Final Report - Addendum

Fuel consumption and emissions testing of a best-in-class tractor-trailer in the US
Addendum: *Emissions results*

Submitted to:
International Council on Clean Transportation (ICCT)

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July 7th, 2018

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1 INTRODUCTION

This addendum details tailpipe emissions measured from a heavy-duty (HD) diesel Class 8 tractor tested on a heavy-duty chassis dynamometer in the US. Detailed description of emission measurement setup and instrumentation, test cycles, and chassis dynamometer testing procedures can be found in section 4.3.1 of the final report published on May 2018. Emission factors (CO_2, CO, THC, NO, NO_2 and NO_x) are represented in SI units in the following section in order to allow for comparison of the emissions results with EURO VI emission limits.

2 RESULTS AND DISCUSSION

2.1 Emissions over Transient Test Cycles

Figure 2.1 shows the average CO_2 emissions in grams per ton-kilometer over the different test cycles. The highest CO_2 emissions (i.e. 102.05 g/t-km) were observed over the GEM ARB transient cycle due to higher transient operation and higher load demand of the engine. Between two VECTO cycles, the regional delivery cycle tended to have higher CO_2 emissions since it had more transient operation compared to the long haul cycle. The GEM 55 mph flat cycle (i.e. without application of road grade) had the lowest CO_2 emissions (i.e. 40.76 g/t-km) since it is steady state operation and the engine operates highly efficient during steady-state type operation at typical highway speeds. In general, on average, it was observed that the engine mostly operates at 40% engine load while the engine speed is 1100 rpm during the flat GEM 55 mph cycle. The thermal efficiency map of the engine supports the observation that the engine operates highly efficient during engine speed ranges from 1000 to 1200 rpm at 40-100% engine load operating conditions. Thus, low CO_2 emissions were expected during this cycle.

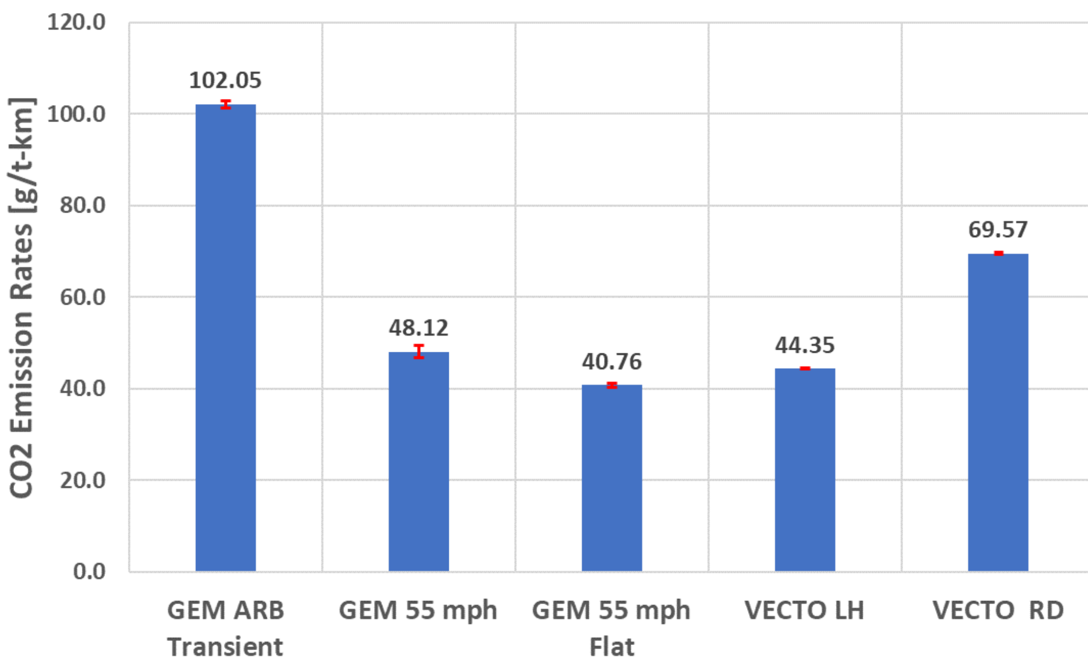

Figure 2.1: Comparison of weight-distance-specific CO_2 emissions in [g/ton-km] for the different chassis dynamometer cycles.

