CUSTOMER REPORT

VTT-CR-00544-19

City bus performance evaluation

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Summary

The public transport authority (PTA) in Helsinki Metropolitan Area, Helsinki Region Transport (HSL) and VTT Technical Research Centre of Finland have been assessing and documenting performance (regulated emissions, carbon dioxide emissions and energy consumption) of city buses for some 20 year. The data generated is used by HSL as an element supporting the tendering of bus services, but also to develop future bus fleet strategies.

The report at hand is the first report in English on the continuous bus performance evaluation for HSL. It is based on the Finnish 2018 annual report, but it has been expanded to serve as a stand-alone summary report of the activities.

Between the spring of 2002 and end of 2018, VTT has tested in total 178 city buses for HSL. The sample includes Euro I - Euro VI diesel buses, Euro II - VI gas (CNG) buses and EEV ethanol buses. This report presents a summary of all data generated

It is fair to say that current buses are much cleaner than the ones of the early 90's. The results clearly show the positive development in NO_x and PM emission levels over the years, from Euro I to Euro VI. It is also evident that the step from Euro V/EEV to Euro VI brought about the biggest relative reduction so far.

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Preface

Since the inauguration of its heavy-duty vehicle test facility in 2002, VTT Technical Research Centre of Finland has been evaluating city bus performance for Helsinki Region Transport (HSL). The collected database now contains performance data for some 180 buses, and HSL uses the data, among other things, for its procurement of bus services.

The results have been reported to HSL on an annual basis in the form of VTT Research Reports. These reports have been written in Finnish. VTT's work for HSL, and also some other bus related activities also have been reported in a number of other publications and e.g., conference papers.

The report at hand is the first report in English on the continuous bus performance evaluation for HSL. It is based on the Finnish 2018 annual report, but it has been expanded to serve as a stand-alone summary report of the activities.

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List of abbreviations

BR	Braunschweig test cycle
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2eqv}	Carbon dioxide equivalent
CVS	Constant volume sampler
DPF	Diesel particulate filter
Euro…	European emission certification class
HC, THC	Hydrocarbons, total hydrocarbons
HD	Heavy-duty
HKL	Helsinki City Transport
HSL	Helsinki Region Transport
NO_x	Nitrogen oxides
PEMS	Portable emission measurement system
PM	Particulate mass
PTA	Public transport authority
SCR	Selective catalytic reduction (urea catalyst)
TWC	Three-way catalyst
VTT	Technical Research Centre of Finland Ltd
WHVC	World harmonised vehicle cycle
YTV	Helsinki Metropolitan Council

1. Introduction

The public transport authority (PTA) in Helsinki Metropolitan Area, Helsinki Region Transport (HSL) and VTT Technical Research Centre of Finland have been assessing and documenting performance of city buses for some 20 year. The data generated is used by HSL as an element supporting the tendering of bus services, but also to develop future bus fleet strategies. In addition to systematic evaluation of new bus models entering service, a number of research and piloting projects have been carried out as well. Fuel and drivetrain options evaluated include liquid renewable fuels (renewable diesel, additive treated ethanol), methane (bio/natural gas), hybrids and battery-electric buses. Retrofitted exhaust after-treatment systems have been evaluated, as well.

At the turn of the millennium, VTT made an initiative to establish a new test facility for heavy-duty vehicles. HSL and VTT could anticipate that future engine would become increasingly complex, and saw the need for truthful, distance-based emission data for buses. The Directive 1999/96/EC, introducing Euro classes III, IV, V and EEV, and in addition, transient type testing for "diesel engines fitted with advanced exhaust after-treatment systems" and gas engines, was finally approved in 1999 [1]. The Euro III emission limits could still be met without advanced diesel emission control systems, but Euro IV, which came into force 2005, in most cases, required "advanced systems". However, the certification procedure does not cover carbon dioxide emissions (CO_2) nor fuel consumption, and for HSL it is imperative to acquire data on these parameters, as well.

VTT's heavy-duty vehicle test facility comprising chassis dynamometer, full-flow CVS system and analytical systems was commissioned in the spring of 2002 (more details in Chapter 2). The predecessors of HSL, the transport division within Helsinki Metropolitan Council (YTV) and the planning division within Helsinki City Transport (HKL), were among the "founding members" and provided funding for the new test facility.

Between the spring of 2002 and end of 2018, VTT has tested in total 178 city buses for HSL [2]. The sample includes Euro I - Euro VI diesel buses, Euro II - VI gas (CNG) buses and EEV ethanol buses. This report present a summary of all data generated. VTT has also measured some electric buses, but these results are not incorporated in the main bus database.

In addition to chassis dynamometer testing, VTT also uses other techniques to monitor bus performance [3]. In 2018, VTT acquired a PEMS measurement system, capable of delivering real driving emission data. In addition, a selection of Euro VI diesel buses is continuously monitored for SCR catalyst performance using on-board measurement and data logging systems. However, what comes to accuracy and repeatability, chassis dynamometer measurement is still the best option for vehicle-to-vehicle comparisons and, e.g., measuring effects of fuels on emissions. The resolution power of the PEMS system is simply not high enough, as PEMS systems are originally designed for "pass/fail" type of testing.

2. Methodology

2.1 General

Type approvals for light-duty vehicles are carried out by running complete vehicles on a chassis dynamometer. Thus, the results will depict the performance of the total vehicle, not only the engine. Parameters are typically reported in the form of g/km, i.e. relative to driven distance.

The situation for heavy-duty (HD) on-road engines is different, as homologation is done for the engine only. The rationale for this is that a particular engine can be applied in different kinds of vehicles, i.e. transit buses, coaches and trucks.

The current European testing scheme for HD engines depicts truck rather than bus operation. This and the fact that the testing in no way takes into account the properties of the vehicle itself makes it difficult to predict bus performance just based on emission certification class. To determine the actual emissions of the complete vehicle, e.g. a city bus, the vehicle can be measured on a chassis dynamometer in the same way as the type approval for light-duty vehicles is done.

Although there is no universal methodology or standard for chassis dynamometer measurements of heavy-duty vehicles, several laboratories around the world are producing emission results for complete heavy-duty vehicles. One widely recognized guideline for this kind of measurements is SAE J2711, SAE Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles.

For transient-type measurements of heavy-duty vehicles on a chassis dynamometer, VTT developed its own in-house method covering both emission and fuel consumption measurements. The method is partly based on SAE J2711, partly on the European Directive 1999/96/EC on emission measurements. In June 2003, FINAS, the Finnish Accreditation Service, granted accreditation for the method of VTT (T259, In-house method, VTT code MK02E). A description of VTT's facility and test methodology can be found in, e.g., [4, 5].

2.2 Equipment

VTT's heavy-duty chassis dynamometer is capable of simulating the inertia weight and road loads that buses and trucks are subjected to during normal on-road operation. The machine is a single-roller, 2.5 meter diameter chassis dynamometer with electric inertia simulation. The system has the capability of testing vehicles from 2,500 to 60,000 kilograms of GVW. Maximum absorbed power (continuous) is 300 kW at the driven wheels. The machine is ideal for measurements on buses.

For emission measurements VTT uses full-flow CVS dilution system. The analytical equipment (Pierburg CVS-120-WT CVS and analyser set AVL AMA i60) is compliant with Directive 1999/96/EC. The analytical equipment was renewed in 2018.

The total exhaust stream produced by the vehicle is collected and diluted using the CVS dilution system. In this system the raw exhaust is diluted with filtrated laboratory background air, and the mixture is drawn through a critical flow venturi. During the exhaust emissions tests, continuously proportioned samples of the dilute exhaust mixture and the dilution air are collected and stored in sample bags for analysis. Modal analysis is also possible.

Figure 1 presents the schematic of VTT test facility, and Figure 2 an actual photo of the facility.

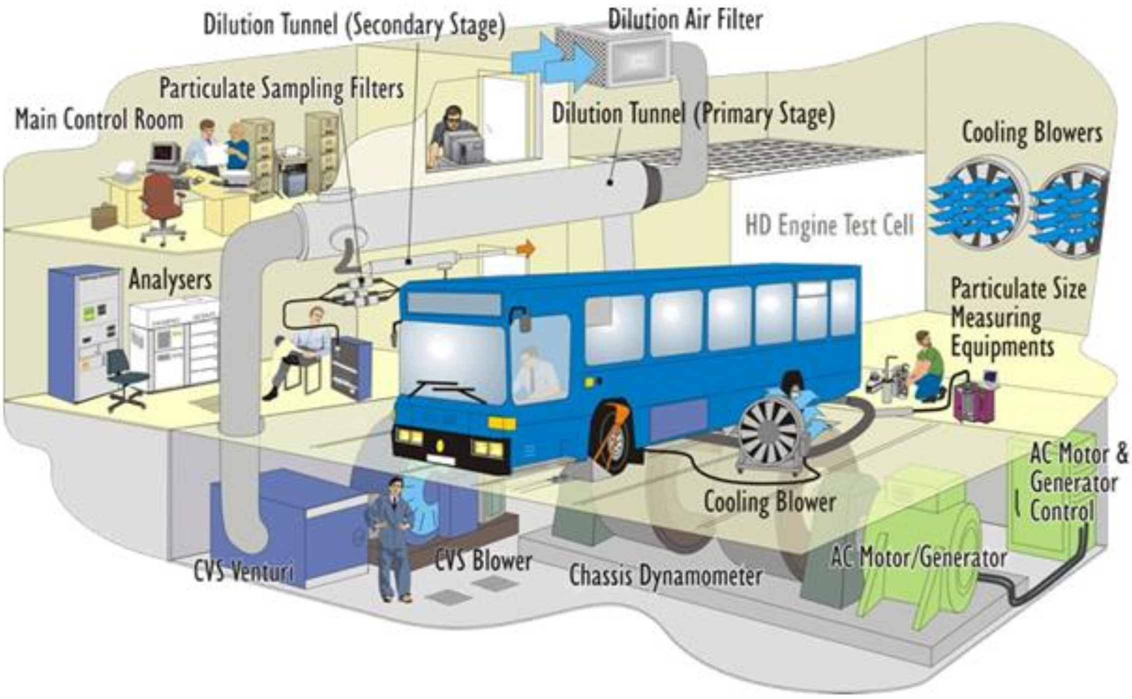

Figure 1. Schematic of VTT's heavy-duty vehicle test facility. Drawing by Juhani Laurikko.

