Emissions Testing of Urban Delivery Commercial Vehicles

The results of tests to measure the greenhouse gas and pollutant emission performance of various urban freight delivery vehicles, on behalf of Transport for London.

Prepared by Low Carbon Vehicle Partnership

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Executive Summary

To examine some technologies and options of particular relevance to the capital, Transport for London have funded a LowCVP testing programme to develop a representative, city-centre test cycle and to assess the greenhouse gas and pollutant emissions performance of some emerging technologies relevant to urban and city-centre operations, thus informing its own policy making and the development of its LoCITY programme.

The available resources were deployed to cover what were considered to be the three technologies of greatest immediate interest and with the greatest short-term market potential. Each vehicle was compared with conventional diesel (Euro VI or 6) equivalents:

- 1 pure battery electric 2t van (Urb01)
- 1 plug-in series hybrid 7.5t truck with battery-electric drivetrain and diesel generator/range-extender (Urb02)
- 1 natural gas (CNG) 3.5t van (Urb03)

Testing was carried out according to the protocols developed by LowCVP for its aftermarket technologies accreditation scheme, and using its regional delivery and urban delivery cycles. To adequately represent the heavily-congested, low speed operations typical of multi-drop delivery vehicles working in the city centre, an additional “city-centre” cycle was developed as part of this test programme.

To supplement the track-based testing and provide additional data, dyno testing was completed to either the World Light-Duty Test Cycle (WLTC) or the World Heavy-Duty Vehicle Cycle (WHVC). To aid comparability between track and dyno testing, energy consumption and CO_2 emissions figures were normalised to the same kinetic intensities as used for the track-based cycles. Pollutant emissions were not normalised but the results from each phase (low, medium and high speed for WLTC and urban, suburban & motorway for WHVC) were allocated to the nearest equivalent track cycle.

The pure electric van (Urb01) delivers significant GHG savings over its diesel equivalent, particularly in the city-centre cycle. These conditions are particularly well suited to the electric vehicle, where it achieves low energy consumption (0.13 kWh/km), whereas the diesel equivalent is very inefficient in these low speed, transient conditions. There was found to be very good agreement between the track-based and dyno-based testing for the Urb01 vehicles, in that both methods found GHG savings of around 30% for the urban and regional cycles, and a little less than 60% for the city-centre cycle (assuming electricity at grid-average carbon intensity). The range for Urb01 is estimated to be around 120 – 180 km, equivalent to about 6 – 8 hours of driving.

In Mode 0 (pure electric mode), the Urb02 vehicle delivers very similar performance to Urb01, both in terms of overall GHG saving percentages (around 60% for the city-centre cycle, 40% for urban and regional) and range (156 km under city-centre conditions, equivalent to around 7 hours of continuous driving).

This range-extender (RE) vehicle has three other operating modes, each drawing increasing amounts of power from the diesel range-extender engine/generator:

- Mode 1 – low revs, low noise, low power (measured at 7.5 kW)

- Mode 2 – medium revs, medium power (35.4 kW)
- Mode 3 – high revs, high noise, high power (57.4 kW)

The engine operates under steady-state conditions (constant RPM) for each of these modes. For a given duty cycle, at a given average speed, each mode can replenish a proportion of the energy being consumed by the battery.

For the pure electric vehicle, Urb01, and the RE vehicle in Mode 0, there are, of course, no tailpipe emissions. The Urb01 diesel comparator vehicle, a similarly sized Euro 6 van, emitted about 0.5 – 0.8 g/km of NOx.

Despite carrying 7 times the payload, the larger Euro VI truck diesel comparator (for Urb02) produced similar quantities of NOx emissions under city centre conditions as the Euro 6 van, but much lower emissions under the urban and regional cycles. Both overall NOx levels and primary NO_2 emissions are lower. This provides further evidence of the effectiveness of the Euro VI emissions standards.

Modelling of the range-extender vehicle's performance for different daily mileages under the city-centre and urban delivery cycles indicates that from a NOx perspective, the range extender vehicle in its current guise (with a Euro 5 diesel car engine using pre-production calibration and having known injector synchronization issues) is only less polluting overall than the Euro VI diesel comparator if its daily mileage is low enough to allow continuous Mode 0 running. It is crucial to emphasize, however, that:

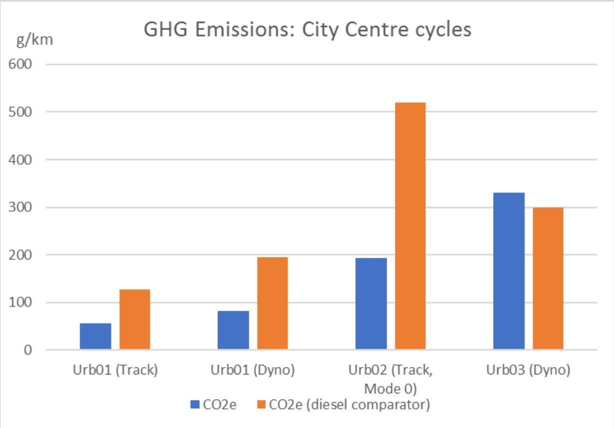
- The vehicle is capable of zero emission operation, so its NOx may be emitted in less sensitive areas, away from heavily populated areas.
- With a more modern car engine (Euro 6), properly calibrated and with the injector synchronization issue corrected, the NOx emissions can be expected to be at least 50% lower than from the current Euro 5 engine.

From a GHG perspective, the vehicle outperforms its Euro VI diesel comparator for all city-centre operations up to 250 km per day, and for all the urban delivery cycle operations up to at least 500 km per day if use of Mode 3 is avoided.

Comparing gas consumption and diesel consumption, using the Carbon Balance Method, indicates that the spark ignition CNG vehicle (Urb03) incurred efficiency losses of between 20% (long haul) and 45% (city-centre). Despite negligible quantities of unburnt methane (THC) or N_2O from the CNG vehicle, therefore, and allowing for measured N_2O emissions of around 10 – 20 mg/km for the diesel vehicle, overall GHG impacts (tank to wheel, assuming 100% fossil fuel in each case) were slightly higher from the CNG vehicle than for the diesel comparator for the city-centre and urban delivery cycles, by about 10%.

For the urban phase of the WHVC cycle, NOx emissions were identical between the two vehicles (0.32 g/km), but the CNG vehicle produced notably lower emissions of primary NO_2.

Summary graphs of the greenhouse gas and NOx emissions results from the city centre and urban delivery cycle tests are presented below.