CO_2 emissions in g/kWh are summarized in Figure 2.2. Once more, highest break-specific (bs) CO_2 emissions (i.e. 790.88 g/kWh) were observed during the GEM ARB transient cycle due to higher transient operation and increased engine load. Overall, *bs*CO_2 emissions were found to be similar over all cycles except the GEM ARB transient cycle. The flat GEM 55 mph cycle had the lowest *bs*CO_2 emissions (i.e. 668.43 g/kWh).

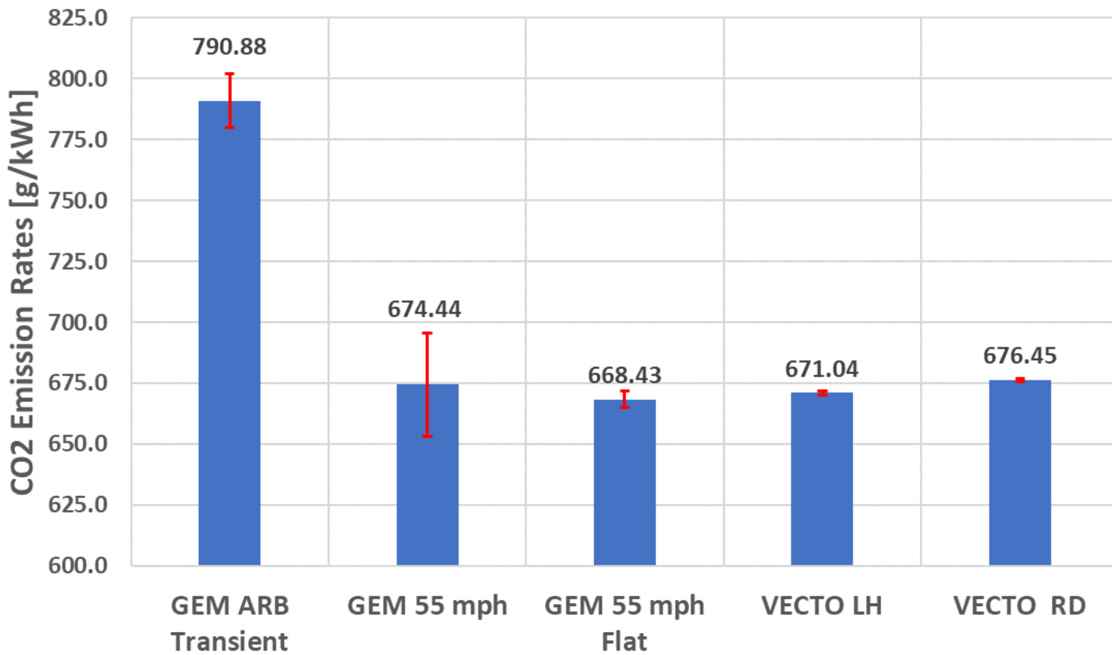

Figure 2.2: Comparison of work-specific CO_2 emissions in [g/kWh] for the different chassis dynamometer cycles.

Figure 2.3 demonstrates CO emissions in g/kWh. Highest *bs*CO emissions (i.e. 0.38 g/kWh) were observed during the GEM ARB transient cycle due to higher transient operation in which the engine operates less efficiently in terms of engine thermal efficiency. One of the main reasons for the increased CO emissions is that at the time of starting and instantaneous acceleration of a HD vehicle a rich mixture is required, thus in-complete in-cylinder combustion occurs when the engine operates inefficiently during high speed and low- load engine operation condition. Between the two VECTO cycles, *bs*CO emissions were found to be at similar levels. *bs*CO emissions were below the instruments detection limit (BDL) during the flat GEM 55 mph cycle since increased combustion efficiency and improved air-fuel-ratio control is expected during sustained high-load, state-steady engine operating conditions.