Figure 2. A view of the test facility. The CVS dilution tunnel can be seen in the upper right-hand corner.

2.3 Procedures

VTT's standard test cycle for buses is the German Braunschweig bus cycle, depicting bus service in a mid-sized European city, and also describing quite well driving in Helsinki. The Braunschweig bus cycle delivers results rather similar to the Orange County Transit Authority bus cycle used in North-America [6].

Up to the year 2017, testing for the bus data based was done using only the Braunschweig cycle. Before running tests, vehicles are first warmed up for 30 minutes on the chassis dynamometer by running at constant speed of some 80 km/h. Then the test cycle is driven three times, and the final results are calculated as an average of the two last cycles.

One of the shortcomings of testing fully warmed-up vehicles is that the results can be too positive, overestimating performance and underestimating, in particular, the nitrogen oxide (NO_x) emissions of Euro VI vehicles.

As of 2017, testing is now carried out using the World Harmonised Vehicle Cycle (WHVC), as well. The transient engine testing cycle used for homologation, World Harmonised Transient Cycle (WHTC); was originally derived from a vehicle cycle, the WHVC. The WHVC is carried out as a combination of a cold start test (from room temperature) and a hot start test. The pause in between the test is 10 $\pm$ 1 minutes. The result is reported as a weighted average, based on cold start cycle (14 %) and hot start cycle (86 %). The combined WHVC was added to the program, as it provides a link to the engine certification cycle, and that it, in addition, accentuates the temperature-sensitivity of the newest and most sophisticated emission control systems.

In fact, for a short period, also, Braunschweig testing was carried out as a combination of cold and hot start, using the same weighting as stipulated for WHTC/WHVC testing.

The use of two testing cycles or methods in parallel can be justified as follows:

- Braunschweig (warm)
    - ties back to testing all the way back to the year 2002, making comparisons possible
- World Harmonised Vehicle Cycle (combination of cold and hot)
    - as the cycle relates to the one used for homologation of engines, a comparison against regulatory emission limit values can be done more easily
    - more truthful depiction especially of NO_x emissions, in particular for engines with sophisticated exhaust after-treatment systems

WHVC testing has only been carried out on Euro VI vehicles and vehicles retrofitted to Euro VI.

Whatever duty-cycle is used on the chassis dynamometer, the risk of so-called cycle beating is minuscule. In homologation, the engine only is tested. On the chassis dynamometer, not only the engine itself, but also the characteristics of the vehicle affect the performance and the results.

At the end of 2018, there were results available for altogether 178 buses on the Braunschweig cycle and for 33 buses on the WHVC cycle.

Figure 3 presents the speed profile of the Braunschweig cycle and Figure 4 that of the WHVC cycle.

In principle, the Braunschweig cycle is closer to normal city bus operation than the WHVC, which is a general HD vehicle cycle. In the Braunschweig cycle, which is more challenging of the two cycles, the amount of work at the driving wheels in typically some 1 kWh/km for a two-axle bus, whereas the corresponding figure for the WHVC is lower, some 0.7 kWh/km.

Translated into fuel consumption this is typically some 43 l/100 km for the Braunschweig cycle and 28 l/100 km for the WHVC.

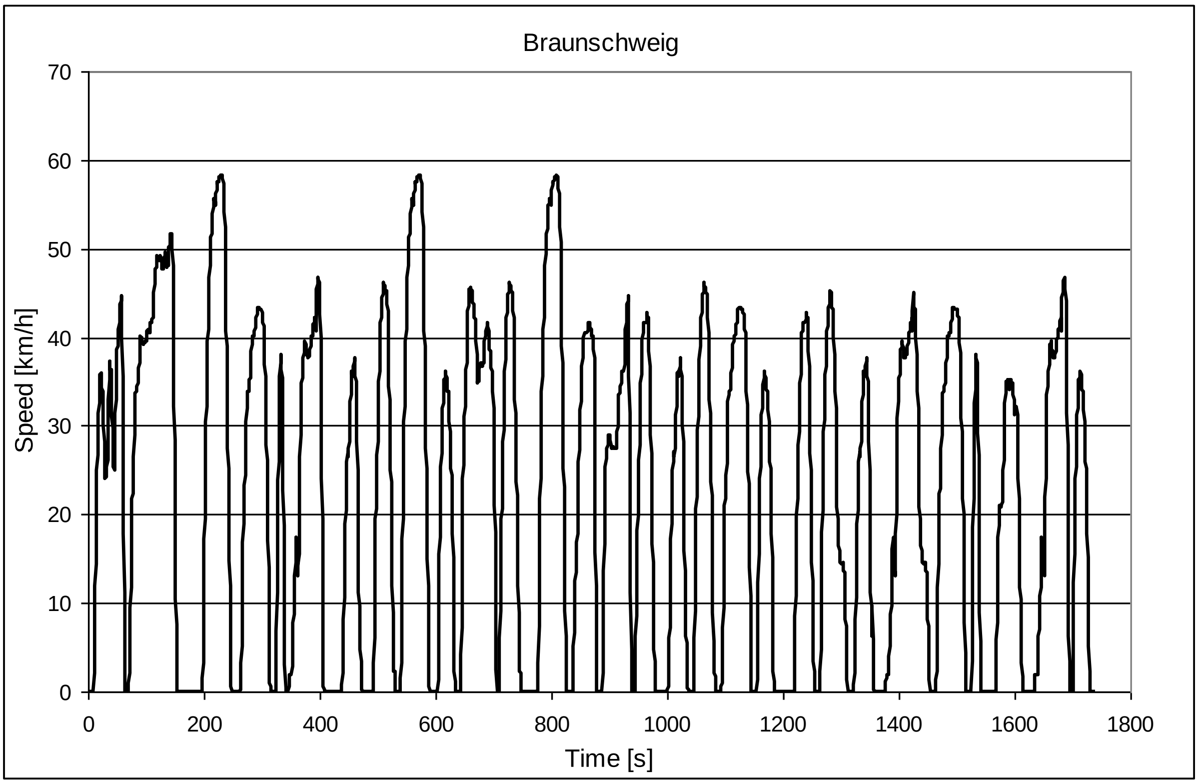

Figure 3. Speed profile of the Braunschweig bus cycle.

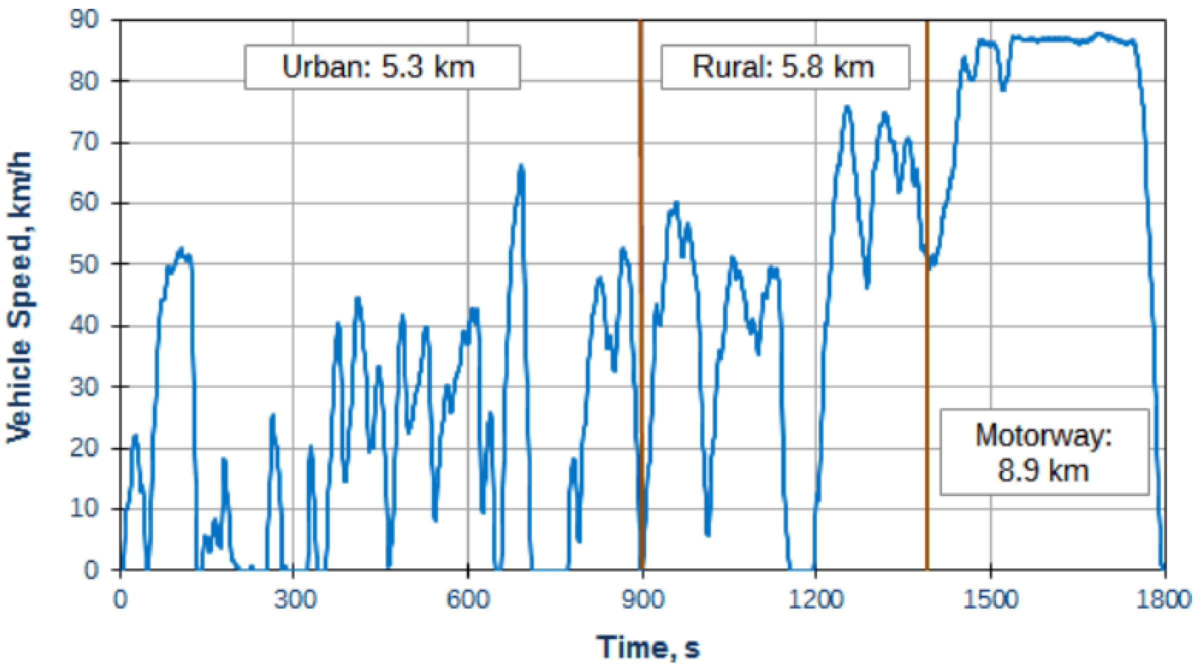

Figure 4. Speed profile of the WHVC cycle and its division into three distinct phases.