GHG Emissions: City Centre cycles
g/km
600
500
400
300
200
100
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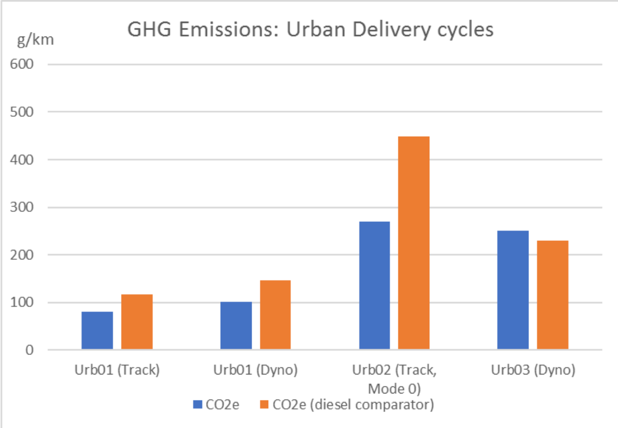
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
CO2e
CO2e (diesel comparator)


GHG Emissions: Urban Delivery cycles
g/km
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500
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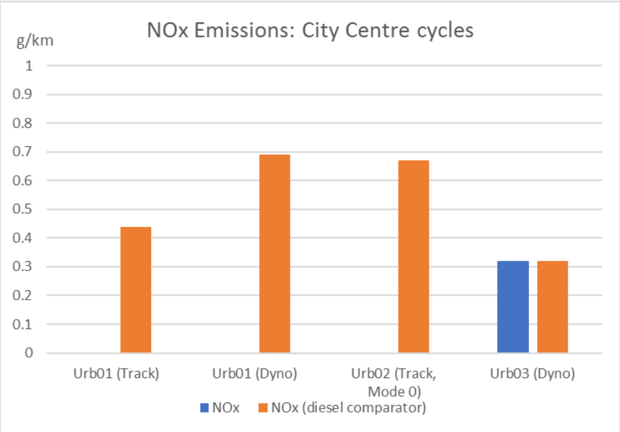
Urb02 (Track, Mode 0)
Urb03 (Dyno)
CO2e
CO2e (diesel comparator)


NOx Emissions: City Centre cycles
g/km
1
0.9
0.8
0.7
0.6
0.5
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0.3
0.2
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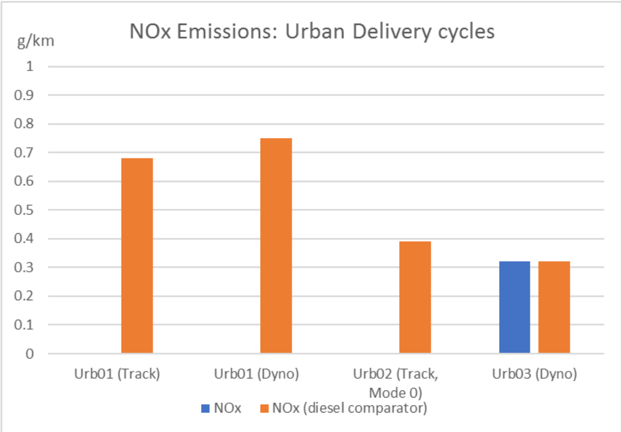
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
NOx
NOx (diesel comparator)


NOx Emissions: Urban Delivery cycles
g/km
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
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0.1
0
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
NOx
NOx (diesel comparator)

1 Introduction

1.1 Background

Freight transport is vital to economic growth, but has significant environmental impacts. HGVs are currently estimated to account for around 17% of UK GHG emissions from surface transport and around 18% of NOx emissions[1]. The 2008 Climate Change Act set an ultimate target for 2050 of an 80% reduction in GHG emissions from 1990 levels. Meeting this target will be challenging and the transport sector is under increasing pressure to decarbonize. Displacing conventional fuels and powertrains with alternative fuels and technologies has the potential to significantly reduce GHG emissions from difficult-to-decarbonize sectors such as road freight.

Air pollution presents a major threat to public health. Exposure increases hospital admissions and the chance of premature death due to conditions including cardiovascular and respiratory diseases. The total mortality burden in London from poor air quality is equivalent to 9,416 deaths per year. The economic cost of these health impacts is estimated to be up to £3.7 billion. London is in breach of legal limits for NO_2 and the Mayor has recently proposed various measures to deliver improvements to the capital's air quality, including:

- Bringing forward the introduction of the Ultra Low Emission Zone (ULEZ) to 2019 instead of 2020.
- Extending the ULEZ from Central London to London-wide for heavy vehicles (heavy goods vehicles (HGVs), buses and coaches) as early as 2019.
- Extending the ULEZ from Central London up to the North and South Circular roads for all vehicles as early as 2019.

Transport is a major contributor to pollution in Greater London, accounting for 50 per cent of NOx emissions in 2013. Vans and HGVs are responsible for 32 per cent of all transport NOx emissions in the capital. Road freight movement is expected to increase 20 per cent by 2031 to serve London's growing population and economy. Substantial action must be taken to mitigate the potential environmental costs associated with this trend. LoCITY is TfL's initiative for lowering London's commercial vehicle emissions. It is an industry-led, collaborative programme which brings together fleet operators, central and local government and other public sector organisations, vehicle manufacturers, and refuelling and recharging suppliers to improve air quality. LoCITY will also contribute to London's target to reduce CO_2 emissions to 60 per cent below 1990 levels by 2025.

To reduce air pollution in London and help meet targets on climate change, LoCITY's aims include supporting freight and fleet operators, vehicle manufacturers and infrastructure suppliers to

[1] https://www.gov.uk/government/statistical-data-sets/tsgb03 - 2013 data, calculated from Table TSGB0308 (ENV0301). GHG figure taken from https://documents.theccc.org.uk/wp-content/uploads/2016/06/2016-CCC-Progress-Report.pdf

increase the availability and uptake of ultra-low and zero emission commercial vehicles, defined in broad terms as those going well beyond Euro 6/VI compliance in air quality emissions or GHG impact terms, and ideally both.

There is also considerable interest amongst fleet operators in the use of methane as a road fuel, either in its fossil fuel form as natural gas or as a biofuel, bio-methane. However, there is currently a limited evidence base on the cost effectiveness, carbon abatement potential and wider impacts (e.g. air quality) of displacing diesel with methane in commercial vehicles. The £11.3 million Low Carbon Truck Trial, LCTT[2], which ran between 2012 and 2016, part-funded industry consortia to purchase and trial around 370 alternatively-fuelled commercial vehicles (the majority of which were dual fuel, diesel/natural gas aftermarket conversions), and to commission refuelling infrastructure. Nearly all the vehicles trialled were Euro V but the Trial came at a time when the commercial vehicle market was making the major shift (and investment) to Euro VI. Euro VI gas-fuelled trucks were unavailable until towards the end of the trial period and the project was therefore unable to gather comprehensive evidence on the emissions performance of these vehicles. Evidence to date strongly supports the view that the shift to Euro VI has led to very significant reductions in pollutant emissions, including NO_x, for conventional diesel vehicles.

