Development of test cycles and measurement protocols for a low carbon truck technology accreditation scheme

by

Brian Robinson and **Andy Eastlake**

Introduction

During 2014/15, the Low Carbon Vehicle Partnership (LowCVP), funded directly by the Office for Low Emission Vehicles (OLEV) and through in-kind donations from industry stakeholders, developed the test procedures and evidence base underpinning its accreditation scheme for aftermarket truck technologies ('the Scheme'). This report describes the progress made and the evidence gathered, with particular emphasis on the data analysis techniques deployed and developed, and proposes some further work to formally and successfully launch the Scheme and to help ensure its potential contribution to reducing the carbon footprint of UK road freight transport is fully realised.

Background & objectives

In 2010, LowCVP, with the Department for Transport (DfT) and other stakeholders identified a need for a scheme to provide confidence to truck operators that after-market, low carbon/fuel efficiency aids would deliver real savings under their particular real-world conditions. Work by TRL and Millbrook at that time, for LowCVP and funded by DfT, demonstrated the basic feasibility of such a scheme and outlined an initial certification scheme model[i].

In 2012 LowCVP published a report identifying the need for an independent accreditation/certification scheme to unlock the potential for significant uptake of retrofit technologies to reduce carbon in the existing fleet of HGVs. This study involved a series of interviews with fleet operators and other stakeholders, as well as an online survey. It concluded that the biggest barrier to uptake is uncertainty over the business case, in particular over the payback period, with also a significant lack of trust in technology providers' fuel economy claims and difficulty in measuring quite modest real world fuel savings being cited[ii].

Over the last few years the European Commission's research group has been working on methods to report (and potentially ultimately legislate) CO_2 from Heavy Duty Vehicles (HDVs). The focus is now on the Vehicle Energy Consumption Calculation Tool (VECTO), the computer simulation tool likely to form part of future type approval processes. VECTO is still under development but uses a range of simulated duty cycles for truck, bus, municipal and construction vehicles. Of particular relevance to the work described in this report are its Long Haul, Regional Delivery and Urban Delivery cycles. These cycles define particular journey profiles, on the basis of a pre-set distance, over defined terrain (up and down gradients), with target speeds defined for each section of the journey. The tool combines information about the route (i.e. vehicle speed and gradient) with a wide range of vehicle and engine parameters to calculate what it believes will be the fuel consumption for that vehicle, at various loading conditions, over the course of that journey.

In 2014, OLEV part-funding allowed LowCVP and its members (in particular, Millbrook and Horiba-Mira Ltd) to develop a solution for the UK which aims to relate to the EU activity and strategic direction, but "unlock" the UK market in the near term. The objectives of the work (described in the remainder of this report) were to:

- Develop a method by which to correlate test track-based duty cycles with those simulated by VECTO;
- Develop a set of test cycles that adequately represent typical UK operating duties and that correlate appropriately with the VECTO cycles;
- Test a range of aftermarket technologies to prove/validate the test cycles and assess the likely fuel/CO_2 savings;
- Develop robust data analysis techniques to adequately measure the likely savings within acceptable statistical uncertainty limits;
- Validate the test cycles and data protocols on at least two different test tracks;
- Engage with industry and other stakeholders to ensure the protocols developed have their support and backing.

Methodology

This section describes the techniques used during the research programme. These have been sub-divided into three areas; cycle correlation, track test procedures and, finally, test data analysis and reporting.

Cycle correlation

Most of the research literature regarding heavy duty vehicle test cycles focuses on correlating specific test cycles to specific real-world duty profiles or routes. Some work has been done in the USA, however, to examine the correlation between different test cycles. Of particular relevance to the LowCVP research is work on which cycle metrics correlate most strongly with vehicle fuel consumption and CO_2 emissions. Such metrics could then be used to ensure any track-based cycles used can be engineered to be representative of the VECTO cycles, for example, and to ensure test cycles at different test facilities can be shown to be equivalent, at least in terms of their likely resultant fuel consumption (litres per 100 km) and emissions (g/km) for a given vehicle.

Two research papers were found to be of particular significance. The first, by O'Keefe et al[iii], introduces the parameters Characteristic Acceleration (CA), Aerodynamic Speed (AS) and Kinetic Intensity (KI). All are derived from the basic road-load equation which is the summation of the power required to overcome:

1. Aerodynamic drag
2. Rolling resistance
3. Vehicle inertia
4. Gravitational potential energy

The characteristic acceleration measures the inertial work to accelerate and/or raise the vehicle. It is the positive part of the specific kinetic and potential energy per distance associated with moving a vehicle over a duty cycle. The characteristic acceleration reduces to the actual acceleration for a linear speed increase over constant grade.

The aerodynamic speed (or more accurately, the square of the aerodynamic speed) measures the ratio of the overall average cubic speed to the average speed. It is directly linked to the impact of aerodynamics on vehicle fuel usage. The aerodynamic speed for a constant speed cycle would be the constant speed of the cycle.

These two parameters (CA and AS) thus characterize the changes in speed and elevation over time for any given duty cycle. The third, parameter, kinetic intensity, combines CA and AS into one. KI is the ratio of the characteristic acceleration to the square of the aerodynamic speed, and is most commonly expressed in units of per km or per mile:

$KI = CA/AS^2$

The second paper, by Tu, Wayne and Perhinschi[iv], investigates the effects of drive cycle characteristics on distance-specific emissions (g/mile) and fuel economy (mpg) and determines the most influential cycle metrics for subsequent modelling work. Their results, from an analysis of twelve different truck and bus duty cycles, showed that average speed with idle, number of stops per mile, percentage idle, and kinetic intensity were the most important cycle metrics affecting emissions and fuel economy overall.

Of these, for truck duty cycles (as opposed to bus cycles), it is likely that only two would be of potential usefulness, namely average speed with idle and kinetic intensity, as truck cycles would tend to have very low numbers of stops per mile and percentage idle, and thus the range of values over which to correlate would be too small. Furthermore, average speed with idle is likely to be of much weaker correlation when changes in elevation are considered (the work by Tu et al was based on chassis dynamometer cycles that do not simulate changes in elevation), i.e. two cycles with the same overall average speeds but with one on flat ground and the other over hilly terrain would be unlikely to produce very similar fuel/emissions performance. For these reasons, kinetic intensity (KI) was selected as the likely most suitable cycle parameter to use for correlating the LowCVP track-based test cycles. It is recognised that KI is, strictly speaking, two parameters (CA and AS) and that the strength of the correlations may vary between these two, but for simplicity, KI was chosen as the parameter with which to start.

