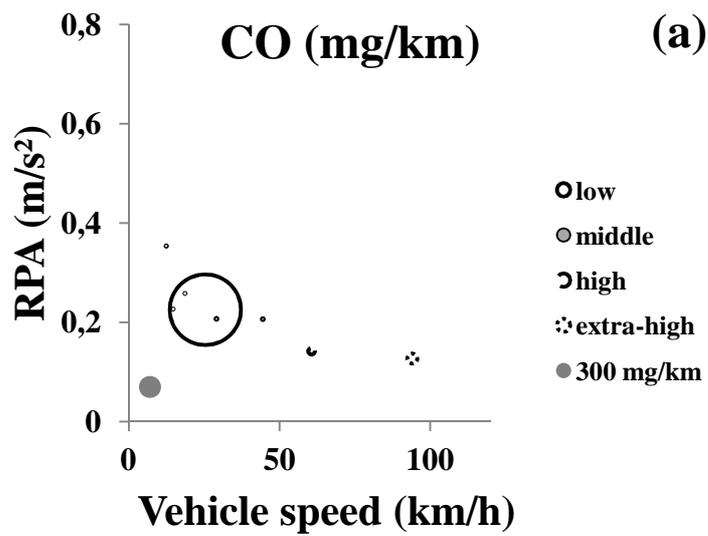


Figure 17: Bubble chart of tailpipe CO emissions of vehicle 5 (WLTC (a) and CADC (b)).