For a vehicle running a transient drive cycle, the mass of the vehicle is decisive for driving resistances. Vehicle mass affects inertia as well as rolling resistance. Emission tests with buses are normally run with inertia that corresponds to half of the payload based on the unladen and maximum permissible weight of the bus.

In the case of the highly transient Braunschweig cycle, typically 70 % of the energy brought to the driving wheels is used for overcoming inertia, 20 % for rolling resistance and 10 % for aerodynamic drag.

In Finland, transit buses are of two- or three-axle configuration, which is reflected in different vehicle masses and rolling resistance. Consequently, results are reported separately for these two categories. Results for lightweight buses and hybrid buses are reported separately, as well.

VTT basically uses a road-load model based on coast-down measurements on the road. To determine the dynamometer settings, the rolling resistances of the rear tires and the rear axle are deducted from the total resistance values, a common practice in setting up the chassis dynamometer. On the chassis dynamometer, VTT uses special sets of tires with longitudinal grooves only to normalize the effects of tires. VTT has built up a library of road load values for different types of heavy-duty vehicles. In the case of transit buses, a very coherent vehicle category, in most cases values from this library can be used, with no need to carry out coast-down measurements on individual vehicles.

VTT measures fuel consumption gravimetrically. The liquid fuel container is placed on a scale and the container is connected to the vehicle with external fuel lines. A similar method is used for urea in the case of SCR equipped vehicles. For diesel vehicles, the CO_2 emission is calculated from the measured fuel consumption and the carbon intensity of the fuel, as this is a more accurate method than measuring CO_2 emissions directly from the sampled exhaust gas.

With gas fuelled vehicles, a special gas meter calibration system, consisting of a compressed natural gas (CNG) cylinder and a special scale, is used to measure the fuel consumption. Alternatively, fuel consumption is calculated from exhaust flow and composition. The natural gas used in Finland originates from Russia, and it has very high methane content (> 98 mol-%).

In the follow-up measurements of buses, VTT uses commercial grade diesel fuel from the energy company Neste. The chosen grade is suitable spring, summer and autumn operation, and is marked ”-5/15” (lowest storage temperature -5 ^{o}C, lowest operability temperature -15 ^{o}C). Fuel deliveries typically take place twice a year. Control samples are taken and stored, to enable analysing, if needed.

In most cases, the fuel parameters (density, specific CO_2 emission, heating value) used for calculations are based on figures from the Joint Research Centre (JRC) of the European Commission [7].

In the case of ethanol for diesel engines (additive treated ethanol, ED95), calculations are based on the carbon content of ethanol and the actual heating value of the fuel blend.

The buses are normally tested in the condition as they are when arriving to VTT from the bus operators. No extra service or maintenance is done prior to testing, and lit malfunction indications or faulty engine operation does not disqualify the vehicle. The motivation for this is that the bus data base should reflect the true condition and performance of buses out in the field.

Some selected vehicles are chosen for regular follow-up measurements to generate information on emission performance over time, as more kilometres are driven. The effect of driving distance on emissions is especially pronounced for the most sophisticated systems.

The database currently contains the following results:

- emission results in g/km (carbon monoxide CO, hydrocarbons HC, methane CH_4, nitrogen oxides NO_x, NO_x standard deviation (some vehicle classes), particulate matter PM (mass), carbon dioxide CO_2, carbon dioxide equivalent CO_{2eqv}
- energy consumption in kg/100 km and MJ/km

3. Results

Over the years, a significant amount of data has generated. The buses tested include emission certification classes from Euro I to Euro VI. In this chapter, a summary of all the data generated will be presented.

This report presents two of the main Tables of the database (data of all buses measured by April 2019):

- Table 1: Average performance data (by emission certification class) for the Braunschweig bus cycle. In addition to emission class, the buses are grouped by architecture (2-axle, 3-axle, conventional, lightweight, hybrid) and by fuel. The bulk of the data is for hot start, combined results (cold and hot) presented for some vehicles (mainly Euro VI certified)
- Table 2: Average performance data (actual Euro VI vehicles and vehicles retrofitted to correspond to Euro VI) for the WHVC cycle (weighted average; cold start cycle 14 % and hot start cycle 86 %). The buses are grouped by architecture (2-axle, 3-axle, conventional, lightweight) and by fuel.

In most cases, the result presented are average values for multiple vehicles. As of 2017, the presentation of results was modified. A division by vehicle mileage was introduced for EEV and Euro VI vehicles. The categories are:

1. Mileage less than 150,000 km
2. Mileage 150,000…500,000 km
3. Mileage more than 500,000 km

The division was made to better accentuate the impact of driving distance on the performance of buses with advanced exhaust after-treatment technology. In addition, a column with the standard deviation for NO_x emissions was introduced. This was done to facilitate the interpretation of results, e.g., in case that some vehicle individuals show abnormally high emissions. If no value for standard deviation is presented this means that so far only one specimen has been tested.

In general, it can be said that diesel buses with less sophisticated exhaust control systems are rather stable, whereas for buses with more advanced systems, relative variations can be quite substantial. Still, the advanced vehicles in most cases deliver low absolute emission levels.

Figures 5 (NO_x emissions), 6 (PM emissions) 7 (CO_{2eqv} emissions and 8 (energy consumption) show progress in performance going from Euro I to Euro VI (hot Braunschweig test cycle, 2-axle buses, conventional architecture, average of all measurements).

Figures 9 (EEV certified vehicles) and 10 (Euro VI certified vehicles) show the effect of driving distance on the NO_x performance of diesel and gas buses (Braunschweig), and Figures 11 and 12 correspondingly the PM performance. Also this data is for 2-axle buses with conventional architecture.

Figures 13 (NO_x emissions), 14 (PM emissions) and 15 (energy consumption) show a comparison between Braunschweig and WHVC data. In the case of diesels, data is average data for 150,000…500,000 km driven buses (all in all 11 buses). Data for two CNG buses, with mileages of less than 40,000 km, is included as a comparator. Due to the differences in mileage, the Figures are not meant to be used for diesel to CNG comparisons, but rather to show, how the two technologies respond to test cycle. As in the previous Figures, the data is for 2-axle buses with conventional architecture.

Table 1. Average performance data for Euro I…Euro VI diesel buses, CNG buses and ethanol buses for the Braunschweig bus cycle, division by vehicle architecture. The bulk of the data is for hot start.