Researchers at Cambridge University[v] in the UK have also demonstrated good correlation between measured emissions of Nitrogen Oxides (NOx) and models based on dynamic cycle parameters such as Kinetic Intensity, and much weaker correlation with average speed models.

Track test procedures

For the track-based testing of vehicles, the procedures followed used essentially standard industry practices. These involved having two nominally identical vehicles, with one remaining unmodified and used as a control, e.g. for changes in atmospheric conditions, and the other being the test vehicle run first, in baseline configuration, unmodified and then again, with the technology under evaluation being fitted/operational. This 'back-to-back' test method leads to four data sets for each test cycle:

1. Control vehicle – baseline (CB)
2. Control vehicle – testing (CT)
3. Test vehicle – baseline (TB)
4. Test vehicle – testing (TT)

One of the wider objectives of the LowCVP certification scheme is to ensure any testing is affordable to as wide a part of the technology supplier community as possible. For this reason, testing was limited to two days, with the "baseline" tests on Day 1, and the "testing" tests on Day 2. Days 1 and 2 would not necessarily follow concurrently, depending, for example, on weather suitability and time needed to fit the technology. Three technology types have been tested as part of the scheme development process thus far; aerodynamic aids, alternative (dual) fuels, and low rolling resistance tyres.

Both the control and test vehicles were part loaded to have the same overall mass, varying between 30% and 90% of the maximum permitted payload, believed to be representative of typical UK operations. Each truck had a dedicated driver, and both trucks were driven around each cycle at broadly the same time, that is with one following the other but with sufficient distance between them to avoid any direct influences. Both vehicles were equipped with GPS-based, speed and position-logging equipment. The control vehicle was fitted with a fuel-flow meter, while the test vehicle was fitted with full PEMS (Portable Emissions Measurement System) kit, directly measuring tailpipe CO_2 emissions and many other (regulated) pollutants (as well as a fuel-flow meter).

The natural consequence of limiting the testing to two days was that only a limited number of runs for each cycle could be performed. This restricted the number of data points with which to perform the correlation analyses, but not to the extent that adequately repeatable, statistically valid results could not be produced. Additional mathematical techniques were used to further improve the robustness of the data gathered, described in the following sub-section.

Test data analysis and reporting

Three different approaches were used to assess the extent of any fuel savings/emissions reduction arising from the use of the technologies being evaluated. The first uses in-cycle averages, and is conventionally used by test houses, while the second has been developed specifically for the purposes of the LowCVP Scheme, and uses a KI regression analysis model derived from the test data across all three cycles. The third is a hybrid combination of these two approaches.

Method 1

The "in-cycle averages" technique, hereafter referred to as Method 1, uses the average fuel consumption (FC), or CO_2 measurements, found from each vehicle configuration, and for each cycle. The percentage savings between the average FC from the test vehicle in testing configuration and from the same vehicle in baseline configuration are calculated as discrete data sets between the three test cycles. Any differences in FC from the control vehicle between baseline and testing are subtracted from the savings (or added if FC was higher in testing than in baseline)[1]. Statistical validity can be further enhanced by ensuring the individual runs within a test cycle sequence are repeatable, by monitoring the overall average speed with idle (equal to the distance completed divided by the overall time taken to complete the run); with any outliers rejected.

The main drawback of this approach, however, is that there is no allowance made for any variations between tests in the exact cycle kinetic intensity. Given that KI is known to strongly correlate with FC, even quite small differences in average KI between vehicle configurations could potentially lead to differences in FC performance.

---

[1] An alternative method, not described fully here, only adds or subtracts the measured changes in average in-cycle control vehicle FC if those changes are statistically significant to a prescribed confidence level, e.g. 95%, using the Student's t test. Given the inevitably low number of test runs possible within the two-day test window, such detailed statistical tests were considered overly difficult to apply for the purposes of the Scheme. In particular, the test for statistically significant variations in control vehicle results was found to lead to inconsistencies between one cycle and another in whether the changes measured fed through into the final calculated savings.

Such differences could, for example, explain some or all of any apparent differences in control or test vehicle performance between baseline and test conditions and, unless allowed for, could lead to an over- or under-estimate of the savings being assigned to whatever technology is being evaluated. While good test practice (including the check for consistency in average speed with idle performance) helps to minimise such risks, it is unrealistic to expect each test run to be precisely the same as any other, especially within the context of developing an affordable test procedure that can be delivered within two days.

Method 2

Having established a high degree of linear correlation between FC (or CO2) and KI (as shown in the results section of this report), an entirely new approach (Method 2) was developed, based on KI regression analysis. Further details of this (and Method 1) are also provided in the results section of this paper, but in outline the technique involves correlating the measured FC (or CO_2) results against KI for each run, across all three cycles, and for each of the four vehicle configurations separately. The resulting graphical plots model the vehicles' performance against variations in KI. A best-fit regression equation is then derived for each configuration and used to calculate the modelled FC/CO_2 for the specific values of KI corresponding to the three test cycles. Percentage savings are then calculated in the same way as per Method 1. By modelling the variation of fuel/emissions performance with KI, this method can also be used to estimate the savings at other, intermediate values of KI, corresponding, for example, to other duty cycles of interest.

The main drawback of this approach, however, is felt to be that it forces the performance of each vehicle configuration into a purely linear model and thus potentially misses, or at least under-estimates, important variations within particular cycles. It is possible, for example, that some technologies will perform much better in low KI cycles that simulate long haul type operations rather than high KI cycles simulating more urban conditions, or vice-versa. Such non-linearities with KI could potentially be modelled using other, non-linear regression modelling techniques, but again within the context of few data points because of the limited number of test runs possible, such complications would be difficult to justify. It is also an important objective for the Scheme that the results presented, and the methods used to derive them, are credible and understandable to the wider stakeholder community, including technology suppliers and vehicle operators, further restricting the potential for overly-complex mathematical modelling.