To develop its evidence base and inform future policy on gas vehicles, and allow the results of the Low Carbon Truck Trial to be set in their proper GHG impacts context, the Department for Transport commissioned an HGV emissions testing project with the Low Carbon Vehicle Partnership (LowCVP) and its members to carry out vehicle testing across a representative range of gas-fuelled HGVs. The results have been published (in January 2017) by DfT[3].

To examine some technologies and options of particular relevance to the capital, Transport for London have funded the expansion of the LowCVP testing programme to develop a representative, city-centre test cycle and to cover a wider range of emerging technologies, particularly those relevant to city-centre operations, thus informing its own policy making and the development of its LoCITY programme. This report describes the testing carried out as part of this TfL-funded programme, and its results.

1.2 Programme management

The test programme was managed on behalf of DfT and TfL (the funding partners) by LowCVP, who were in overall charge of the work and responsible for delivery of this report, as well as all the day-to-day decisions, in conjunction with its funding partners. The urban delivery vehicle testing was carried out under contract to LowCVP by specialists at Millbrook, on vehicles and technologies supplied by a wide range of industry partners, including OEMs, after-market

[2] The final report into these Trials is available via https://www.gov.uk/government/publications/low-carbon-truck-and-refuelling-infrastructure-demonstration-trial-final-report

[3] https://www.gov.uk/government/publications/emissions-testing-of-gas-powered-commercial-vehicles

converters and leading freight vehicle operators. All such participants were also invited to join a programme Steering Group, which was used to discuss and refine the detailed test plans and methodology as it progressed, as well as to peer review the emerging findings. In addition, a workshop, hosted by TfL, was held at the start of the project and provided an opportunity for various stakeholders to help shape and contribute to the programme.

2 Vehicles, test procedures and cycles

2.1 Vehicles selected

A wide range of vehicles and technologies exist with the potential to reduce emissions from urban delivery vehicles. The available resources were deployed to cover what were considered to be the three of greatest immediate interest and short-term market potential:

- 1 pure battery electric 2t van.
- 1 plug-in series hybrid 7.5t truck with battery-electric drivetrain and diesel generator/range-extender.
- 1 natural gas (CNG) 3.5t van.

Each vehicle was compared with conventional diesel (Euro VI or 6) equivalents[4], carrying the same load.

2.2 Test method

Work by Ricardo – AEA in 2015 developed a test protocol[5] for the gas-powered vehicles being tested as part of the DfT programme, and made the following main recommendations regarding the test method to be followed:

- Track testing was advocated over on-road tests (too difficult to achieve repeatability) or chassis dynamometer tests (expensive, limited facility availability and difficult to demonstrate to satisfaction of the road freight industry that tests are genuinely representative of real-world conditions)
- Driving cycles should reflect real-world operations of the vehicles being tested, and the cycles for the test vehicles and their diesel/diesel-only comparators should be similar (at least in terms of average speeds and kinetic intensities)
- A combination of urban, rural and motorway driving conditions was likely to be suitable
- PEMS equipment should be used for emissions analysis, with Total Hydrocarbon (THC) acceptable as a proxy for methane if a dedicated methane sensor was not available.

The programme management team (including the funding partners and external stakeholders) agreed at the outset that the test procedures and three drive cycles developed originally by LowCVP for its HGV retrofit (CO_2 reducing) technology accreditation scheme, meet all of the above requirements. They thus formed the basis for this test programme[6].

For the TfL-funded test programme, however, it was further agreed that of the three original cycles, only the regional delivery and urban delivery test cycles would be relevant to London

[4] The CNG van and its conventional diesel van testing was also used as part of the DfT-funded work.
[5] Available via https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/468172/hgv-emissions-testing.pdf
[6] Details of the LowCVP retrofit technologies accreditation scheme and test protocols are at http://www.lowcvp.org.uk/projects/commercial-vehicle-working-group/hgv-accreditation-scheme.htm

freight operations (and the long haul cycle would not). Furthermore, it was agreed that a new, fourth cycle would be needed to adequately represent the heavily-congested, low speed operations typical of multi-drop delivery vehicles working in the city centre (the development of which is described more fully later in this report).

As well as using the scheme's back-to-back vehicle comparison method (testing the diesel baseline vehicle on one day and its alternatively-powered equivalent on another (usually the following) day, the test programme also followed, where appropriate[7], the scheme's recommended practice of using a control vehicle on each test day to measure, and allow correction for if necessary, any changes in ambient conditions affecting fuel consumption.

It was thought at the outset of the research that nitrous oxide (N_2O, a GHG ten times more potent than methane) was likely to be emitted in very low (and similar) quantities from both diesel and gas-fuelled vehicles. Evidence emerged during the project, however, to indicate that some modern (Euro VI) diesel engines may emit quite substantial amounts of nitrous oxide in consequence of their NOx reduction technologies. As such emissions cannot currently be robustly measured with PEMS, a limited programme of chassis dyno testing was thus incorporated into the DfT programme. This chassis dyno testing was also used to complement and enhance the track-based testing of urban delivery vehicles for TfL.

2.3 Instrumentation

In accordance with the protocol recommendations and LowCVP accreditation scheme procedures, for the track-based testing, Portable Emissions Monitoring Systems (PEMS) were used. The emissions monitoring included the following:

- Carbon Monoxide, CO
- Carbon Dioxide, CO_2
- Oxides of Nitrogen, NO and NO_2 (measured separately and combined to give NO_x)
- Total Hydrocarbons, THC

Particulates (particle mass or particle number) were not measured, as current PEMS technology is not considered sufficiently robust to accurately and reliably measure them, particularly as in any event such emissions are likely to be very low due to the presence on all vehicles tested of diesel particulate filters. Such filters have been shown by other research (including the TfL tests mentioned earlier) to be highly effective.

NO_x measurements were complemented with separate measures of Nitric Oxide (NO) and Nitrogen Dioxide (NO_2), as the fraction emitted as primary NO_2 is known to be of particular concern from an air quality perspective.

[7] The use of a control vehicle is appropriate where differences in GHG performance between the test and baseline vehicles are likely to be quite small and thus changes in ambient conditions could significantly affect the measured changes. It is less appropriate where changes are likely to be large.

As well as the direct measurement of the above tailpipe emissions, fuel flow meters were used to accurately measure fuel consumption. Energy meters were used to monitor the consumption of electrical energy by the pure electric and hybrid-electric vehicles. For tests involving use of the chassis dyno, emissions monitoring included the following additional species:

- Nitrous Oxide, N_2O
- Particulate Mass, PM

2.4 Test cycles

For the larger HGVs in the (DfT) test programme (18t gross weight and over), the three test cycles already developed as part of the accreditation scheme were used; long haul, regional delivery and urban delivery. For the smaller (up to 7.5t) urban delivery vehicles, the consensus view from stakeholders was to develop a fourth, city-centre delivery cycle.