Braunschweig	*Number n*	*Mileage Min*	*Max*	*CO g/km*	*HC g/km*	*CH_4 g/km*	*NOx g/km*	*NOx g/km std.*	*PM g/km*	*CO_2 g/km*	*CO_2 eqv** g/km*	*FC kg/100km*	*FC MJ/km*
2 - axle													
Diesel Euro I	2	555025	672700	1,39	0,32		15,59		0,436	1220	1220	38,6	16,6
Diesel Euro II	13	160500	1125674	1,60	0,21		12,86		0,213	1286	1286	40,7	17,5
Diesel Euro III	14	15934	786164	0,85	0,12		8,48		0,209	1213	1213	38,4	16,6
Diesel Euro IV	8	6105	474152	2,96	0,10		8,36		0,112	1207	1207	38,2	16,5
Diesel Euro V***				2,96	0,10		7,51		0,089	1207	1207	38,2	16,5
Diesel EEV	17	0	150000	0,93	0,03		5,88	1,09	0,061	1160	1160	36,7	15,8
Diesel EEV	14	150001	500000	0,90	0,03		6,21	0,76	0,065	1130	1130	35,8	15,4
Diesel EEV	3	500001	727134	3,65	0,10		5,59	0,30	0,147	1204	1204	38,3	16,5
Diesel Euro VI	7	0	150000	0,14	0,00		0,10	0,13	0,017	1117	1117	35,3	15,2
Diesel Euro VI	11	150001	500000	0,09	0,00		1,07	0,53	0,011	1127	1127	35,7	15,4
Diesel Euro VI	0	500001	-										
Ethanol EEV	4	25249	133297	4,01	0,69		6,25		0,022	1321	1321	69,2	17,5
Diesel Hyb. EEV	5	2602	136255	0,89	0,02		5,12		0,046	848	848	26,9	11,6
Diesel Hyb. Euro VI	1	68310	68310	1,66	0,00		0,21		0,011	943	943	29,8	12,9
CNG Euro II *	2	211000	672946	4,32	7,12	6,76	16,92		0,009	1140	1295	42,1	20,7
CNG Euro III	2	37600	237189	0,05	2,64	2,38	9,44		0,019	1185	1240	43,7	21,5
CNG EEV	6	0	150000	1,25	1,19	0,98	2,91	1,43	0,009	1302	1325	48,0	20,7
CNG EEV	2	150001	500000	2,53	0,44	0,37	2,06	0,34	0,004	1187	1195	43,8	18,9
CNG EEV	3	500001	640252	10,52	2,07	1,85	6,64	0,44	0,005	1263	1306	46,6	20,1
CNG Euro VI	2	347	36047	0,53	0,06	0,04	0,09	0,02	0,025	1068	1068	39,4	19,4
2 - axle combined cold and hot test cycle *****													
Diesel Euro VI*****	3	0	150000	0,16	0,01		1,59	1,10	0,030	1138	1138	36,0	15,5
Diesel Euro VI*****	3	150001	500000	0,26	0,01		0,82	0,37	0,015	1075	1075	34,0	14,7
Diesel Euro VI*****	0	500001	-										
CNG Euro VI*****	2	347	35992	0,61	0,19	0,13	0,42	0,26	0,024	1078	1081	39,8	19,6
2 - axle, lightweight													
Diesel****	4	993	26436	0,88	0,03		6,70		0,047	953	953	30,17	13,0
Diesel Euro VI	5	8977	190356	0,08	0,00		0,30	0,25	0,009	965	965	30,53	13,2
3 - axle													
Diesel Euro V	4	1400	232494	6,68	0,03		3,16		0,089	1414	1414	44,8	19,3
Diesel EEV	7	0	150000	1,24	0,04		6,02	3,33	0,072	1462	1462	46,3	19,9
Diesel EEV	0	150001	500000										
Diesel EEV	2	500001	830076	0,80	0,08		6,28	1,61	0,134	1457	1457	46,1	19,9
Diesel EEV Retro E6	4	297530	838336	0,08	0,00		0,77	0,43	0,015	1474	1474	46,6	20,1
Diesel Euro VI	11	0	150000	0,10	0,00		0,42	0,28	0,037	1373	1373	43,4	18,7
Diesel Euro VI	8	150001	500000	0,13	0,00		2,07	0,65	0,009	1409	1409	44,6	19,2
Diesel Euro VI	0	500001	-										
CNG EEV	1	0	150000	4,91	1,75	1,62	8,77		0,012	1396	1434	51,5	25,4
CNG EEV	2	150001	350000	3,31	0,98	0,86	3,38	2,55	0,005	1411	1431	52,1	25,6
CNG EEV	3	350001	651529	16,19	1,98	1,78	7,22	3,04	0,016	1424	1465	52,5	25,9
CNG Euro VI	1	41390	41390	0,47	0,04	0,02	0,01		0,006	1318	1319	48,6	23,9
3 - axle combined cold and hot test cycle *****													
Diesel Euro VI*****	1	0	150000	0,39	0,00		1,03		0,022	1390	1390	44,0	19,0
Diesel Euro VI*****	3	150001	500000	0,22	0,00		2,25	0,14	0,013	1444	1444	45,7	19,7
Diesel Euro VI*****	0	500001	-										
Total number of tests	180												

*Methane fueled buses CH_4 = THC * 0.95

** CO_2 eqv = CO_2 + 23 * CH_4

*** Euro V results estimated with the results of Euro IV

**** Include test results from Euro III, Euro IV and EEV

***** Weighted average from cold (14%) and hot (86%) cycles test results

Table 2. Average performance data for actual and retrofitted Euro VI diesel buses for the WHVC cycle, division by vehicle architecture.

WHVC	*Number n*	*Mileage Min*	*Max*	*CO g/km*	*HC g/km*	*CH_4 g/km*	*NOx g/km*	*NOx g/km std.*	*PM g/km*	*CO_2 g/km*	*CO_2 eqv** g/km*	*FC kg/100km*	*FC MJ/km*
2 - Combined cold and warm start *													
Diesel Euro VI	1	0	150000	0.06	0.00		2.44	0.00	0.011	790	790	25.0	10.8
Diesel Euro VI	11	150001	500000	0.11	0.00		0.57	0.27	0.009	730	730	23.1	10.0
Diesel Euro VI	0	500001	-										
Diesel Euro VI***	1	0	150000	0.17	0.00		0.10	0.00	0.022	691	691	21.9	9.4
Diesel Euro VI***	3	150001	500000	0.06	0.00	0.00	0.27	0.15	0.020	680	680	21.5	9.3
CNG Euro VI	2	347	36102	0.66	0.14	0.11	0.21	0.12	0.013	713	715	26.3	12.9
3 - Combined cold and warm start *													
Diesel EEV Retro E6	4	297433	392436	0.03	0.01		1.06	0.24	0.006	945	945	29.9	12.9
Diesel Euro VI	3	0	150000	0.09	0.01		0.38	0.26	0.009	845	845	26.7	11.5
Diesel Euro VI	7	150001	500000	0.18	0.01		1.32	0.04	0.010	883	883	27.9	11.9
Diesel Euro VI	0	500001	-										
CNG Euro VI	1	41280	41280	0.47	0.22	0.17	0.15		0.002	821	824	30.3	14.9
Total number of tests	33												
* Weighted average cold (14 %) and warm (86 %) start results													
** CO2 eqv = CO2 + 23 * CH4													
*** Lightweight													

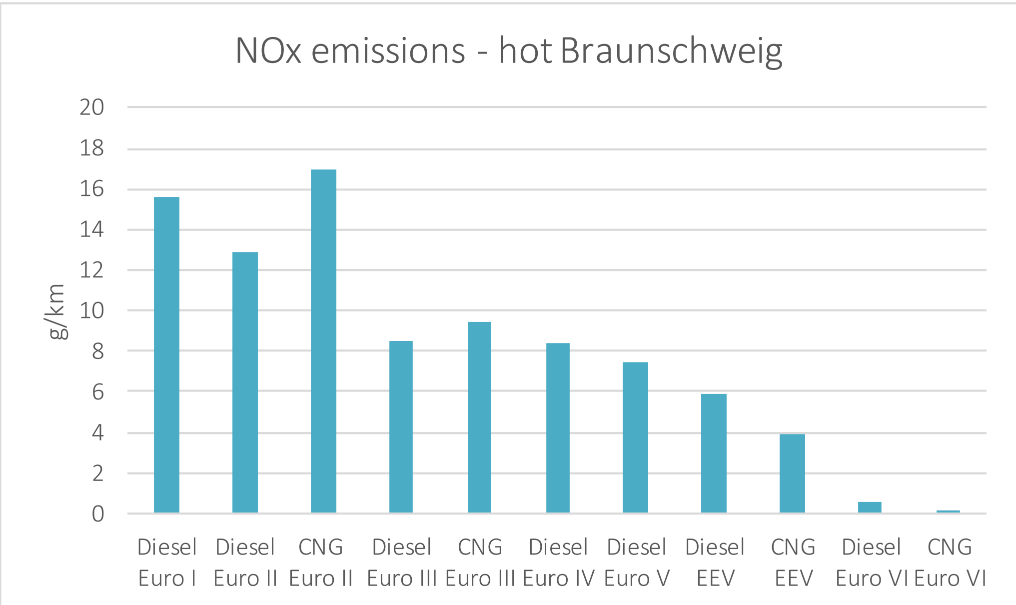

Figure 5. NO_x emissions (hot Braunschweig test cycle, 2-axle buses, average of all measurements).

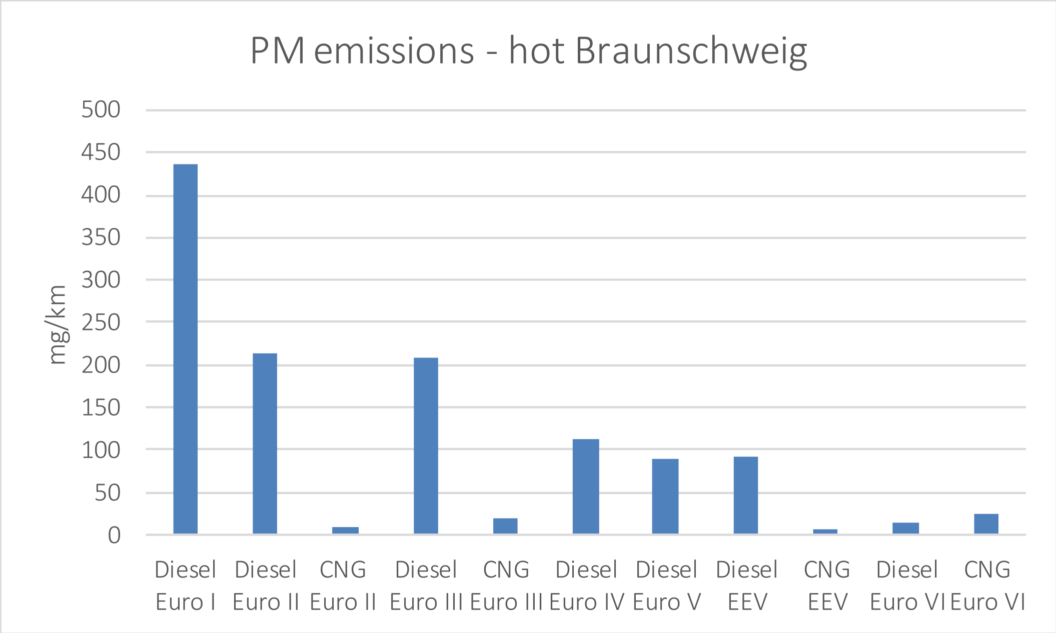

Figure 6. PM emissions (hot Braunschweig test cycle, 2-axle buses, average of all measurements).