Method 3

The third approach has been developed as a hybrid between Methods 1 and 2, with the intention of overcoming the drawbacks in each. As with the first two methods, further details are provided in the results section, but in outline this approach uses the slope of the linear regression line calculated as per Method 2 to make small corrections (allowances) for any variations in KI between the averaged FC (or CO2) results calculated as per Method 1. In this way, the results are based mostly on those derived by Method 1, which is the accepted and recognised industry standard, but making use of the linear KI regression model enhances the robustness of that approach by correcting for small variations in KI. In the extreme, if all the testing is done in such a way that the average KI value for each configuration is precisely at the target KI value for each cycle, then no corrections are needed and, in such circumstances, Method 3 is exactly the same as Method 1. A fundamental point in Method 3's favour, however, over Method 1 is that it does allow for what is believed to be appropriate use of the identified strength in KI to FC correlation. Potentially it has the further advantage that fewer test runs will need to be rejected, because as long as the KI and FC are known (and have been measured accurately), the results can still be used because a robust method of correcting the results is available.

Results

The following sub-sections present the results of the various testing and analyses performed. These are divided into four areas; test cycle to VECTO correlation, KI to FC correlation, the CO_2 savings achieved from the three technologies tested and, finally, the correlation between the two test tracks (Millbrook and Horiba-Mira Ltd).

Test cycle to VECTO correlation

An evaluation copy of the VECTO simulation tool was provided to LowCVP. This tool uses target-speed cycles as its input, and combines those with vehicle performance parameters to model a vehicle's second-by-second speed and elevation over the course of the cycle. The tool is currently able to model two generic truck types; a 12t rigid and 40t artic. The model can be run with the vehicles unladen, fully laden and partly laden at a pre-defined "reference" load. Because the performance of each vehicle varies according to the load carried and, of course, between different vehicles, the modelled cycles vary in their kinetic intensity, but not by very much

(Table 1). Although not broken down by specific vehicle configuration, the Table also shows the average CA and AS for each cycle; these too were not found to vary significantly.

The starting point for correlating these cycles with track-based cycles (initially at Millbrook) was some existing test cycles developed by Millbrook over recent years and thought to be broadly representative of UK operations. A test vehicle was driven around these cycles (which varyingly use their large loop and hill circuits) to gather per second speed and elevation data, and these data were used to calculate the KI, CA and AS values. Table 2 shows the results, with the initial Millbrook cycles named as MBK01 and the VECTO cycle values also shown.

Table 1. Calculated Kinetic Intensities and other parameters from VECTO simulations

Vehicle & loading	Long Haul	Regional Delivery	Urban Delivery
12t rigid - unladen	0.15	0.27	0.72
12t rigid - reference load	0.15	0.27	0.71
12t rigid - fully laden	0.15	0.27	0.71
40t artic - unladen	0.15	0.26	0.67
40t artic – reference load	0.15	0.25	0.67
40t artic – fully laden	0.15	0.24	0.67
Overall average KI (per km)	**0.15**	**0.26**	**0.69**
Characteristic Acceleration (CA, ms^{-2})	0.08	0.11	0.15
Aerodynamic Speed (AS, km/h)	82	75	53

Table 2. Initial Millbrook cycle parameter values

	Long Haul		Regional Delivery		Urban Delivery	
	MBK01	**VECTO**	**MBK01**	**VECTO**	**MBK01**	**VECTO**
Kinetic Intensity (per km)	**0.07**	**0.15**	**0.77**	**0.26**	**1.83**	**0.69**
Characteristic Acceleration (CA, ms^{-2})	0.04	0.08	0.16	0.11	0.27	0.15
Aerodynamic Speed (AS, km/h)	79	82	51	75	43	53

By a process of planned iterations, a series of modifications were then made to the Millbrook cycles to improve not only the KI matches to VECTO, but also the constituent CA and AS parameters. A further consideration was to ensure, as far as practicable, that the overall time needed for the three cycles did not increase too much, as this would cut down the number of individual runs that could be completed during a day's testing and thus might restrict the statistical validity (repeatability) of the resulting data. The three MBK01 cycles together totalled about 40 minutes of running time; by way of comparison, the VECTO simulated cycles involve a combined running time of almost 3 hours.

Table 3. Final Millbrook cycle parameter values

	Long Haul		Regional Delivery		Urban Delivery	
	MBK02	**VECTO**	**MBK02**	**VECTO**	**MBK02**	**VECTO**
Kinetic Intensity (per km)	**0.17**	**0.15**	**0.31**	**0.26**	**0.84**	**0.69**
Characteristic Acceleration (CA, ms^{-2})	0.09	0.08	0.11	0.11	0.19	0.15
Aerodynamic Speed (AS, km/h)	81	82	69	75	54	53

Table 3 shows the final iterations of the Millbrook cycles (labelled MBK02), with much closer correlations to the VECTO (target) values demonstrated. While it may have been possible to further refine the cycles to give even closer matches, these values were selected as being sufficiently close to VECTO while also retaining a good KI gap between each cycle (the difference between the VECTO Regional and Long Haul cycles is, for example, quite small) and having a good overall spread of KI values to work with (the wider this spread, the more potential there is for interpolating results for other cycles). It was also felt (by stakeholders consulted during the research) that the current (MBK02) cycle iterations were already sufficiently representative of UK operations. As the primary purpose of the accreditation scheme is to unlock the UK market for low carbon technologies, this feedback was fundamental to the decision not to attempt any closer matches to VECTO. The techniques developed, however, could be further utilised to achieve such matches in future.

The overall running time for the three cycles combined increased slightly to 45 minutes, but this did not materially affect the number of runs that could be performed in a single day.

In the latter stages of the research, and as part of the testing of one particular fuel saving technology, test cycles were also developed at Horiba-Mira Ltd (using their large loop). Here the intention was to match the Horiba-Mira cycles to the MBK02 cycles described above, rather than VECTO, to assess the extent to which similar cycles (in KI, CA and AS terms) at two different locations could produce similar FC performance for a given vehicle.

Table 4 shows the final set of Horiba-Mira cycles (labelled MIRA02), which were achieved after a similar process of planned iterations as described with the Millbrook cycles, and that show very close correlation to the MBK02 cycle values.