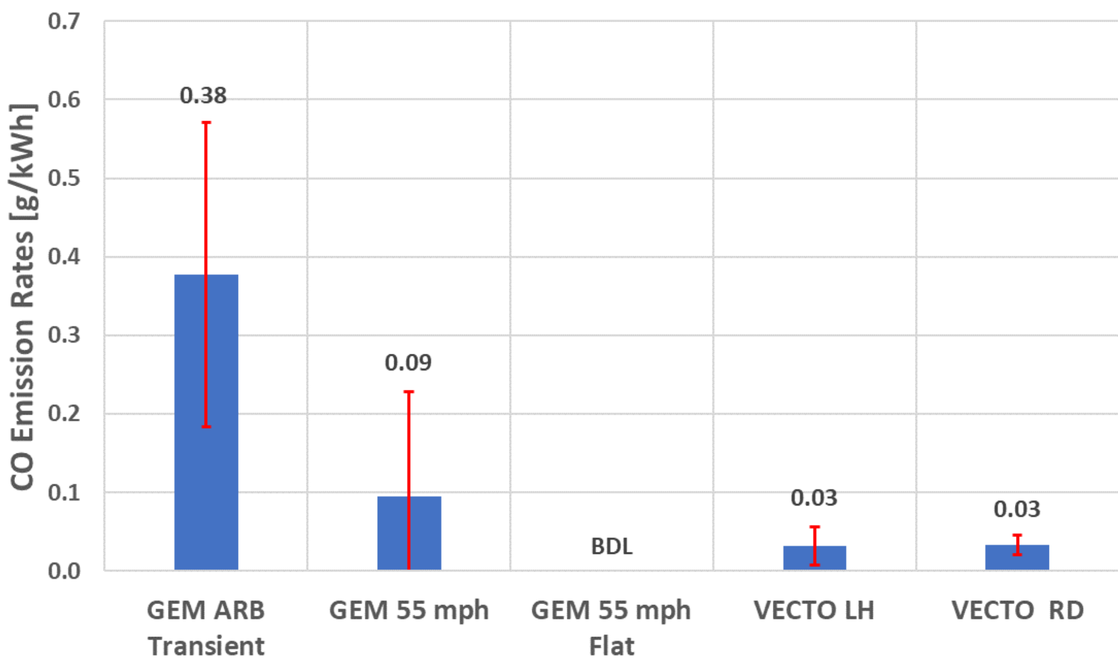

Figure 2.3: Comparison of bsCO emissions in [g/kWh] for the different chassis dynamometer cycles.

Figure 2.4 shows the average *bs*NO_x, *bs*NO and *bs*NO_2 emissions in g/kWh over the different cycles. The highest *bs*NO_x, *bs*NO and *bs*NO_2 emissions (i.e. 1.22, 1.17 and 0.05 g/kWh, respectively) have been found during the GEM ARB transient cycle due to an inactivate SCR state which was caused due to low aftertreatment temperature conditions, thus the conversion efficiency of SCR was poor. Lowest *bs*NO_x, *bs*NO and *bs*NO_2 emissions (i.e. 0.01, 0.01 and BDL g/kWh, respectively) were observed during the flat GEM 55 mph cycle, during this cycle aftertreatment temperatures were at the condition where the SCR exhibits high NO_x conversion efficiencies. Between the two VECTO cycles, the regional delivery cycle tended to have higher *bs*NO_x, *bs*NO and *bs*NO_2 emissions since this cycle has more low-load engine operation as compared to the long-haul cycle, thus lower aftertreatment temperatures are expected.