A detailed discussion on the development of the original three cycles is beyond the scope of this report, but in essence they have been designed to follow in principle the long haul, regional delivery and urban delivery cycles being developed by the European Commission as part of the VECTO tool[8], using the correlation characteristics of the Kinetic Intensity cycle parameter, but modified slightly to reflect UK traffic conditions (felt by stakeholders to be generally somewhat more "intensive", that is with lower average speeds and more transient conditions associated with congested roads). The cycles developed, and used for this test programme, thus have slightly higher KI's than the current VECTO cycles (as of 2015), as shown in Table 1. The Table also shows the average speed, kinetic intensity and estimated fuel consumption (for an 18t rigid vehicle with 70% payload) felt by the programme steering group to be most appropriate for the fourth, city-centre delivery cycle. The fuel consumptions shown in the Table for the original three cycles are derived from actual testing of such a vehicle on each cycle during development of the accreditation scheme procedures.

To comply with these target values for the city-centre cycle, Millbrook developed the test cycle shown in Figure 1,which has an average speed of about 22 km/h, over a distance of 4.6 km, and a Kinetic Intensity of around 2.8 per km.

Table 1. Main test cycle parameters

	Long Haul	Regional Delivery	Urban Delivery	City-Centre Delivery
Average speed (km/h)	> 70	50 - 60	30 - 45	15 - 25
Kinetic Intensity (per km) (equivalent VECTO cycle figure in brackets)	0.14 – 0.20 (0.15)	0.24 – 0.36 (0.26)	0.70 – 1.00 (0.69)	2.60 – 3.00 (N/A)
Fuel consumption of 18t rigid 70% payload (l/100km)	22 - 27	26 - 31	29 - 35	45 – 55 ?

[8] likely to be used for future measurement, reporting and regulation of heavy duty vehicle CO_2 emissions.

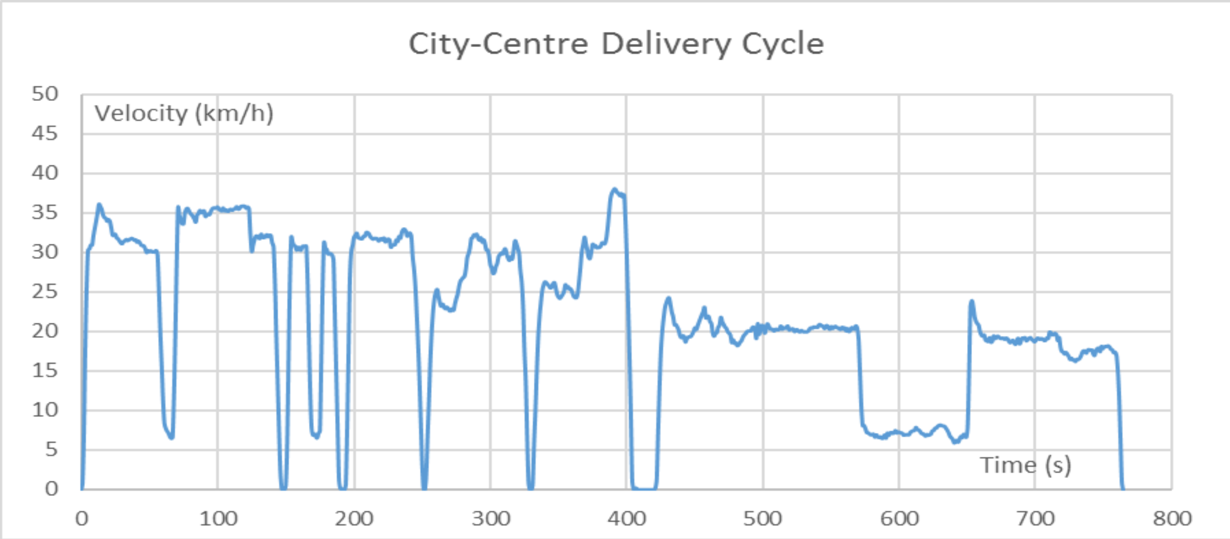


Figure 1. City-Centre Delivery Cycle

Dyno testing was completed to either the World Light-Duty Test Cycle (WLTC, for vehicles less than 3.5t gross weight) or the World Heavy-Duty Vehicle Cycle (WHVC, for vehicles with gross weight of 3.5t or over). To aid comparability between track and dyno testing, energy consumption and CO_2 emissions figures were normalised to the same kinetic intensities as used for the track-based cycles. Pollutant emissions were not normalised but the results from each phase (low, medium and high speed for WLTC and urban, suburban & motorway for WHVC) were allocated to the nearest equivalent track cycle.

3 Test results

The overall test matrix is shown in Table 2, consisting of the three test vehicles and the three diesel comparators, and the combinations of track-based and chassis dyno testing. Limited availability of the Euro VI 3.5t diesel van comparator (for Urb03) meant it was only possible to test this vehicle on the dyno. Dyno testing of the 7.5t range extender (Urb02) was also not possible, for similar reasons.

The range-extender vehicle (Urb02) provided for testing is a demonstrator vehicle fitted with a rather elderly (Euro 5) diesel car engine as the generator. While its fuel consumption, and thus equivalent CO_2 emissions, are likely to be broadly representative of the more modern engine types that would be likely to feature in future iterations of the technology, its pollutant emissions performance may not. These issues do not, of course, affect its (zero tailpipe) emissions performance in pure electric mode.

Table 2. Vehicle test matrix

Vehicle Code	Technology	Tests	Gross weight	Payload	Tested Weight
Urb01	Pure electric van (vs Euro 6 diesel van comparator)	Track & Dyno	2t	0.5t	2t
Urb02	7.5t electric truck with 1.6l diesel (car, Euro 5) engine range extender (vs 7.5t Euro VI diesel comparator)	Track & Dyno	7.5t	3.5t	6.5t
Urb03	Euro VI CNG dedicated-bas 3.5t van (vs Euro VI diesel van comparator)	Dyno only	3.5t	1t	3.5t

3.1 Electric Vehicles

3.1.1 Energy consumption, greenhouse gas emissions and range

The GHG emissions results for the two electric vehicles tested are shown in Table 3. The results for Urb02 relate to the vehicle operating in pure electric mode, i.e. without the range-extender engine in use and based on (plug-in) battery energy replenishment via the grid. This mode (referred to hereafter as “Mode 0”) is the only mode applicable to the pure electric van, Urb01. Electricity consumption is converted to GHG emissions using the current (2016) Defra reporting guidelines, based on UK average carbon-intensity of grid electricity of 449 g/kWh. Consumption here is defined as grid-supplied energy, which is the measured energy consumption of the battery during each test run divided by the (separately measured or estimated) charging efficiency. Where N_2O was measured (on the dyno, for the diesel equivalent vehicles), a Global Warming Potential of 298 is used to produce overall GHG emissions in CO_2e terms, in accordance with current reporting guidelines. For the track-based testing with PEMS, the CO_2e figures include only CO_2.