Table 4. Final MIRA cycle parameter values

	Long Haul		**Regional Delivery**		**Urban Delivery**	
	MBK02	**MIRA02**	**MBK02**	**MIRA02**	**MBK02**	**MIRA02**
Kinetic Intensity (per km)	**0.17**	**0.16**	**0.31**	**0.31**	**0.84**	**0.85**
Characteristic Acceleration (CA, ms^{-2})	0.09	0.08	0.11	0.11	0.19	0.18
Aerodynamic Speed (AS, km/h)	81	81	69	67	54	53

KI to FC correlation

Two techniques were deployed to validate the basic premise that kinetic intensity correlates strongly to fuel consumption for the cycles developed, as indicated by the research evidence described above. The first method used the VECTO tool to predict the fuel consumption performance of the two VECTO vehicles (12t rigid and 40t artic) over the full range of VECTO cycles (so including various bus and coach cycles, not just the three truck ones). The results are shown in the upper part of Figure 1. In the lower part, more detailed results from the 40t artic, at various loads, are shown for the three truck drive cycles and one of the bus cycles (used to extend the covered range of KI values, but not affecting the R^2 values).

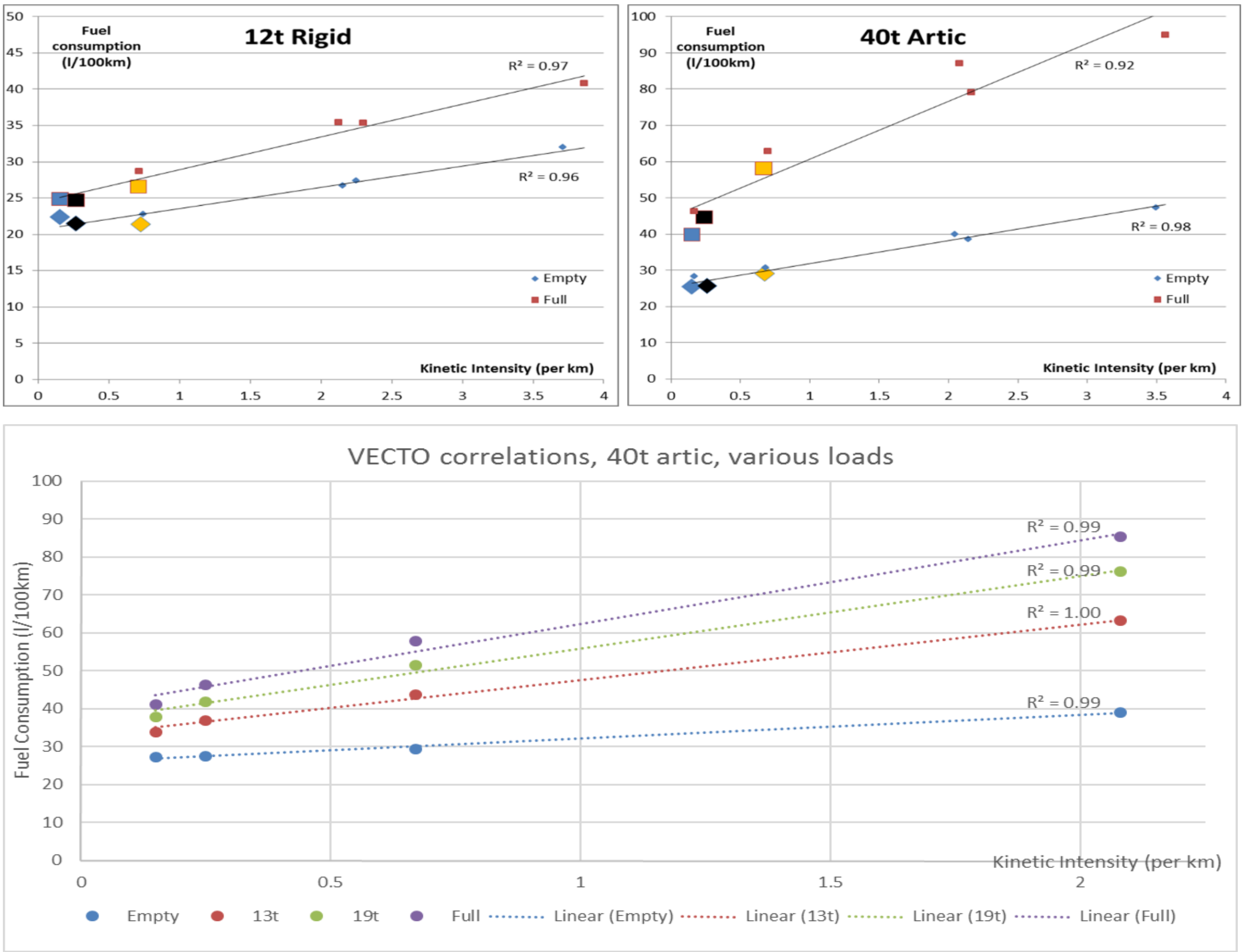


Figure 1. KI to FC correlations from various VECTO cycles (the larger icons indicate results from the three truck cycles – long haul, regional and urban in ascending order of KI)

While it must be pointed out that VECTO is still under development and there is little evidence, as yet available, to prove its ability to accurately predict real-world fuel consumption, there are uniformly strong linear correlations (R^2 values > 0.9) evident between the cycle KIs and the simulated FCs. It is also evident from the graphs that over the much lower and more restricted range of KIs relevant to the three truck cycles alone, the correlations may not be quite as strong. The differences, however, between the line-of-best-fit values (the straight lines shown on the graphs) and the actual simulated cycle values at these low KI's do not appear to conform to any consistent pattern, perhaps indicating that they are the result of attributes of the specific vehicle and component models within VECTO, rather than any more fundamentally systemic errors.

To investigate further the KI to FC correlations at low KI values, results were used from the full range of track tests, with six different vehicles and three technologies, one tested at two different test tracks. These together form a rich data set, potentially representative of quite a wide range of vehicle types and operating conditions.

For each test run of each test cycle, the FC and KI were measured or calculated. In some cases, the tailpipe CO_2 emissions were also measured. Once a complete set of runs for all three cycles had been completed, with a particular vehicle configuration (control/test vehicle in baseline/testing condition), the strength of the linear correlation between KI and FC (and CO_2 where possible) was assessed using the R^2 value of the line of best fit through the data points collected. The results are shown in Table 5. Note that vehicles A and B (aerodynamic aids tests) were subjected to the original Millbrook cycles, so cover a wider range of KI values than subsequent tests. This may help to explain the very high correlations found for those tests, but the correlations are generally strong (R^2 > 0.9) for most of the other tests also. The only exception was for the tyre testing at Millbrook, with two 18t rigid vehicles. Here the correlations were somewhat weaker, but still moderate (around 0.8 – 0.9). It is thought this slight weakening in the correlation strength, when compared to the other tests, may be due to the use of lighter (rigid) vehicles, which tend to have flatter best-fit lines, in that the FC rises less rapidly for a given increase in KI than was typical with the artics. This is illustrated in Figure 2, which shows (in the left hand graph) a KI vs FC plot for the 18t rigid vehicle which produced the weakest overall correlation (R^2 = 0.79). A plot showing the strongest correlation (from the near fully loaded 44t artic) is shown alongside.