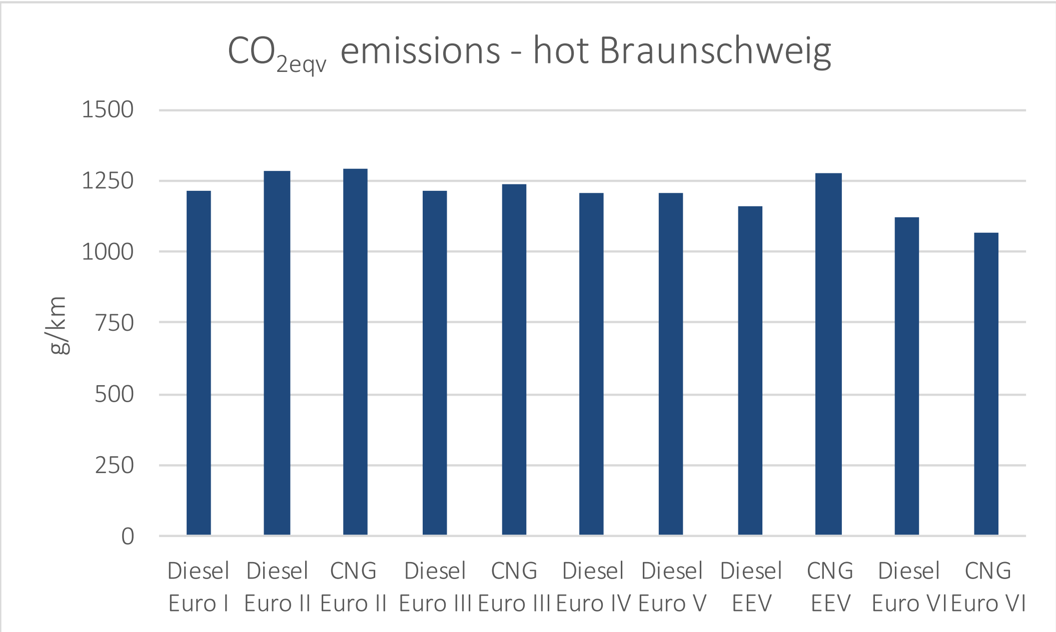

Figure 7. CO_{2eqv} emissions (hot Braunschweig test cycle, 2-axle buses, average of all measurements).

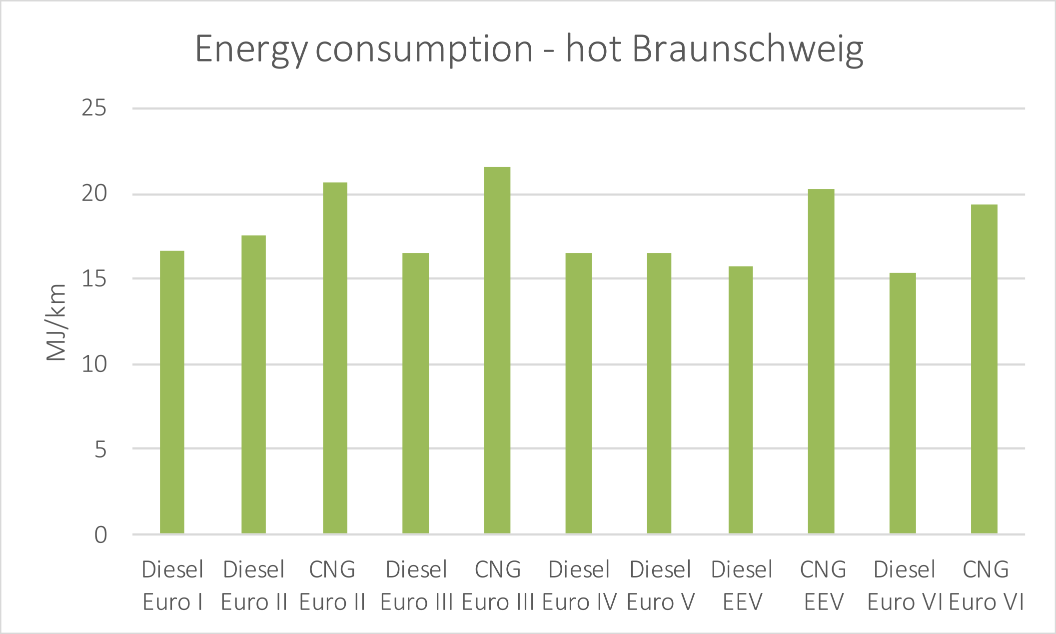

Figure 8. Energy consumption (hot Braunschweig test cycle, 2-axle buses, average of all measurements).

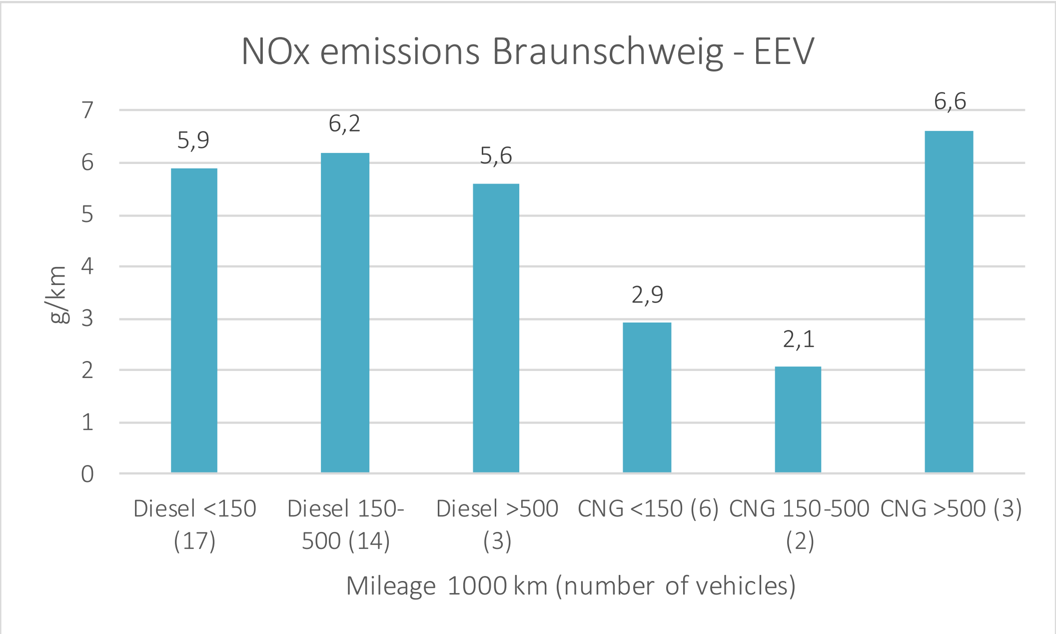

Figure 9. The effect of driving distance on NO_x emissions (EEV certified 2-axle diesel and gas buses, Braunschweig).

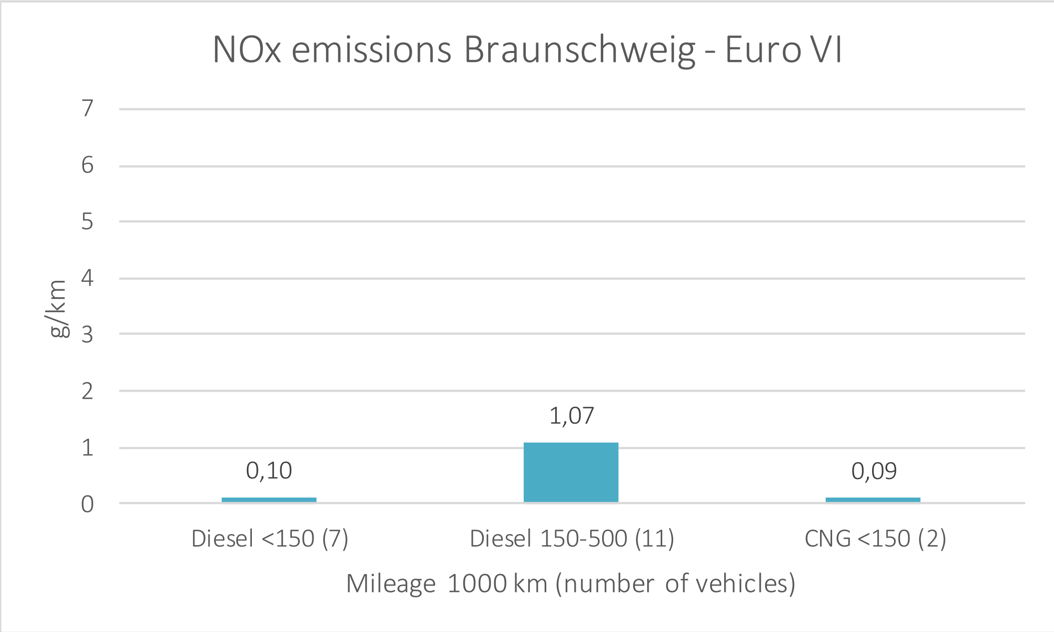

Figure 10. The effect of driving distance on NO_x emissions (Euro VI certified 2-axle diesel and gas buses, Braunschweig).