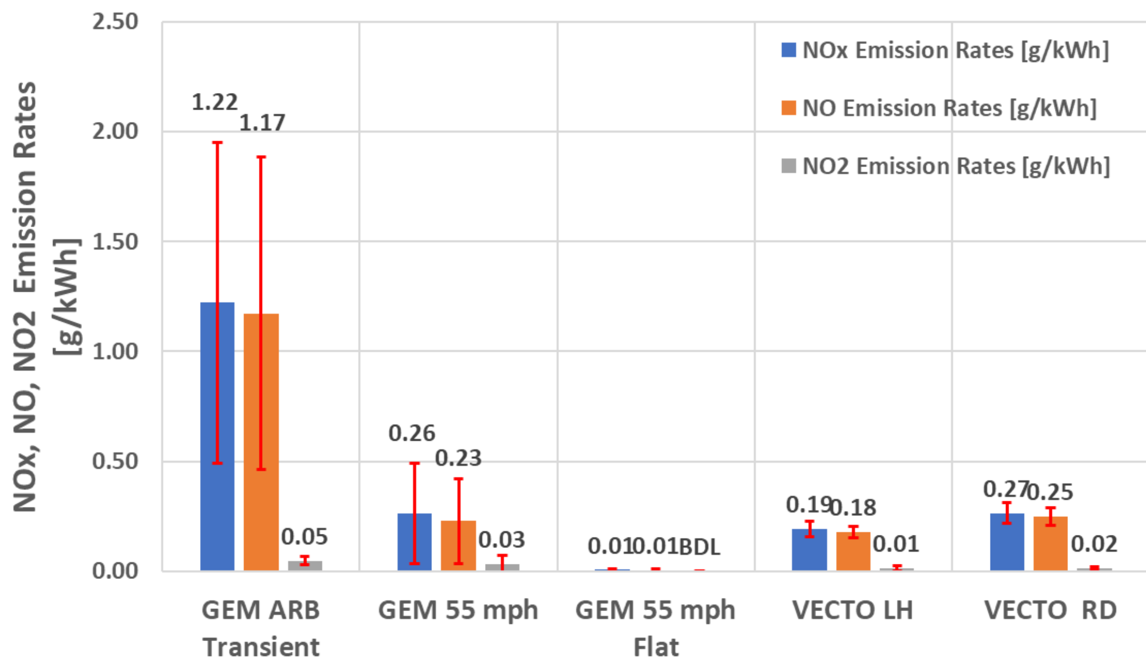

Figure 2.4: Comparison of bsNO$_x$, bsNO and bs NO$_2$ emissions in [g/kWh] for the different chassis dynamometer cycles.

Figure 2.5 shows the results for total hydrocarbons (THC). Emission levels of THC from all cycles were found to be below the U.S. EPA 2010 emissions standard. *bs*THC emissions were below the analyzer's detection limit (BDL) during the flat GEM 55 mph cycle since a near-fully complete combustion is expected during sustained high-load, state-steady engine operating condition. Therefore, THC emissions are expected to be near-zero. The highest *bs*THC emissions (i.e. 0.0210 g/kWh) have been observed over the GEM ARB transient cycle. Emission levels of NO$_x$ from all cycles were found to be below the EURO IV NO$_x$ standard over the WHTC test cycle (i.e. 0.46 g/kWh) and the U.S. EPA 2010 standard (i.e. 0.2 g/bhp-hr or 0.27 g/kWh) except *bs*NO$_x$ emissions obtained from the GEM ARB transient cycle since this cycle mainly consist of low-load engine, as well as stop-and-go operating conditions in which the SCR performs less efficiently due to low aftertreatment temperatures. Therefore, the *bs*NO$_x$ emissions measured during the GEM ARB transient cycle are not comparable to the EU and US *bs*NO$_x$ emission standards.

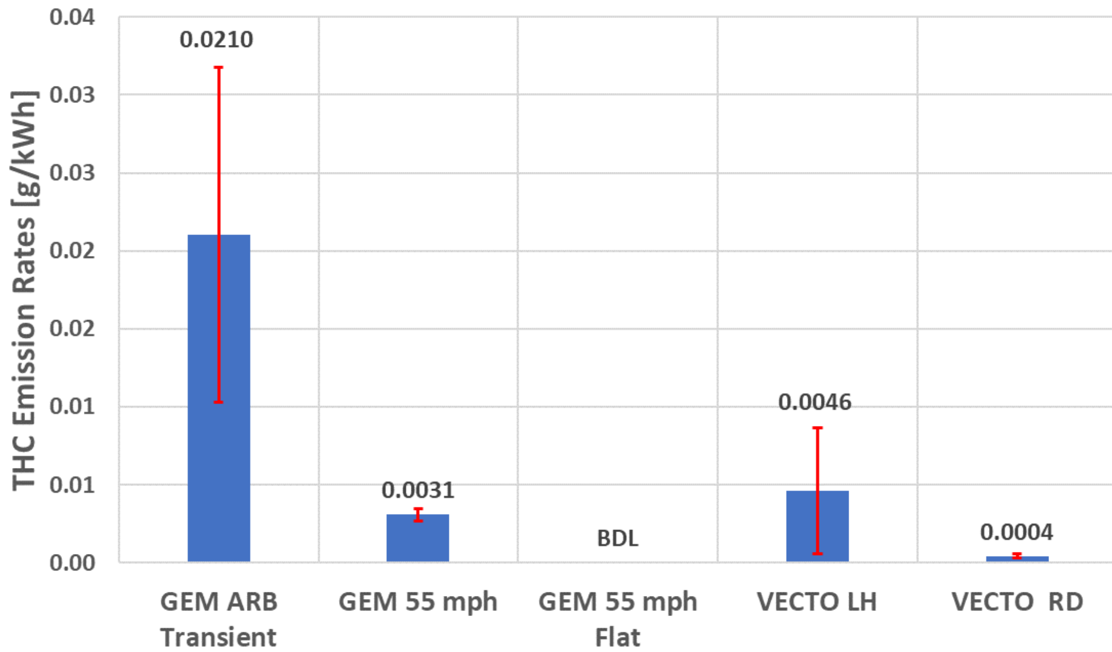

Figure 2.5: Comparison of bs THC emissions for the different chassis dynamometer cycles.