Urb01

It can be seen that the pure electric van (Urb01) delivers significant GHG savings over its diesel equivalent, particularly in the city-centre cycle. These conditions are particularly well suited to the electric vehicle, where it achieves low energy consumption (0.13 kWh/km), whereas the diesel equivalent is very inefficient in these low speed, transient conditions. It can also be seen that there is very good agreement between the track-based and dyno-based testing for the Urb01 vehicles, in that both methods found GHG savings of around 30% for the urban and regional cycles, and a little less than 60% for the city-centre cycle. The absolute values of energy consumption and emissions are notably higher under the dyno-testing conditions than was found on the track.

Assuming a usable battery capacity of 20 kWh, and a charging efficiency of 90%, the estimated ranges (maximum distance achievable between charges) for Urb01 are also shown in the Table. In city-centre operation, the range is estimated to be around 120 – 180 km, equivalent to about 6 – 8 hours of driving.

Table 3. Greenhouse gas emissions results (electric vehicles)

Vehicle Code	Cycle	Test vehicle emissions (g/km)				Diesel comparator emissions (g/km)			Overall GHG saving
(Test method)		CO_2 (tailpipe)	Electric (kWh/km)	Range (km)	CO_2e	CO_2		CO_2e	
Urb01 (Track)	CC	0	0.12	179	56	128		128	**56%**
	UD	0	0.18	123	81	117		117	**31%**
	RD	0	0.19	118	85	125		125	**32%**
Urb01 (Dyno, WLTC)	CC	0	0.18	122	82	192		195	**58%**
	UD	0	0.23	98	102	145		147	**31%**
	RD	0	0.25	90	111	150		151	**26%**
Urb02 (Track)	CC	0	0.43	156	194	520		520	**63%**
	UD	0	0.60	112	269	449		449	**40%**
	RD	0	0.61	110	274	442		442	**38%**
	LH	0	0.68	99	304	462		462	**34%**
Urb02 (Dyno, WHVC)	CC*	Vehicle not available for dyno testing				608		614	
	UD					513		518	
	RD					494		502	
	LH					473		482	

* The most kinetically intense phase of the dyno test cycle used had a KI of 1.5, so this figure is used for the CC cycle here

Urb02

In Mode 0 (battery only), the Urb02 vehicle delivers very similar performance to Urb01, both in terms of overall GHG saving percentages (around 60% for the city-centre cycle, 40% for urban and regional) and range (156 km under city-centre conditions, equivalent to around 7 hours of continuous driving). For this vehicle, the usable battery capacity is assumed to be 60 kWh, and the charging efficiency was measured at 89.3%.

This range-extender (RE) vehicle has three other operating modes, each drawing increasing amounts of power from the diesel range-extender engine/generator:

- Mode 1 – low revs, low noise, low power (measured at 7.5 kW)
- Mode 2 – medium revs, medium power (35.4 kW)
- Mode 3 – high revs, high noise, high power (57.4 kW)

The engine operates under steady-state conditions (constant RPM) for each of these modes. For a given duty cycle, at a given average speed, each mode can replenish a proportion of the energy being consumed by the battery. If that proportion is less than 100%, then operating in that mode can extend the maximum range between charges. If it is more than 100%, then there would be no need to plug-in at all (the vehicle could run indefinitely on diesel). The maximum ranges for each mode, and each cycle, are shown in Table 4.

Table 4. Effect of range extender modes on range, Urb02

Cycle	Mode 0		Mode 1		Mode 2		Mode 3	
(average speed, km/h)	Range (km)	RE CO_2 (g/km)	Range (km)	RE CO_2 (g/km)	Range (km)	RE CO_2 (g/km)	Range (km)	RE CO_2 (g/km)
City-Centre (23)	156	0	647	291	Unlimited	1230	Not required	
Urban Delivery (45)	112	0	155	149	Unlimited	629	Not required	
Regional Delivery (54)	110	0	143	124	Unlimited	524	Not required	
Long Haul (78)	99	0	115	86	297	363	Unlimited	624

For city-centre delivery operations, a daily mileage of up to 156 km can be completed in Mode 0, that is without any need for the range extender engine to be deployed. Deploying the range extender in Modes 1,2 and/or 3 is needed for any daily distances of above 156 km. In theory, constant operation in Mode 1 would allow a daily range of 647 km, but a more realistic maximum daily mileage for city centre operations would be, say, 250 km (roughly 11 hours of continuous driving at an average speed of 23 km/h). For this daily mileage, the vehicle would need to operate in Mode 1 for a minimum of 124 km, allowing the remaining 126 km to be completed in Mode 0. In Mode 2 (or 3), there is sufficient power from the RE to re-charge the battery while driving, so an alternative strategy could be to make use of that mode for short distances, but have additional Mode 0 miles available.

For the urban delivery cycle, the extra energy consumption required means that the RE engine in Mode 1 can only provide quite a small increase in range (from 112 km to a maximum of 155 km if running constantly in Mode 1). The Modes 2 and 3 power delivery are sufficient, however, to re-charge the battery so while daily mileages of between 112 and 155 km could be achieved either with increasingly frequent use of Mode 1 or less frequent bursts of Mode 2 to allow additional use of Mode 0. For daily mileages above 155 km, some combination of modes would be needed that involved Mode 2 or 3 deployment. Under these operating conditions (average speed 44 km/h), a realistic maximum daily range could be as high as 500 km.

Further analysis of the effects of these differing strategies under the city-centre and urban delivery cycles (the two of most direct relevance to operations within London) is discussed in the following section, reflecting not just the overall GHG impacts but those from air quality pollutant emissions also.

3.1.2 Pollutant emissions

Table 5 shows the emissions of air quality pollutants for the two diesel comparators for the electric vehicles Urb01 and Urb02. For the pure electric vehicle, Urb01, and the RE vehicle in Mode 0, there are, of course, no tailpipe emissions. The Urb01 diesel comparator vehicle, a similarly sized Euro 6 van, emitted about 0.5 – 0.8 g/km of NOx. As with the GHG results above, there is generally good agreement between the dyno and track-based results; the NO_2 results are very similar while the NOx emissions measured on the dyno are about 50% higher than those measured with PEMS on the test track.