Table 5. Linear correlations between KI and FC/CO_2 as measured during the track tests

Vehicle	Site	Test Condition	KI min	KI max	R^2 - FC	R^2 – CO_2
Aero testing:						
A – Scania 40t artic (30% load)	Millbrook	CB	0.18	1.90	0.98	
A – Scania 40t artic (30% load)	Millbrook	CT	0.18	2.09	0.99	
B – Scania 40t artic (30% load)	Millbrook	TB	0.16	1.98	0.98	0.96
B – Scania 40t artic (30% load)	Millbrook	TT	0.17	2.14	0.99	0.99
Dual-fuel testing:						
C – DAF 44t artic (90% load)	Millbrook	CB	0.16	0.84	0.97	
C – DAF 44t artic (90% load)	Millbrook	CT	0.16	0.86	0.98	
D – DAF 44t artic (90% load)	Millbrook	TB	0.14	0.81	0.97	0.97
D – DAF 44t artic (90% load)	Millbrook	TT	0.15	0.84	^	0.97
Tyre testing:						
E – Mercedes 18t rigid (70% load)	Millbrook	CB	0.16	1.00	0.79	
E – Mercedes 18t rigid (70% load)	Millbrook	CT	0.17	0.86	0.82	
F – Mercedes 18t rigid (70% load)	Millbrook	TB	0.17	0.82	0.90	0.97
F – Mercedes 18t rigid (70% load)	Millbrook	TT	0.17	0.91	0.89	0.93
E – Mercedes 18t rigid (70% load)	Horiba-Mira	CB	0.30*	0.88	0.99	
E – Mercedes 18t rigid (70% load)	Horiba-Mira	CT	0.15	0.82	0.94	
F – Mercedes 18t rigid (70% load)	Horiba-Mira	TB	0.15	0.84	0.93	!
F – Mercedes 18t rigid (70% load)	Horiba-Mira	TT	0.14	0.84	0.92	!
Overall average R^2 values					**0.94**	**0.97**

* All CB Long Haul runs were rejected, so KI min here relates to the Regional Delivery cycle tests

^ FC in this configuration not applicable (diesel and dual fuel combination)

! The Test vehicle at Horiba-Mira was equipped with only a fuel-flow meter, not PEMS, hence no CO2 correlations were possible

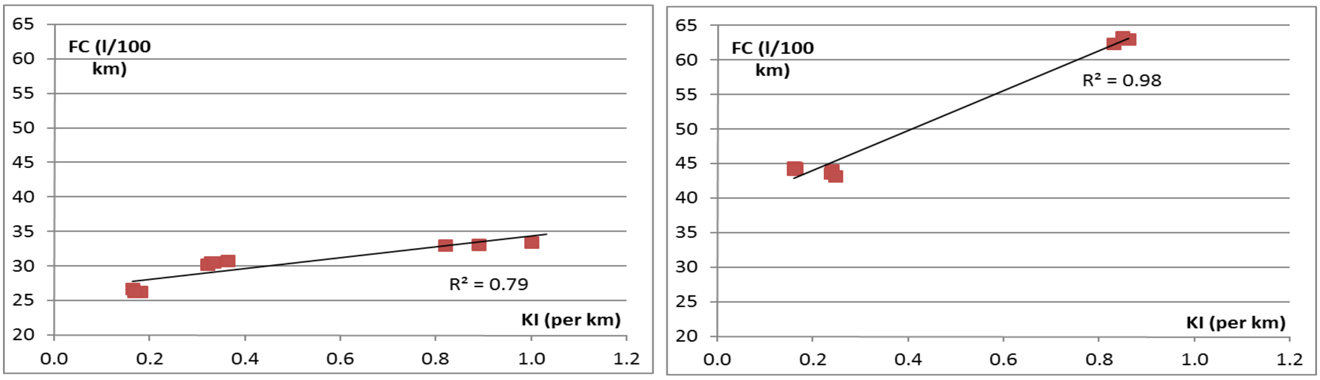


Figure 2. Examples of lowest and highest recorded correlations (within MBK02 cycles KI range)

CO_2 savings calculation methods

As discussed earlier, three basic methods were used to calculate the fuel/CO_2 savings achieved by the three technologies evaluated as part of the research programme.

Method 1 treats each set of results (from the four control/test vehicle and baseline/testing conditions) for each of the three cycles completely independently, and does not attempt to deal with any variations (e.g. in KI) between individual runs, except under extreme circumstances (e.g. if a run is interrupted in some way), in which case that run's data is rejected.

For each of the three cycles, Method 1 involves the following key steps:

1. Measure the average FC obtained from the control vehicle, in both baseline and testing conditions.
2. Measure the average FC (or CO_2) emissions from the test vehicle, in baseline and testing conditions.
3. Calculate the difference between the two (as a % saving) and add or subtract the calculated % difference in control vehicle FC performance, as appropriate.
4. The % saving becomes the headline result for that cycle.

So the percent saving for Method 1 = $100 \times (1 – (F_{TT}/F_{TB}) - (1-F_{CT}/F_{CB})) = 100 \times (F_{CT}/F_{CB} – F_{TT}/F_{TB})$

Where F_x is the averaged fuel consumption for each of the four vehicle configurations (CB, CT, TB and TT).

Method 2 combines together all the results from each of the four vehicle configurations, from all three cycles. The best-fit linear regression equations linking KI to FC (for the control vehicle) and KI to CO_2 (for the test vehicle, if measured, to FC if not) are calculated, and used to model the FC/CO_2 at the exact target KI values corresponding to the three cycles (0.17, 0.3 and 0.85 per km). The % differences between the so modelled test vehicle results are then combined with those from the control vehicle to derive the overall % savings, in the same way as Method 1.