Finally, Table 2.1 summarizes the average CO_2, CO, NO_x, and THC emissions results in grams per ton-kilometer (g/t-km), grams per kilometer (g/km), grams per mile (g/mile), grams per kilowatt-hour (g/kWh) and grams per brake horse power-hour (g/bhp-hr) over test cycles exercised during chassis dynamometer testing.

Table 2.1: Average CO_2, CO, NO_x and THC Emissions over different cycles.

	GEM ARB Transient	GEM 55MPH	GEM 55 MPH Flat	VECTO LH	VECTO RD
$CO2\ [g/t-km]$	102.05	48.12	40.76	44.35	69.57
$CO2\ [g/kWh]$	790.88	674.44	668.43	671.04	676.45
$CO2\ [g/bhph]$	589.77	502.94	498.46	500.41	504.44
$CO2\ [g/km]$	1755.25	827.62	701.05	855.94	897.46
$CO2\ [g/mile]$	2824.81	1331.93	1128.23	1089.59	1444.32
$CO\ [g/t-km]$	0.049	0.007	0.000	0.002	0.003
$CO\ [g/kWh]$	0.377	0.095	0.000	0.032	0.034
$CO\ [g/bhph]$	0.281	0.071	0.000	0.024	0.025
$CO\ [g/km]$	0.84	0.12	0.000	0.041	0.045
$CO\ [g/mile]$	1.359	0.186	0.000	0.052	0.072
$NOx\ [g/t-km]$	0.158	0.019	0.0004	0.013	0.027
$NOx\ [g/kWh]$	1.222	0.262	0.006	0.191	0.265
$NOx\ [g/bhph]$	0.911	0.195	0.005	0.143	0.198
$NOx\ [g/km]$	2.711	0.324	0.013	0.248	0.351
$NOx\ [g/mile]$	4.361	0.519	0.011	0.310	0.566
$THC\ [g/t-km]$	0.0027	0.0002	0.0000	0.0003	0.0000
$THC\ [g/kWh]$	0.0210	0.0031	0.0000	0.0046	0.0004
$THC\ [g/bhph]$	0.0157	0.0023	0.0000	0.0035	0.0003
$THC\ [g/km]$	0.0466	0.0038	0.0000	0.0059	0.0006
$THC\ [g/mile]$	0.0750	0.0061	0.0000	0.0075	0.0009

2.2 Emissions over Steady-State Modes

Figure 2.6 shows the average *bs*CO_2 emissions in g/kWh for various steady-state operating points. The highest *bs*CO_2 emissions (1,919.7 g/kWh) were seen during highest speed (1800 rpm) and lowest engine load operation (20%). The lowest *bs*CO_2 emissions (626.3 g/kWh) were observed during the engine operating at 1200 rpm and 100% load. Overall, the engine operates efficiently during sustained high engine load (40-100%) while engine speed ranges between 1000-1400 rpm. As expected, low- load and high engine speed operating conditions result in high *bs*CO_2 emissions.