Table 5. Pollutant emissions results

Vehicle Code	Cycle	Test vehicle emissions (g/km)				Diesel comparator emissions (g/km)				NO_x saving
		CO	NO_x	NO_2	PM	CO	NO_x	NO_2	PM	
Urb01 (Track)	CC	0	0	0		0.10	0.44	0.10		**0.44**
	UD	0	0	0		0.21	0.68	0.19		**0.68**
	RD	0	0	0		0.13	0.53	0.18		**0.53**
Urb01 (Dyno, WLTC)	CC	0	0	0	0	0.39	0.69	0.07	-	**0.69**
	UD	0	0	0	0	0.02	0.75	0.02	-	**0.75**
	RD	0	0	0	0	0.00	0.82	0.20	-	**0.82**
	Combined*	0	0	0	0	0.06	1.02	0.14	0.005	**1.02**
Urb02 (Track)	CC	0	0	0		0.25	0.67	0.02		**0.67**
	UD	0	0	0		0.10	0.39	0.00		**0.39**
	RD	0	0	0		0.10	0.12	0.00		**0.12**
	LH	0	0	0		0.13	0.07	0.00		**0.07**
Urb02 (Dyno, WHVC)	CC	Vehicle not available for dyno testing				0.09	0.67	0.06	-	
	UD					0.02	0.12	0.01	-	
	RD					0.00	0.02	0.00	-	
	Combined					0.03	0.22	0.02	0.003	

* The combined dyno cycle here includes the extra high speed phase of the WLTC, results from which have otherwise been excluded on basis of not being relevant to London delivery operations.

Despite carrying 7 times the payload, the larger Euro VI truck diesel comparator (for Urb02) produced similar quantities of NOx emissions under city centre conditions as the Euro 6 van, but much lower emissions under the urban and regional cycles. Both overall NOx levels and primary NO_2 emissions are lower. This provides some evidence of the effectiveness of the Euro VI emissions standards. Tests on the Euro 5 range extender engine for Urb02, operating in each of its 3 modes, revealed the NOx emissions results shown in Table 6.

Table 6. Effect of range extender modes on NOx emissions, Urb02

Cycle (average speed, km/h)	Mode 0		Mode 1		Mode 2		Mode 3	
	NOx (g/km)	NO2 (g/km)	NOx (g/km)	NO2 (g/km)	NOx (g/km)	NO2 (g/km)	NOx (g/km)	NO2 (g/km)
City-Centre (23)	0	0	3.3	1.6	18.7	4.0	22.1	1.2
Urban Delivery (45)	0	0	1.7	0.8	9.6	2.1	11.3	0.6
Regional Delivery (54)	0	0	1.4	0.7	8.0	1.7	9.4	0.5
Long Haul (78)	0	0	1.0	0.5	5.5	1.2	6.5	0.3

3.1.3 Modelling of Urb02 Emissions

The results shown above, combined with those from the preceding section allow the GHG and pollutant emissions performance of the Urb02 vehicle in different operating modes to be modelled. To simplify this modelling, three basic scenarios have been modelled:

- Scenario 1 – maximize use of the lowest modes. This means avoiding, as far as possible, use of Modes 3, 2 and 1 in that priority order.
- Scenario 2 – maximize use of Mode 0 through short bursts of RE if necessary, but at no higher than Mode 2.
- Scenario 3 – maximize use of Mode 0 through short bursts of RE if necessary, in Mode 3.

The modelling results, in terms of average equivalent per km CO_2 and NOx emissions are shown in Table 7. Daily mileages up to 250 km have been modelled for the city centre cycle, and 500 km for the urban delivery cycle. Cells highlighted in red indicate where the average emissions are the same or higher than the measured emissions of the Euro VI diesel equivalent vehicle.

Table 7. Modelling of Urb02 emissions, city-centre and urban delivery cycles

Cycle & daily km	Scenario 1			Scenario 2			Scenario 3		
	CO2e (g/km)	Mode 0 distance (km)	NOx (g/km)	CO2e (g/km)	Mode 0 distance (km)	NOx (g/km)	CO2e (g/km)	Mode 0 distance (km)	NOx (g/km)
City 100	194	100	0	194	100	0	194	100	0
City 150	194	150	0	194	150	0	194	150	0
City 200	235	142	0.95	227	188	1.14	231	192	0.83
City 250	265	127	1.62	250	224	1.96	258	234	1.43
Urban 100	269	100	0	269	100	0	269	100	0
Urban 150	336	13	1.53	322	121	1.85	330	132	1.34
Urban 200	375	0	2.92	362	133	3.21	375	159	2.33
Urban 250	397	0	3.78	385	145	4.03	401	185	2.93
Urban 300	411	0	4.35	401	157	4.58	419	212	3.32
Urban 350	422	0	4.75	412	168	4.97	432	238	3.61
Urban 400	430	0	5.06	421	180	5.26	442	265	3.82
Urban 450	436	0	5.30	427	192	5.49	449	291	3.99
Urban 500	440	0	5.49	432	204	5.67	455	318	4.12

The modelling indicates that from a NOx perspective, the range extender vehicle in its current guise (with a Euro 5 diesel car engine using pre-production calibration and having known injector synchronization issues) is only less polluting overall than the Euro VI diesel comparator if its daily mileage is low enough to allow continuous Mode 0 running. It is crucial to emphasize, however, that:

- The vehicle is capable of zero emission operation, so its NOx may be emitted in less sensitive areas, away from heavily populated areas.
- With a more modern car engine (Euro 6), properly calibrated and with the injector synchronization issue corrected, the NOx emissions can be expected to be at least 50% lower than from the current Euro 5 engine.

From a GHG perspective, the vehicle outperforms its Euro VI diesel comparator for all city-centre operations up to 250 km per day, and for all the urban delivery cycle operations under scenarios 1 and 2, but only up to about 400 km per day if deploying scenario 3.

Of the three scenarios modelled, Scenario 3, which maximizes Mode 0 operation by using short bursts of Mode 3, consistently generates the lowest overall NOx emissions. Scenario 2, on the other hand, which uses somewhat longer bursts of Mode 2 to extend the Mode 0 range instead of Mode 3, consistently generates the lowest overall CO_2 impacts. Scenario 1 emissions tends to sit somewhere mid-way between the other two scenarios. Overall, however, the differences between the individual scenarios are generally quite small, particularly for CO_2.

3.2 Gas Vehicle

3.2.1 Greenhouse gas emissions

The tailpipe greenhouse gas emissions for the CNG van (Urb03) and its Euro VI diesel comparator are shown in Table 8.

Table 8. Greenhouse gas results for gas-fuelled vehicle

Vehicle Code	Cycle	Test vehicle emissions (g/km)			Diesel comparator emissions (g/km)			Overall GHG saving
		CO_2	THC	CO_2e	CO_2	THC	CO_2e	
Urb03 (Track)	CC	343	0.03	344	Vehicle not available for track testing			
	UD	225	0.02	226				
	RD	236	0.02	237				
	LH	225	0.01	226				
Urb03* (Dyno, WHVC)	CC#	331	0.03	331	294	0.00	299	**-11%**
	UD	250	0.01	250	227	0.00	229	**-9%**
	RD	235	0.01	235	229	0.00	233	**-1%**
	LH	199	0.01	199	213	0.00	217	**8%**

* CO_2e figures include any measured contributions from N_2O.
# The most kinetically intense phase of the dyno test cycle used had a KI of 1.5, so this figure is used for the CC cycle here

Comparing gas consumption and diesel consumption, using the Carbon Balance Method, indicates that the spark ignition CNG vehicle incurred efficiency losses of between 20% (long haul) and 45% (city-centre). Despite negligible quantities of unburnt methane (THC) or N_2O from the CNG vehicle, therefore, and allowing for measured N_2O emissions of around 10 – 20 mg/km for the diesel vehicle, overall GHG impacts (tank to wheel, assuming 100% fossil fuel in each case) were slightly higher from the CNG vehicle than for the diesel comparator for the city-centre and urban delivery cycles, by about 10%.