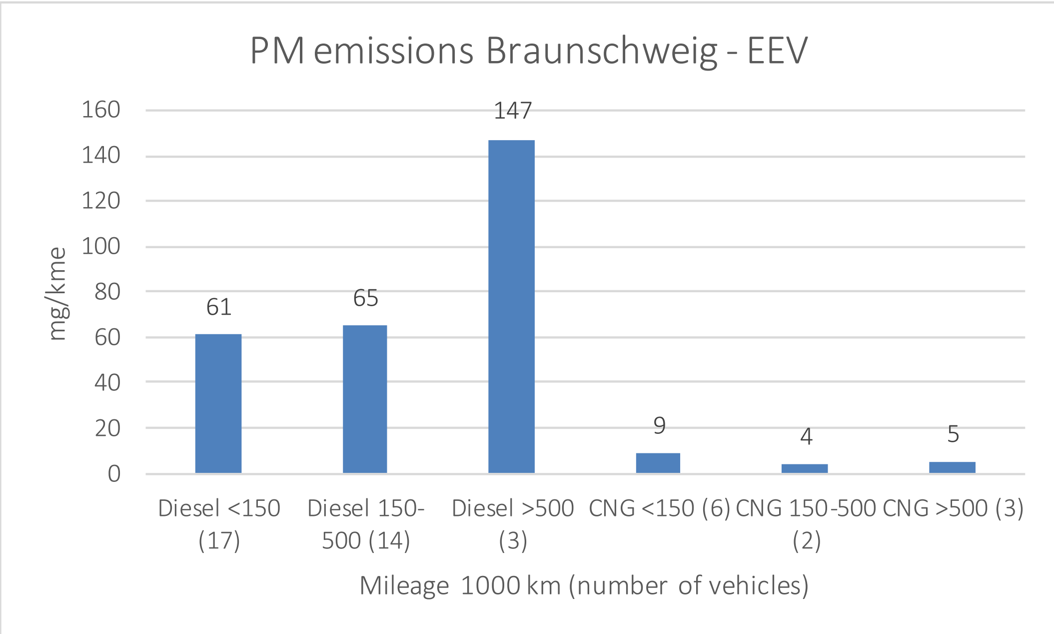

Figure 11. The effect of driving distance on PM emissions (EEV certified 2-axle diesel and gas buses, Braunschweig).

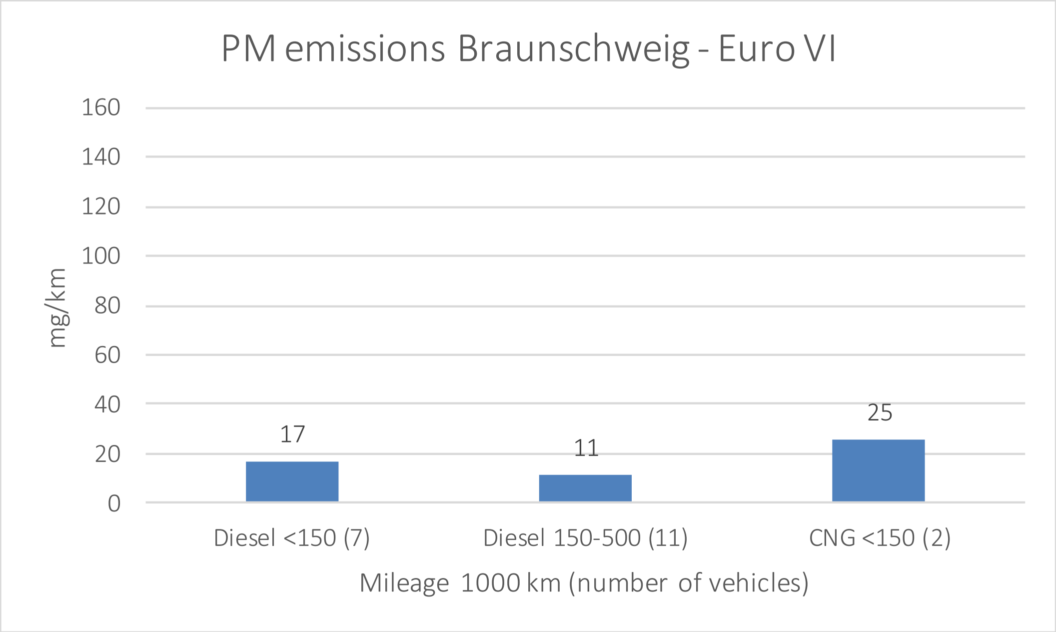

Figure 12. The effect of driving distance on PM emissions (Euro VI certified 2-axle diesel and gas buses, Braunschweig).

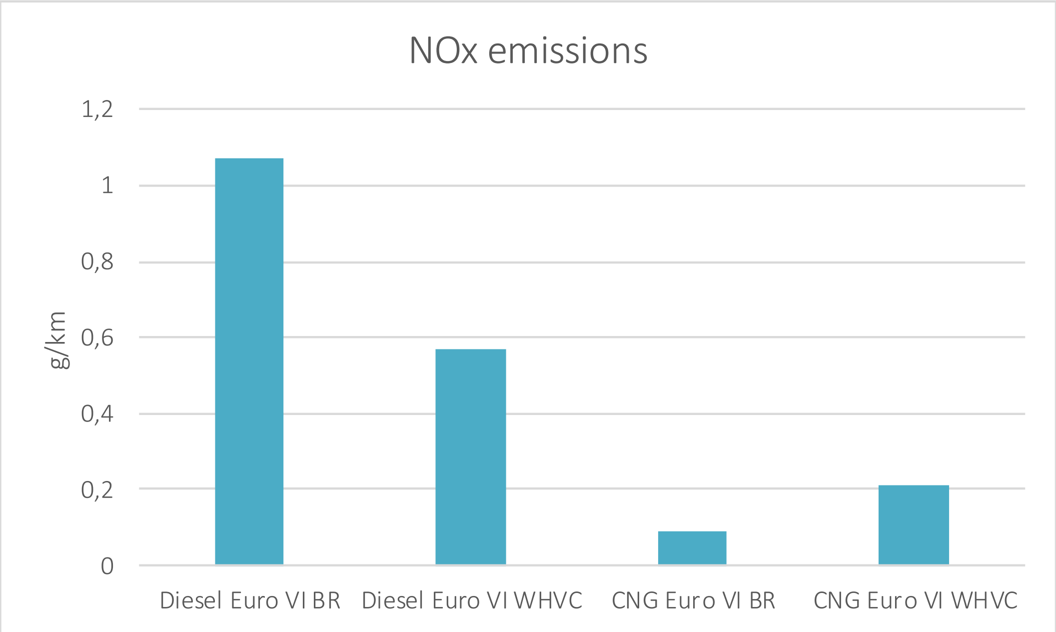

Figure 13. Comparison of Braunschweig and WHVC NO_x data. Diesel average values for 150,000…500,000 km driven buses (11 vehicles). CNG data for two, less than 40,000 km driven buses. (2-axle Euro VI certified buses, hot Braunschweig and combined WHVC).