One further potential enhancement to Method 2 would be to consider non-linear correlations, e.g. quadratic. This would have the effect of forcing the line of best fit more closely through the individual cycle averages, thus achieving higher R^2 values. Another option, yet to be fully explored, is to use some parts of the test cycles (known in the literature as "micro-trips"), with known KI and FC/CO_2 values, to widen the KI range over which the correlation equation is calculated.

Method 3 takes some elements from Method 2 to correct Method 1 for any variations in average KI from the target values. The full set of results for each vehicle configuration are used to produce linear regression models (exactly as per Method 2), but rather than use the full model, only the slope of the line is used to make a small upward or downward correction to the measured average FC/CO_2.

This is shown diagrammatically in Figure 3. The graph shows four imaginary data points from a series of tests under the urban cycle, with averaged FC and KI values as follows[2]:

CB: FC = 58 (at KI of 0.74), or F_{CB} =58 and K_{CB} = 0.74
CT: FC = 57 (at KI of 0.78), or F_{CT} =57 and K_{CT} = 0.78
TB: FC = 52 (at KI of 0.82), or F_{TB} =52 and K_{TB} = 0.82
TT: FC = 50 (at KI of 0.96), or F_{TT} =50 and K_{TT} = 0.96

The linear regression lines for each configuration are also shown in the Figure, which would be based on all the individual test run data points from all the long haul, regional and urban cycle tests.

For Method 1, we simply measure the change in fuel consumption between TT and TB, and subtract any change measured between CT and CB, while ignoring the variances in KI.

So % saving for Method 1 = 100 x ($F_{CT}/F_{CB} – F_{TT}/F_{TB}$) = 100 x (57/58 – 50/52) = 2%

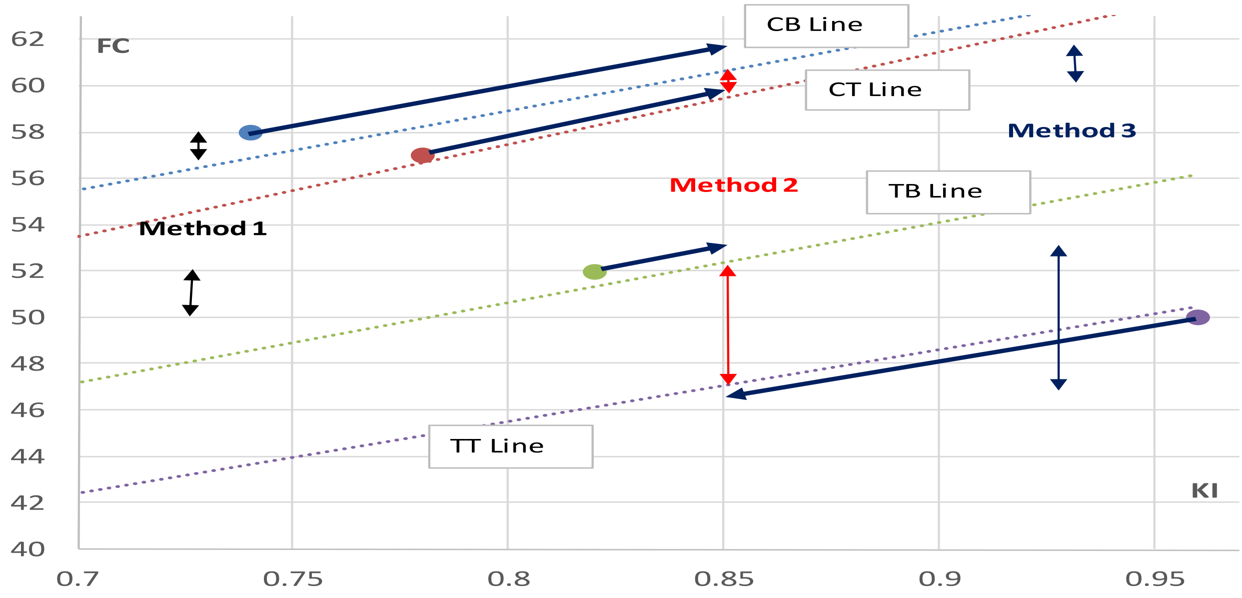


Figure 3. Illustration of Methods 1, 2 and 3

For Method 2, we make use of the regression lines for each vehicle configuration to estimate the FC values at the target value of KI (in this case 0.85). The values are thus those at the points of intersection between the regression lines and the KI = 0.85 line on the graph, while ignoring any variations between the actual measured points for the particular cycle in question and the linear regression line of best fit derived from all the data points from all the test cycles:

F_{CB} =60.5; F_{CT} =59.5, F_{TB} =52.5, F_{TT} =47

So % saving for Method 2 = 100 x ($F_{CT}/F_{CB} – F_{TT}/F_{TB}$) = 100 x (59.5/60.5 – 47/52.5) = 9%

Method 3 uses the slope of the appropriate regression line to correct for variations between the actual average KI of each data point and the target value, but retains any differences in FC between the measured data and that modelled, and thus accounts to some extent for any possible non-linearities in the results. The Figure above shows how the measured data points are adjusted by the arrows moving parallel to each regression line:

F_{CB} =61.5; F_{CT} =60, F_{TB} =53, F_{TT} =46.5

So % saving for Method 3 = 100 x ($F_{CT}/F_{CB} – F_{TT}/F_{TB}$) = 100 x (60/61.5 – 46.5/53) = 10%

---

[2] In practice, such wide variations in average KI are unlikely within a controlled and managed test programme, with professional test drivers driving a prescribed and highly repeatable drive cycle; the figures used here are exaggerated simply to better illustrate the differences between the methods.

CO_2 savings achieved

The full set of test results are summarised in Table 6. Where two sets of results are shown for each method; the first relates to the Fuel Consumption results (from a fuel-flow meter) and the second to the tailpipe CO2 (from PEMS). Only the CO2 results are shown for the Dual Fuel tests, and only the FC results are shown for the tyre tests at Horiba-Mira (PEMS was not used for those tests).

It can be seen that the savings measured are generally quite small, and their magnitude depends on the test cycle, the parameter being measured and the method used to calculate them. A detailed review of all these results is beyond the scope of this short summary paper, but there is generally no better than reasonable agreement between the three methods; very good agreement for the dual-fuel tests, but much less so for the aero and, to a slightly lesser extent, tyre testing. That said, the methods are all in agreement at least to within 5% in the worst case. The (later) tyre testing at Millbrook showed very good agreement between the FC and CO_2 results, whereas there were appreciable differences found from the (earlier) aero test data. This may reflect growing confidence and expertise in the calibration and interpretation of PEMS data, rather than any fundamental differences between the two measurement techniques (which would normally be expected to produce very similar/equivalent savings).