The conventional Euro VI diesel van (Urb03) produced substantially higher GHG emissions than the smaller, lighter Euro 6 diesel van (Urb01). Comparing results from the dyno testing, the Euro VI van typically produced about 50 – 90% more GHG emissions, but since it was carrying double the payload, emissions per tonne-km carried would be slightly lower for the Euro VI vehicle in the City Centre cycle (by about 3%) and by over 20% for the urban and regional delivery cycles.

In these logistical efficiency terms of grammes per tonne-km, neither of the diesel vans can compete with the 7.5t diesel truck, Urb02. While its g/km emissions were found to be around twice those of the Euro VI van, it was carrying 3.5 times the load, meaning its g/tkm figures are around 40 - 50% lower in all the cycles than the Euro VI van. Even in these terms, however, the 7.5t diesel truck produces higher g/tkm than the pure electric small van under city centre delivery cycle conditions (and assuming grid average carbon intensity for the electricity). For the urban and regional cycles, the larger diesel truck is more carbon efficient in g/tkm terms.

3.2.2 Pollutant emissions

Pollutant emissions from the Euro VI CNG van and its Euro VI diesel comparator are shown in Table 9. For the Urban phase of the WHVC test cycle, overall NOx emissions were identical between the two vehicles (0.32 g/km), but the CNG vehicle produced notably lower emissions of primary NO_2.

For the Euro VI (heavy duty) diesel comparator, NOx emissions were found to be substantially lower than the smaller Euro 6 (light duty) diesel van, Urb01, by a factor of typically 3 – 4 (when comparing results from the dyno testing but ignoring the different test cycles used). Emissions of primary NO_2 were, however, found to be very similar between these two vehicles. Particulate emissions (not shown in the Table) were also notably lower for the Euro VI vehicle, by a similar factor, and in the range 1 – 5 mg/km.

Table 9. Pollutant emission results for gas-fuelled vehicle

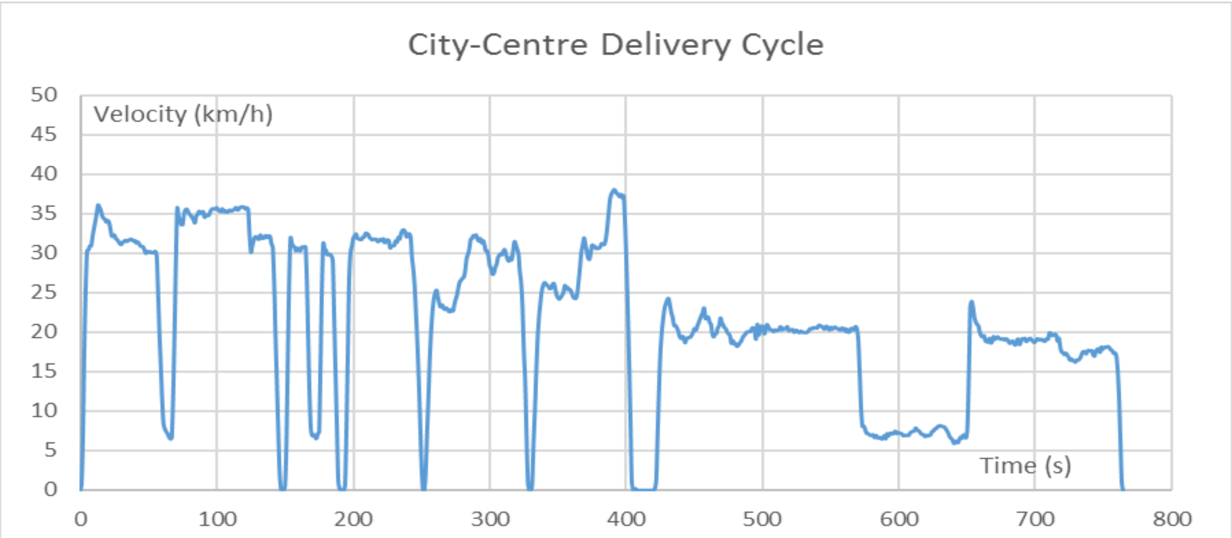
Vehicle Code	Cycle	Test vehicle emissions (g/km)			Diesel comparator emissions (g/km)			NO_x saving
		CO	NO_x	NO_2	CO	NO_x	NO_2	
Urb03 (Track)	CC	0.05	0.42	0.02	Vehicle not available for track testing			
	UD	0.10	0.38	0.01				
	RD	0.08	0.24	0.01				
	LH	0.08	0.13	0.00				
Urb03 (Dyno, WHVC)	CC/UD (Urban)	0.02	0.32	0.01	0.00	0.32	0.10	**0.00**
	RD (Suburban)	0.00	0.17	0.00	0.00	0.32	0.11	**0.15**
	LH (Motorway)	0.01	0.07	0.00	0.00	0.20	0.15	**0.13**

4 Conclusions

1. To examine some technologies and options of particular relevance to the capital, Transport for London have funded a LowCVP testing programme to develop a representative, city-centre test cycle and to assess the greenhouse gas and pollutant emissions performance of some emerging technologies relevant to urban and city-centre operations.

2. The available resources were deployed to cover what were considered to be the three technologies of greatest immediate interest and with the greatest short-term market potential. Each vehicle was compared with conventional diesel (Euro VI or 6) equivalents:
    - 1 pure battery electric 2t van (Urb01)
    - 1 plug-in series hybrid 7.5t truck with battery-electric drivetrain and diesel generator/range-extender (Urb02)
    - 1 natural gas (CNG) 3.5t van (Urb03)

3. Testing was carried out according to the protocols developed by LowCVP for its aftermarket technologies accreditation scheme, and using its regional delivery and urban delivery cycles. To adequately represent the heavily-congested, low speed operations typical of multi-drop delivery vehicles working in the city centre, a new cycle was developed as part of this test programme, as shown in the Figure below.



4. To supplement the track-based testing and provide additional data, dyno testing was completed to either the World Light-Duty Test Cycle (WLTC, for vehicles less than 3.5t gross weight) or the World Heavy-Duty Vehicle Cycle (WHVC, for vehicles with gross weight of 3.5t or over).

5. The pure electric van (Urb01) delivers significant GHG savings over its diesel equivalent, particularly in the city-centre cycle. The range for Urb01 is estimated to be around 120 – 180 km, equivalent to about 6 – 8 hours of driving under that duty cycle.