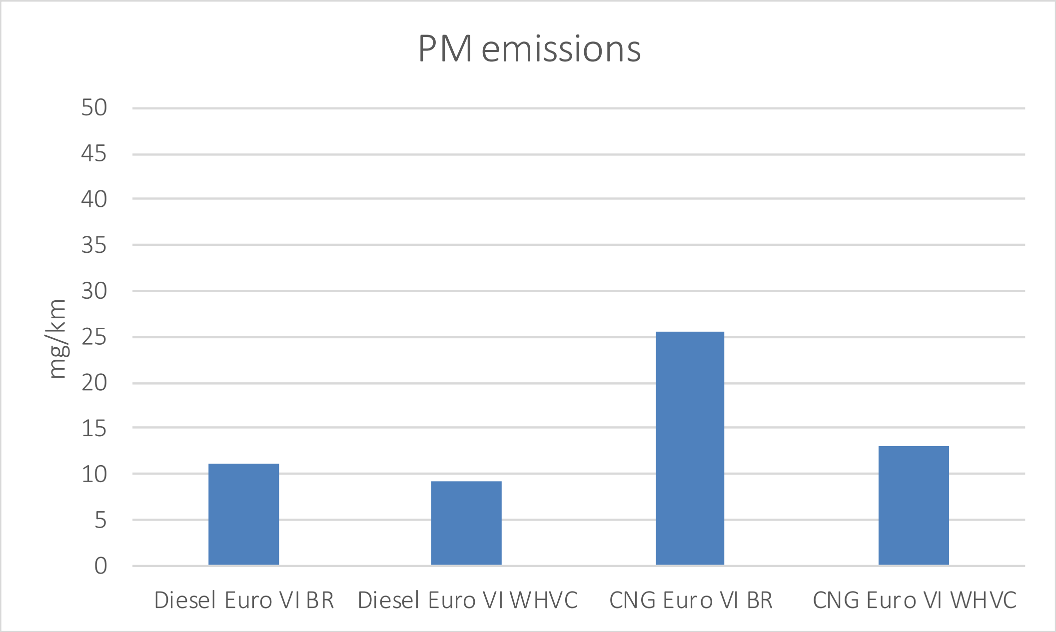

Figure 14. Comparison of Braunschweig and WHVC PM data. Diesel average values for 150,000…500,000 km driven buses (11 vehicles). CNG data for two, less than 40,000 km driven buses. (2-axle Euro VI certified buses, hot Braunschweig and combined WHVC).

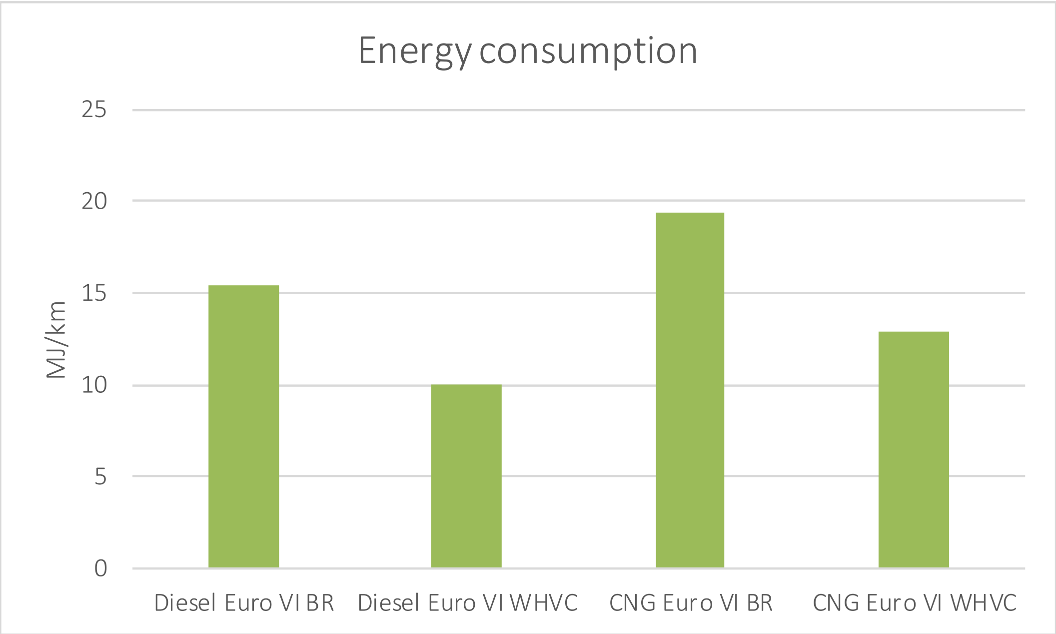

Figure 15. Comparison of Braunschweig and WHVC fuel consumption data. Diesel average values for 150,000…500,000 km driven buses (11 vehicles). CNG data for two, less than 40,000 km driven buses. (2-axle Euro VI certified buses, hot Braunschweig and combined WHVC).

4. Discussion

4.1 General

It is fair to say that current buses are much cleaner than the ones of the early 90's. Figures 5 and 6 (Braunschweig, based on Table 1) clearly show the positive development in NOx and PM emission levels over the years, from Euro I to Euro VI. It is also evident that the step from Euro V/EEV to Euro VI brought about the biggest relative reduction so far. To meet the Euro VI emission limits, diesel engines in practice have to be equipped with a combination of diesel particulate filter (DPF) and an SCR catalyst with an urea additive feed system.

On an average, the NOx and PM emission levels of Euro VI diesel buses are below the levels, which can be derived from the legislative limits for engine homologation. It is also worth noticing, that even though Euro VI brought a significant reduction in NOx and PM emissions, the average energy consumption was reduced slightly, as well.

In the case of CNG buses, Euro VI means a significant reduction in NOx emissions. For Euro V/EEV, there was mix of both lean-burn and stoichiometric engines. Lean-gas engines tend to have high NOx emissions, even higher than their diesel counterparts. This is evident in Figure 5, which shows that in the case of Euro II and Euro III vehicles, CNG vehicles have higher NOx emissions than corresponding diesel vehicles. For Euro VI CNG vehicles, all manufacturers use stoichiometric combustion in combination with a three-way catalyst (TWC), bringing NOx emissions to a very low level.

Figure 6 shows that CNG vehicles have, independent of the certification class, very low PM emissions, equivalent to Euro VI diesels. Earlier on, the big advantage of CNG was specifically low PM emissions, but with Euro VI, this advantage is now gone.

So far, the database only contains data for three Euro VI certified CNG buses, two 2-axle buses and one 3-axle bus, all with a mileage of less than 50,000 km. Thus, there is no information on the emission stability of Euro VI CNG buses yet.

As stated above, emission reductions have been remarkable. However, regarding CO2 emissions and fuel consumption, the development has not been that impressive as shown by Figures 6 and 7. Over the years, for vehicles with conventional architecture, fuel consumption has gone down only some 7...8 % (diesel Euro I vs. Euro VI, CNG Euro II vs. Euro VI). At the Euro II level, CNG had 18 % higher energy consumption than diesels, at the Euro VI level the difference is 26 %. These figures are for the Braunschweig cycle. In the WHVC cycle, Euro VI CNG vehicles consume 26…29 % more energy than their diesel counterparts.

Natural gas (methane) has a more favourable hydrogen-to-carbon ratio than diesel fuel, resulting in a specific CO2 emission (g CO2/MJ) some 25 % lower compared to diesel. However, due to the use of SI-engines, the higher energy consumption of CNG vehicles compared to diesel in practise nullifies this advantage. At the Euro VI level, CNG provides a reduction of tailpipe CO2eqv emissions of some 5 %, compared to diesel.

4.2 Effects of mileage

As of 2017, the data for EEV and Euro VI vehicles in the database is split up according to mileage, in three categories: less than 150,000 km, 150,000…500,000 km, and above 500,000 km. Availability of data is summarised in Table 3.

Table 3. Availability of mileage resolved data for EEV and Euro VI certified vehicles.

	<150,000 km		150,000…500,000 km		>500,000 km	
	BR	WHVC	BR	WHVC	BR	WHVC
EEV diesel	x		x		x	
EEV CNG	x		x		x	
Euro VI diesel	x	x	x	x		
CNG Euro VI	x	x				

There is plenty of data for EEV certified vehicles over the Braunschweig cycle, but less for Euro VI vehicles, especially CNG vehicles, and also less for the WHVC cycle (Euro VI vehicles only).

Figures 9 to 12 present data for the Braunschweig cycle (2-axle buses). Figure 9 (NOx) shows that EEV diesels are rather stable for NOx, whereas CNG show variations over time. Figure 10 shows that for new Euro VI vehicles, NOx levels are very low, around 0.1 g/km. However, a significant increase in NO_x emissions over time (by a factor of 10, <150,000 vs. 150,000…500,000 km) can be seen for diesel vehicles (no data available for CNG vehicles yet). Still, for vehicles driven 150,000…500,000 km, the level for Euro VI vehicles is significantly lower than that for EEV vehicles, roughly 80 % lower.

For 3-axle Euro VI vehicles, the increase in NOx emissions over time (<150,000 vs. 150,000…500,000 km) is smaller, by a factor of 5, the absolute values being some 0.4 and some 2.0 g/km. With low absolute emission levels, the scattering of NOx results tends to increase, both vehicle-to-vehicle scatter and scatter with increasing mileage. A contributing factor is that the vehicles are taken for testing directly out of service, without any checking or maintenance, as to better reflect true performance.

Figure 11 for EEV vehicles shows a significant increase in PM emissions over time for diesel vehicles, whereas CNG vehicles deliver stable and low PM emissions over time. Figure 12 suggests stable and low PM emissions for Euro VI diesels, as well.

With increasing mileage, fuel consumption tends to increase slightly, typically 1…3 %.

4.3 Effects of driving cycle

Figures 13 (NO_x), 14 (PM) and 15 (fuel consumption) show a comparison of Braunschweig and WHVC testing for Euro VI vehicles. These Figures are primarily meant to demonstrate how the two technologies, diesel and CNG, react to test cycle, not to make a comparison between technologies.