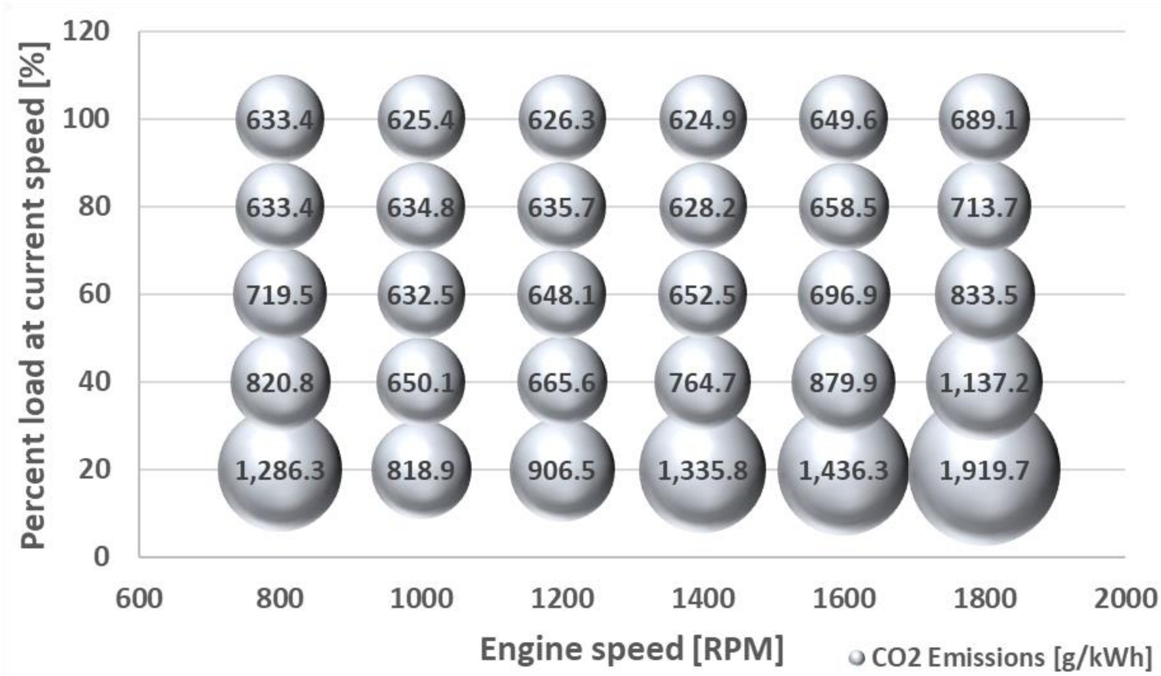

Figure 2.6: bsCO_2 emissions during steady state engine operation.

Figure 2.7 demonstrates carbon balance (CB) and gravimetric fuel consumption. Engine fuel consumption was found to be highest at 20% engine load operating conditions for all engine speed ranges. For a given engine load, fuel consumption increases with respect to engine speed from 1400 to 1800 rpm. Mapping cycle demonstrates that this engine has the highest fuel economy for a given engine load over engine speeds ranging from 1000-1200 rpm. This can be explained by the fact that HDD engines are specifically calibrated to operate most efficiently between these engine speed ranges in terms of fuel consumption for both low and high engine load operating conditions.

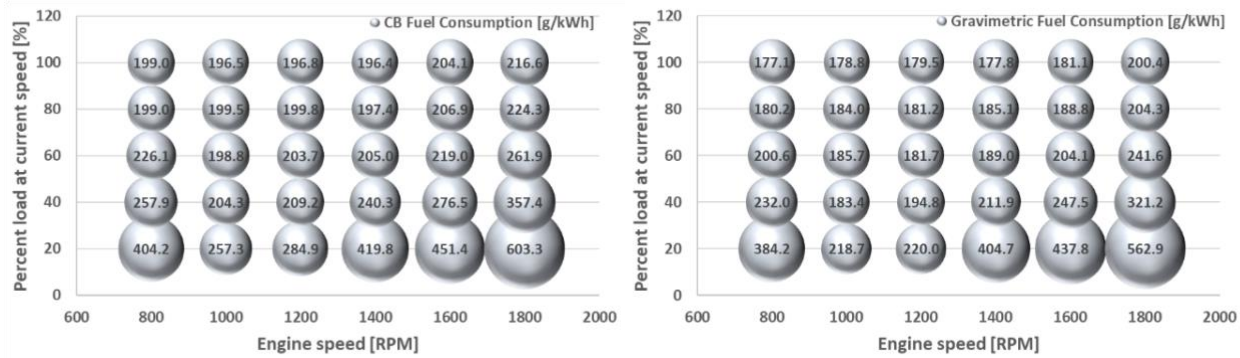

Figure 2.7:CB (left) and gravimetric (right) fuel consumption during steady state operation points

Figure 2.8 shows *bs*CO emissions during steady-state engine operation. Overall, *bs*CO emissions were below the analyzer detection limit for most of the steady state operating points. *bs*CO emissions were only measurable during low engine speed and low to moderate engine load operating conditions in which in-complete in-cylinder combustion can occur. Highest *bs*CO emissions (i.e. 0.0288 g/kWh) were observed at an engine speed of 800 rpm and 20% load.