Table 6. Calculated CO_2 savings from the three technologies evaluated

Technology/Cycle	**Test Site**	**Method 1**		**Method 2**		**Method 3**	
		FC	**CO_2**	**FC**	**CO_2**	**FC**	**CO_2**
Aero testing:							
Long Haul	Millbrook	**2 %**	**4 %**	**6 %**	**9 %**	**2 %**	**5 %**
Regional Delivery	Millbrook	**6 %**	**7 %**	**4 %**	**6 %**	**6 %**	**8 %**
Urban Delivery	Millbrook	**1 %**	**1 %**	**1 %**	**2 %**	**1 %**	**2 %**
Dual-Fuel testing:							
Long Haul	Millbrook		**2 %**		**3 %**		**2 %**
Regional Delivery	Millbrook		**3 %**		**3 %**		**2 %**
Urban Delivery	Millbrook		**2 %**		**2 %**		**2 %**
Tyre testing:							
Long Haul	Millbrook	**4 %**	**4 %**	**2 %**	**2 %**	**4 %**	**4 %**
Regional Delivery	Millbrook	**3 %**	**3 %**	**3 %**	**3 %**	**2 %**	**2 %**
Urban Delivery	Millbrook	**2 %**	**2 %**	**5 %**	**5 %**	**5 %**	**6 %**
Long Haul	Horiba-Mira*	**10 %**		**9 %**		**9 %**	
Regional Delivery	Horiba-Mira	**9 %**		**9 %**		**8 %**	
Urban Delivery	Horiba-Mira	**10 %**		**11 %**		**11 %**	

* NB – The control vehicle baseline runs on the long haul cycle were all rejected so CB is assumed to be the same as CT (the TB and TT runs were actually performed on the same day so this is considered a reasonable assumption)

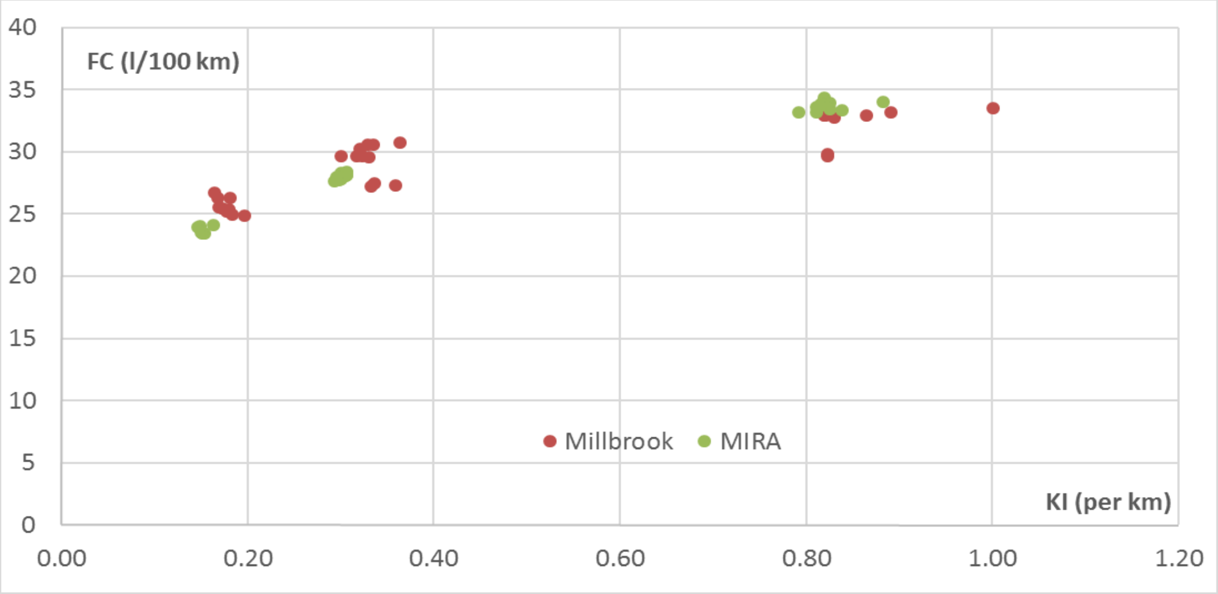
This degree of variation/uncertainty in the likely savings achievable is quite possibly a reasonable representation of the inherent variability in performance of any low carbon technology – aero kits, alternative fuels, tyres and the like will also exhibit different performance as the circumstances vary, e.g. between different vehicles, drivers, routes, loads and weather conditions. In that context, a scheme that attempts to predict precise savings to a very tight margin of error is unlikely to be accurate for the majority of real-world operations. Instead, one that can give broad, but more widely realistic, likely ballpark savings figures may well be more robust and achieve wider respect within the industry.

Millbrook to Horiba-Mira correlation

The tyre testing results obtained from Horiba-Mira were significantly better (higher FC/CO_2 savings) than those measured at Millbrook. These differences may be due to the different track layouts and/or track surfaces used at the two sites, or to the different age/mileage of the tyres being tested, rather than any fundamental problems with the procedures or measurement protocols.

The more fundamental issue with regard to the testing of the 18t rigid vehicles at Millbrook and Horiba-Mira Ltd was to evaluate whether the cycles developed at each site, with similar KI values, would produce comparable fuel consumption performances. The results are shown in Figure 4. The top graph shows the combined results from all the CB, CT and TB tests, while the test vehicle in testing condition, TT (i.e. the configuration with the low rolling resistance tyres fitted), is shown separately, below. While a direct comparison is not appropriate as testing was done on different days (as well as with different drivers), the following observations can be made:

- There is good overall agreement between the FC measurements at the two test sites. The strength of the correlation (if all the points were plotted as one data set) is remarkably good (R^2 of 0.83 for the vehicles with standard tyres fitted and 0.87 for the test vehicle with LRR tyres fitted), despite the unavoidable variations in test conditions;
- What scatter there is (e.g. the test vehicle, baseline results at Millbrook being a little lower than the Horiba-Mira equivalents for the urban cycle) does not show any consistent patterns across all three cycles;