Starting with energy consumption, for both technologies, for 2-axle buses, Braunschweig results in 49…55 % higher energy consumption compared to WHVC. The Braunschweig cycle actually depicts typical bus operation better than the WHVC. Table 4 presents average volumetric fuel consumption values for Euro VI diesel for the two cycles.

Table 4. Volumetrical fuel consumption values (l/100 km) for Euro VI diesel vehicles.

	Braunschweig	WHVC
2-axle	42,7	27,8
3-axle	52,8	33,2

Figure 13 shows that for NO_x emissions, diesel and CNG buses react differently to cycle. In the case of diesel buses, the Braunschweig, although run hot, produces higher emissions than the WHVC, combing cold and hot testing. This means that the effects of the more severe test cycle (highly transient cycle resulting, e.g., challenges in correct urea dosing) overrule the effect of phasing in the cold start in the WHVC cycle. In the case of the two CNG vehicles tested, the WHVC cycle produces higher NO_x emissions compared to the Braunschweig cycle, suggesting higher impact of the cold start part.

For PM emissions (Figure 14), the wall-flow type diesel particulate filters (DPF) mounted on the Euro VI buses bring about low PM emissions, independent of cycle.

For CNG, the particulates originate from the lubricating oil, not from combustion of the fuel itself. As the current CNG vehicles do not have particulate filters, it is easy to appreciate that highly transient operation increases burning of oil, and thus, also particulate emissions. Figure 14 indicates that for CNG vehicles, Braunschweig delivers twice the amount of particulates compared to WHVC.

4.4 Comparison to regulatory emission limit values

The chassis dynamometer testing produces distance-based performance data, in the case of regulated emissions, in the form of g/km. The regulatory limit values for heavy-duty engines, on the other hand, are given in the form g/kWh.

However, it is possible to correlate chassis dynamometer data to engine testing data. In chassis dynamometer testing, work done on the chassis dynamometer over the duty-cycle is recorded. Thus, taking into account the losses (or the efficiency) of the drivetrain, the results can be converted to the engine crankshaft, as in the case of actual certification.

For these calculations, VTT assumes the efficiency of the drivetrain at 75 %. This value also takes into account the energy use of auxiliaries. The value is assumed the same for both Braunschweig and WHVC. Naturally, the assessment is indicative, not absolutely accurate.

Furthermore, comparisons can be made with the limit values as such, or the with in-service-compliance (ISC) values. Basically, ISC testing stipulates on-road measurements using PEMS (Portable Emission Measurement System) instrumentation. For city buses, ISC testing should be done on a route comprising of approximately 70 % of city driving and approximately 30 % of highway driving.

Currently the ISC factor is 1,5, meaning that for vehicles in service, emission levels 50 % higher than the actual limit values are allowed. Thus Euro VI legislation allows a certain degradation of performance over time. It should be noted, that for city buses, the emission regulations stipulate a durability of 300,000 km or 6 years.

NO_x compliance of Euro VI is of highest interest. Figure 16, partly based on Figure 10, presents a comparison of average measured data against certification and ISC limit values (Conformity Factor, CF). The WHVC value for 2-axle buses with a mileage of less than 150,000 km is intentionally left out, as so far only one malfunctioning vehicle has been measured in this category.

For buses with a mileage less than 150,000 km, CF factors are well below 1 (at maximum 0.6), meaning compliance. The Figure clearly demonstrates that NO_x emissions increase over time. For buses driven 150,000…500,000 km, NO_x values are well above the certification limit values, at their best at the ISC level.

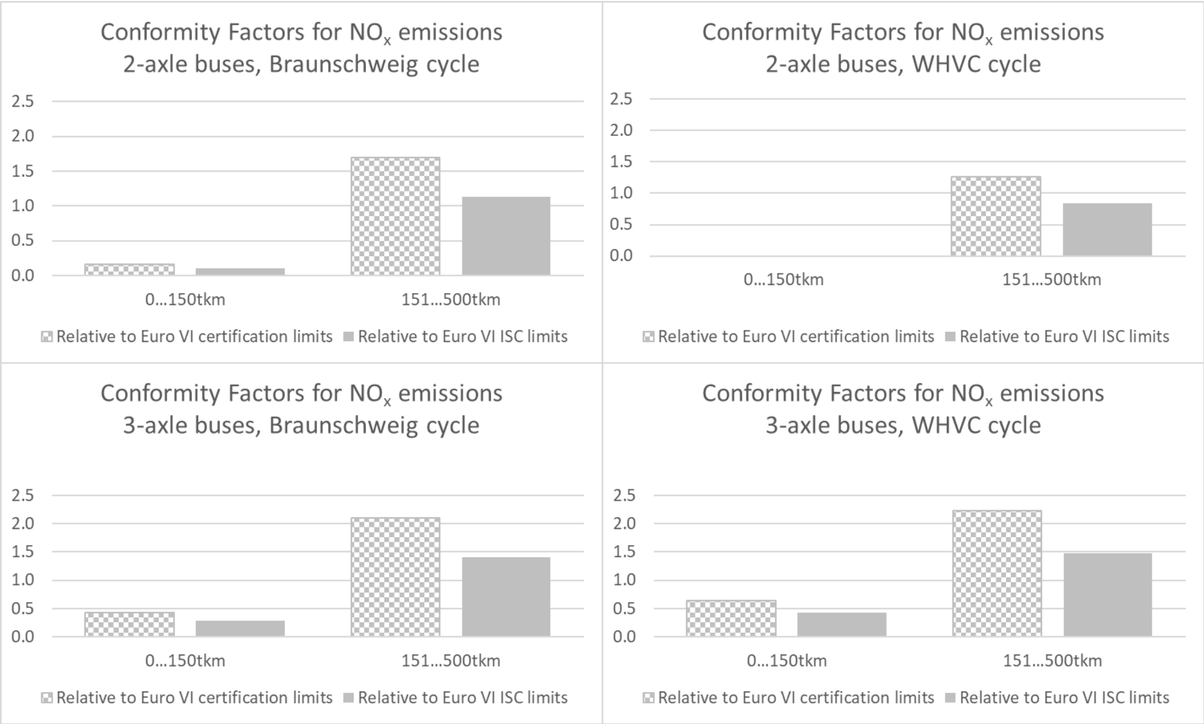

Figure 16. NO_x emissions in relation to Euro VI certification and ISC limit values.

5. Summary

The public transport authority (PTA) in Helsinki Metropolitan Area, Helsinki Region Transport (HSL) and VTT Technical Research Centre of Finland have been assessing and documenting performance of city buses for some 20 year. The data generated is used by HSL as an element supporting the tendering of bus services, but also to develop future bus fleet strategies. In principle, every new bus type entering service in Metropolitan Helsinki is tested.

The database contains the following results:

- emission results in g/km (carbon monoxide CO, hydrocarbons HC, methane CH_4, nitrogen oxides NO_x, NO_x standard deviation (some vehicle classes), particulate matter PM (mass), carbon dioxide CO_2, carbon dioxide equivalent CO_{2eqv}
- energy consumption in kg/100 km and MJ/km

Between the spring of 2002 and end of 2018, VTT has tested in total 178 city buses for HSL. The sample includes Euro I - Euro VI diesel buses, Euro II - VI gas (CNG) buses and EEV ethanol buses. This report present a summary of all data generated. VTT has also measured some electric buses, but these results are not incorporated in the main bus database.

The buses have been tested on VTT's heavy-duty chassis dynamometer. For emission measurements VTT uses full-flow CVS dilution system. VTT's test procedure is accredited by FINAS, the Finnish Accreditation Service.

VTT's standard test cycle for buses is the German Braunschweig bus cycle, depicting bus service in a mid-sized European city, and also describing well driving in Helsinki. As of 2017, testing is carried out using the World Harmonised Vehicle Cycle (WHVC) as well, providing a link to the emission certification process of heavy-duty engines.

It is fair to say that current buses are much cleaner than the ones of the early 90's. The results clearly show the positive development in NO_x and PM emission levels over the years, from Euro I to Euro VI. It is also evident that the step from Euro V/EEV to Euro VI brought about the biggest relative reduction so far. To meet the Euro VI emission limits, diesel engines in practice have to be equipped with a combination of diesel particulate filter (DPF) and a SCR catalyst with urea additive dosing system. It is also worth noticing, that even though Euro VI brought a significant reduction in NO_x and PM emissions, the average energy consumption was reduced slightly, as well.

Also in the case of CNG buses, Euro VI means a significant reduction in NO_x emissions. CNG vehicles have, independent of the certification class, very low PM emissions, equivalent to Euro VI diesels. Earlier on, the big advantage of CNG was specifically low PM emissions, but with Euro VI, this advantage is now gone.

Old diesel vehicles were rather stable for NO_x emissions, but PM emissions tended to increase over time. For Euro VI diesels, an increase in NO_x emissions over time can be seen. Still Euro VI vehicles with relatively high mileage (up to 500,000 km, data for vehicles driven more than 500,000 km is not available yet) deliver some 80 % lower NO_x emissions compared to corresponding EEV certified vehicles. On the other hand, PM emissions of Euro VI diesel vehicles seem to be stable over time.

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