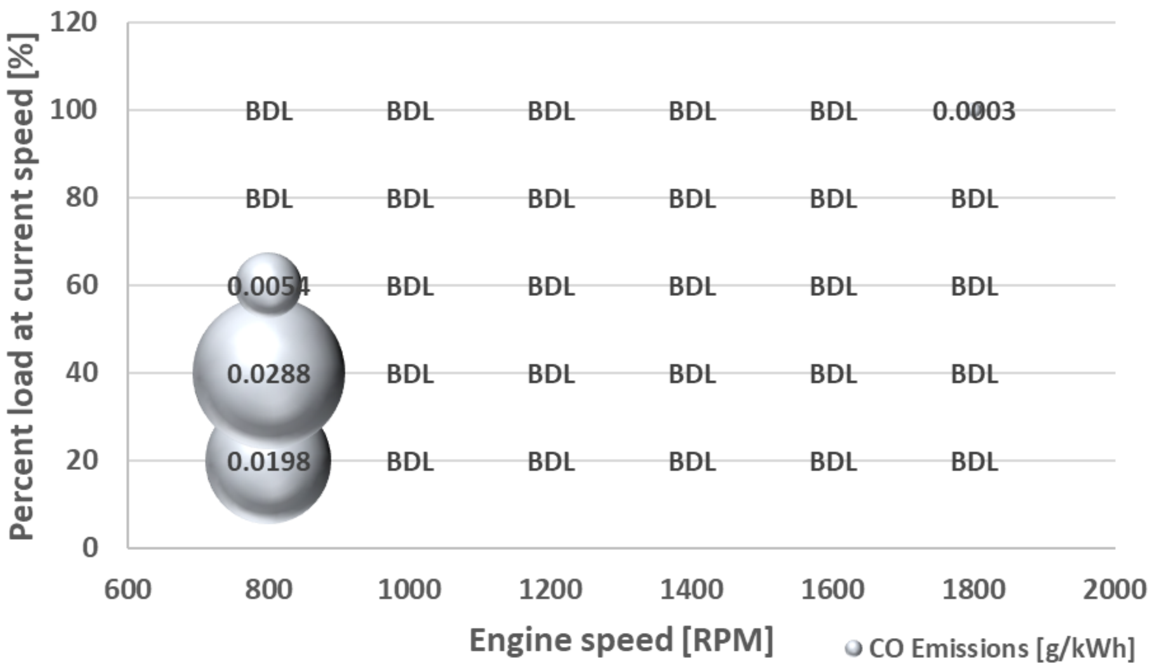

Figure 2.8: bsCO emissions during steady state mapping cycle.

Figure 2.9 illustrates *bs*NO_x emissions during steady-state operation. Overall, *bs*NO_x emissions were found to be low, however, at high engine speed and low to moderate engine load operation, *bs*NO_x emissions were higher, due to lower after-treatment temperature, it resulted in reduced SCR conversion efficiency. Highest *bs*NO_x emissions (i.e. 1.491 g/kWh) were observed when the engine was operating at 1600 rpm with an engine load of 20%.