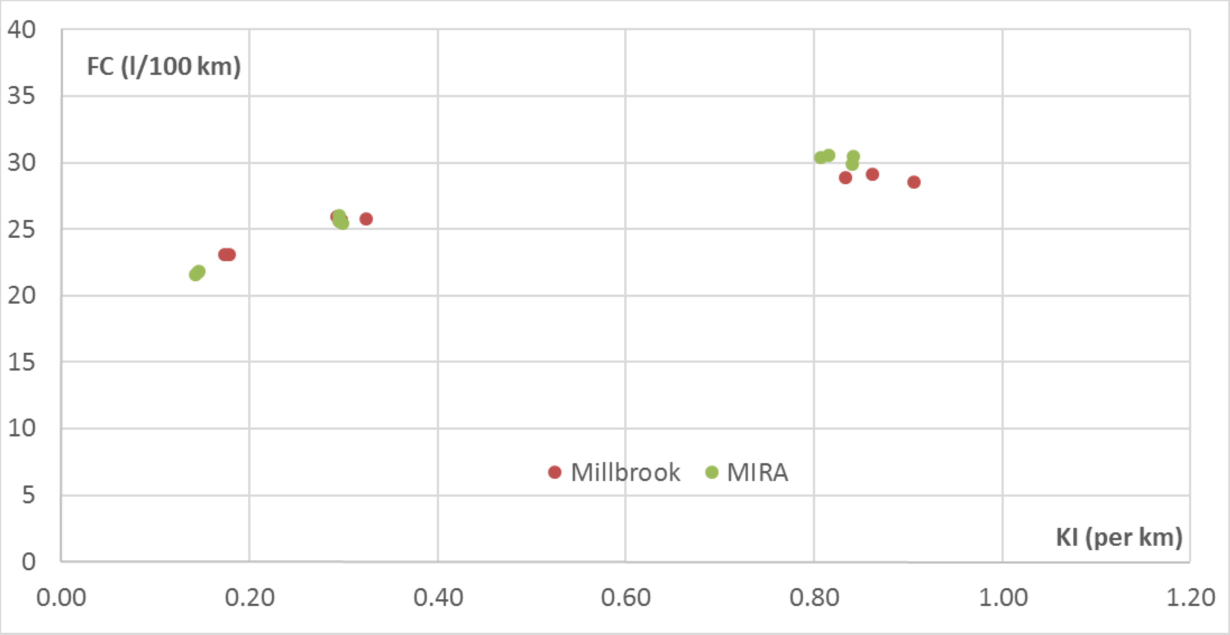


Figure 4. Horiba-Mira to Millbrook comparison of FC measurements for the Control and Test vehicles in Baseline condition (above) and Test vehicles with LRR tyres fitted (below)

Conclusions

The testing and methodology development described above shows that significant progress has been made in building a robust, credible scheme for the industry to use. Most fundamentally, the work has demonstrated that fuel-saving/low carbon truck technologies are able to generate measurable savings under controlled laboratory test conditions, over cycles that correlate well at different test sites and that are likely to represent the long haul, regional and urban delivery operations typical of many UK operations. The test cycles also correlate well with those being developed by the European Commission as part of the VECTO development process. In that sense, the Scheme is ready for wider adoption and the commercial testing of technologies.

In day-to-day operations on real vehicles, such technologies are likely to generate a range of savings, depending on the particular circumstances. A scheme that recognises that variability and that provides a broadly reliable indication of the likely savings is likely to be more useful than one that attempts to give a very precise, but often inaccurate, savings value.

The research has worked with the concept of Kinetic Intensity as a duty cycle parameter and shown that it correlates very well with fuel consumption and CO_2 emissions over the range of truck cycles of interest. Over this range, the correlation seems to be sufficiently close to linear for a linear regression model to be usable, at least to some extent (Method 3). As well as being used to demonstrate the correlation between different test sites and cycles, it has also been used as a modelling tool to predict performance in other operational conditions.

The test and data analysis methods developed, while designed for the purposes of an aftermarket technology accreditation scheme, could also be applied to whole vehicles, e.g. to carry out a thorough greenhouse gas emissions analysis of gas-powered vehicles, whether they be utilising OEM or retrofit technologies.

Other potential enhancements to the methodology developed include extending the range of test cycles, e.g. to cover a relatively high kinetic intensity, city centre parcel delivery type operation, and adapting the protocols for a wider range of technologies and vehicle types, e.g. hybrid vehicles, refuse collection vehicles and vehicle ancillaries such as refrigeration units and compactors.

As experience develops with the testing and data analysis protocols, so further refinements to the methodologies can be made. In particular, it would be useful to develop a clearer understanding of how the technologies perform in real-world usage, so that the correlation between that performance and that predicted by the testing can be properly assessed.

References

---

[i] *Low Carbon HGVs - Technology Accreditation and Whole Vehicle Integration Study, Final Report*. B Robinson, S Greenshields, D Pickavance & C Bowser, TRL Ltd Client Project Report CPR879, September 2010.
Low Carbon HGVs - Technology Testing Study, Final Report. B Robinson (TRL) & L Kennedy (Millbrook), TRL Ltd Client Project Report CPR881, September 2010.

[ii] Opportunities to overcome the barriers to uptake of low emission technologies for each commercial vehicle duty cycle. Duncan Kay & Nikolas Hill, Ricardo-AEA Report ED58189, November 2012.

[iii] *Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications*. Michael P. O'Keefe, Andrew Simpson, Kenneth J. Kelly & Daniel S. Pedersen, presented at the 2007 SAE World Congress. SAE Paper No. 2007-01-0302.

[iv] *Correlation Analysis of Duty Cycle Effects on Exhaust Emissions and Fuel Economy*. Jun Tu, W. Scott Wayne, and Mario G. Perhinschi, Journal of the Transportation Research Forum, Vol. 52, No. 1 (Spring 2013), pp. 97-115.

[v] *Are We Making the Best Use of PEMS Data? Emissions Factors Based on Average Speed and Vehicle Specific Power*. Presentation by Adam Boies, Nick Molden and Justin Bishop to Centre for Sustainable Road Freight meeting, 16th March 2016.

Acknowledgements

The testing and analysis reported in this paper could not have been completed without the funding, expertise and support of a wide range of organisations. In particular, the authors would like to thank the Department for Transport, the Office for Low Emission Vehicles, the Centre for Sustainable Road Freight, Millbrook, Horiba-Mira Ltd, Cenex and Transport & Environment.