6. In Mode 0 (pure electric mode), the Urb02 vehicle delivers very similar performance to Urb01, both in terms of overall GHG saving percentages (around 60% for the city-centre cycle, 40% for urban and regional) and range (156 km under city-centre conditions, equivalent to around 7 hours of continuous driving).

7. This range-extender (RE) vehicle has three other operating modes, each drawing increasing amounts of power from the diesel range-extender engine/generator:
    - Mode 1 – low revs, low noise, low power (measured at 7.5 kW)
    - Mode 2 – medium revs, medium power (35.4 kW)
    - Mode 3 – high revs, high noise, high power (57.4 kW)

8. For the pure electric vehicle, Urb01, and the RE vehicle in Mode 0, there are, of course, no tailpipe emissions. The Urb01 diesel comparator vehicle, a similarly sized Euro 6 van, emitted about 0.5 – 0.8 g/km of NOx. Despite carrying 7 times the payload, the larger Euro VI truck diesel comparator (for Urb02) produced similar quantities of NOx emissions under city centre conditions as the Euro 6 van, but much lower emissions under the urban and regional cycles. Both overall NOx levels and primary NO_2 emissions are lower. This provides further evidence of the effectiveness of the Euro VI emissions standards.

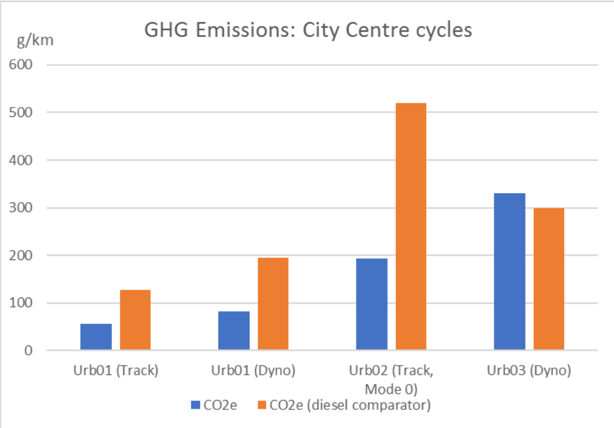
9. Modelling of the range-extender vehicle's performance for different daily mileages under the city-centre and urban delivery cycles indicates that from a NOx perspective, the range extender vehicle in its current guise (with a Euro 5 diesel car engine using pre-production calibration and having known injector synchronization issues) is only less polluting overall than the Euro VI diesel comparator if its daily mileage is low enough to allow continuous Mode 0 running.

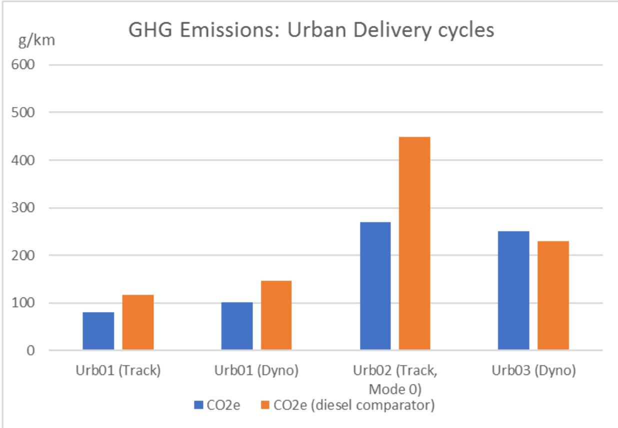
10. From a GHG perspective, the Urb02 vehicle outperforms its Euro VI diesel comparator for all city-centre operations up to 250 km per day, and for all the urban delivery cycle operations up to at least 500 km per day if use of Mode 3 is avoided.

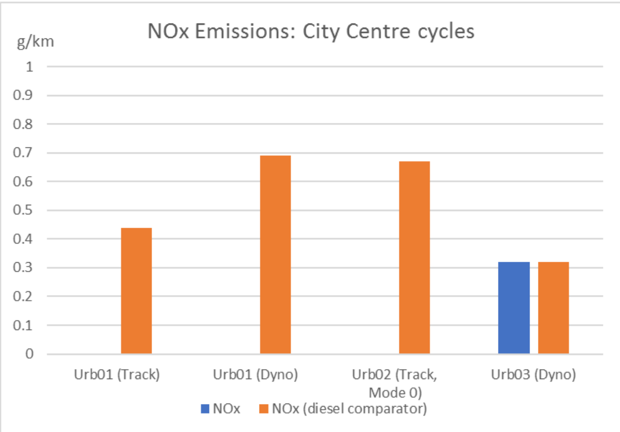
11. Despite negligible quantities of unburnt methane (THC) or N_2O from the CNG vehicle (Urb03), and allowing for measured N_2O emissions of around 10 – 20 mg/km for its diesel comparator vehicle, overall GHG impacts (tank to wheel, assuming 100% fossil fuel in each case) were slightly higher from the CNG vehicle than for the diesel comparator for the city-centre and urban delivery cycles, by about 10%.

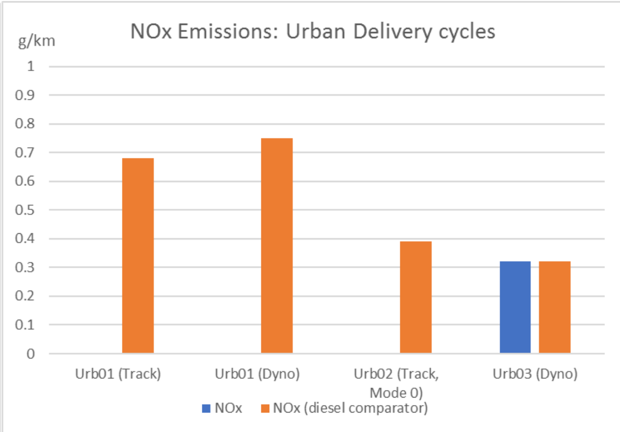
12. For the Urban phase of the WHVC test cycle, overall NOx emissions were identical between the CNG and equivalent diesel vehicles (0.32 g/km), but the CNG vehicle produced notably lower emissions of primary NO_2.

Summary graphs of the greenhouse gas and NOx emissions results from the city centre and urban delivery cycle tests are presented below.


GHG Emissions: City Centre cycles
g/km
600
500
400
300
200
100
0
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
CO2e
CO2e (diesel comparator)


GHG Emissions: Urban Delivery cycles
g/km
600
500
400
300
200
100
0
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
CO2e
CO2e (diesel comparator)


NOx Emissions: City Centre cycles
g/km
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
NOx
NOx (diesel comparator)


NOx Emissions: Urban Delivery cycles
g/km
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Urb01 (Track)
Urb01 (Dyno)
Urb02 (Track, Mode 0)
Urb03 (Dyno)
NOx
NOx (diesel comparator)