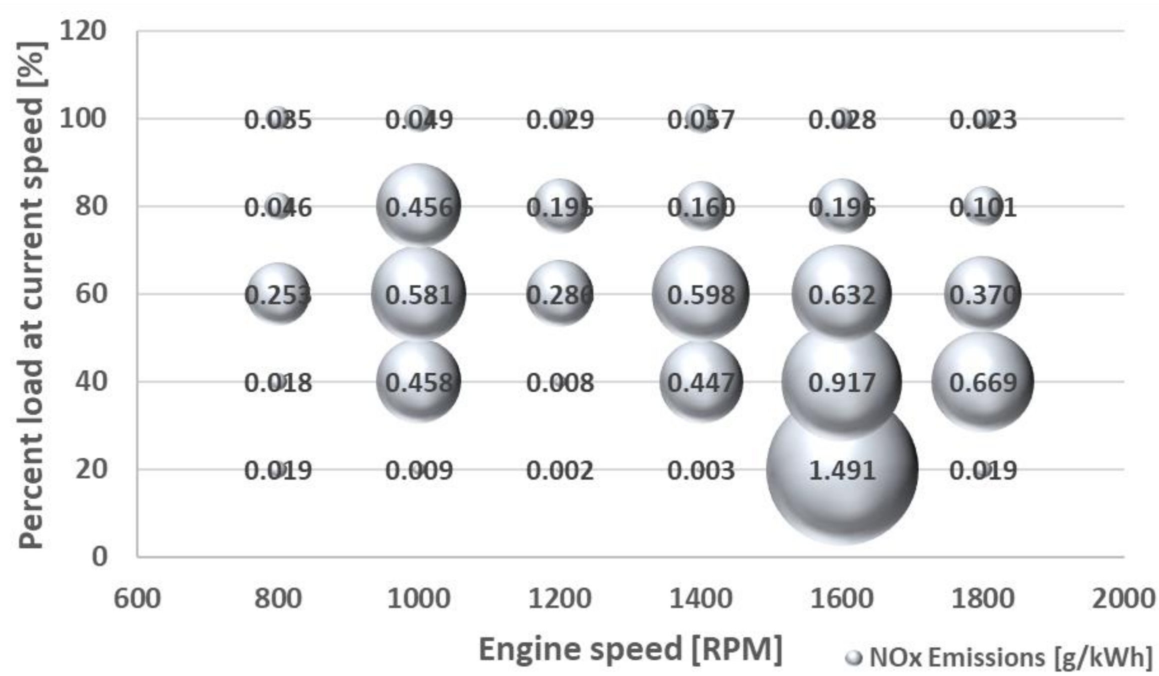

Figure 2.9: bsNO_x emissions during steady state mapping cycle.

Figure 2.10 shows *bs*THC emissions during steady state operation. Overall, *bs*THC emissions were found to be low at any given engine operating point, except during high engine speed (1600-1800 rpm) and low to moderate (20-40%) engine load conditions. *bs*THC emissions are expected to be present at higher speed and low-load engine operating conditions as they are composed of unburned fuels. Because of low temperature conditions occurring near the cylinder wall during low-load and high-speed engine operation, unburned fuel from incomplete in-cylinder combustion is expected. Highest *bs*THC emissions (i.e. 0.0319 g/kWh) were observed with the engine operating at 1800 rpm while having 20% load. Near-zero *bs*THC emissions were observed in the efficient regions (engine speed at 1000-1200 rpm and engine load at 40-100%) of the engine operating area.

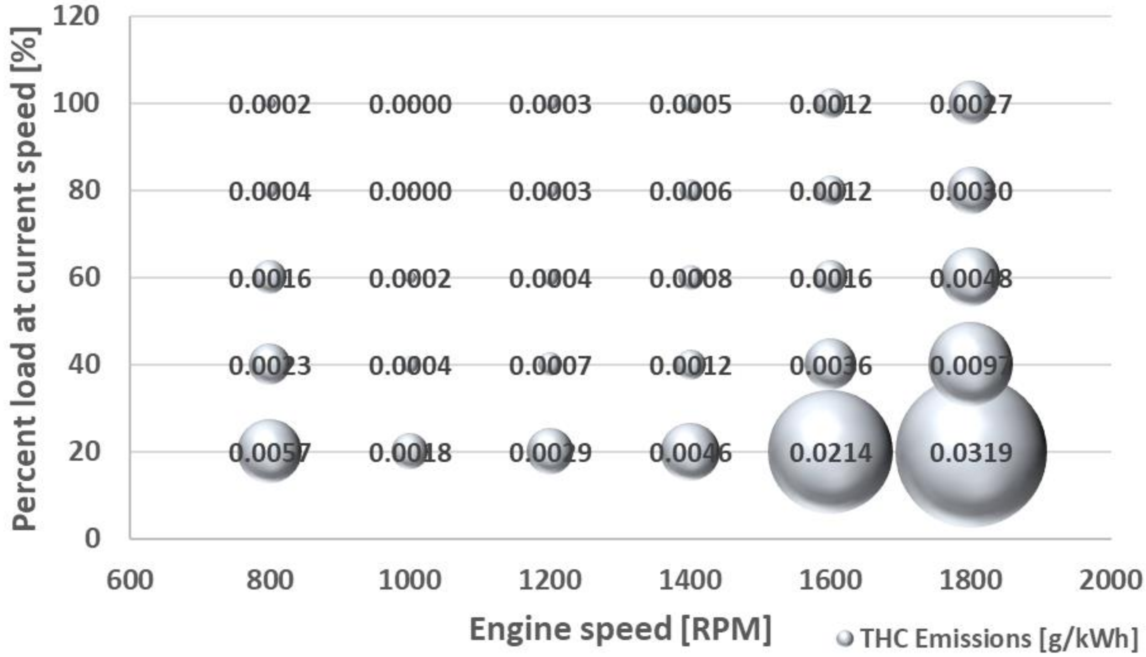

Figure 2.10: bsTHC emissions during steady state mapping cycle.