Modelling the Effect of Road Grade on the CO_2 and NO_x Emissions of a Passenger Car through a Real World-Urban Traffic Network

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Abstract

A Portable Emission Measurement System (PEMS) was utilised to record the on-road Carbon Dioxide (CO_2) emission of a EURO 4 petrol vehicle over 48 test runs through an urban-traffic network. The tests were conducted over a 780 metre micro-scale road segment between Headingley and the City of Leeds, UK, with measurement on both the inbound (Section A) and outbound lanes (Section B). The monitored test runs were conducted under a range of traffic flow conditions from heavily congested to free-flowing traffic.

Vehicle exhaust emission simulations using an instantaneous power-emission model have the capability to generate estimates of real-world vehicle emissions over micro-scale road sections. The Technical University of Graz's (TUG) Passenger car and Heavy duty Emission Model (PHEM) was used to calculate a CO_2 emission estimate for each of the 48 test runs through Sections A and B. The model CO_2 emission estimates were then compared to the real-world PEMS emission measurements, to determine the accuracy of the modelling methodology.

Whilst instrumented vehicles can adequately capture second-by-second (1Hz) absolute position and vehicle speed there is significant instrument error in the measurement of real-world elevation using a Global Positioning System (GPS) as part of a PEMS set-up. These errors make it very difficult to accurately calculate a 1Hz road grade with GPS systems. However, as road grade can have an important influence on engine power demand and hence fuel consumption and exhaust emission it is essential to include a representative road grade estimate for micro-scale emission estimation.

Rather than using a GPS recorded elevation, this study developed a simple road grade estimation methodology which employs Geographic Information System (GIS) software to interpolate the elevation at each second of PEMS data from a 5-metre resolution Digital Terrain Map (DTM) derived from Light Detection And Ranging (LiDAR) data. The method applies an algorithm to compute the road grade from the LiDAR-GIS elevation values and vehicle speed, and alleviates errors resulting from absolute position measurement inaccuracy of the GPS at low speed.

The addition of the LiDAR-GIS road grade to the PHEM modelling was found to improve the accuracy of the PHEM estimate of the PEMS measured real-world CO_2 emission. From the 48 test runs the average PHEM estimate (including road grade) of the real-world measured CO_2 emission through Section A was 93%, and through Section B was 94%. Of the total 96 test runs over Section A and B 91% of the PHEM estimates were between 80% and 110% of the PEMS recorded value.

In further analysis, an assessment of the effect of road grade on both CO_2 and NO_x emission was conducted. Sections A and B were combined for each test run to form Segment AB, which has a net flat road grade. The PEMS recorded speed profiles for each of the test runs through sections A and B were input into PHEM and emission estimates generated under four road grade scenarios. The scenarios were formed by decreasing and exaggerating the LiDAR-GIS road grade for each second of data, multiplying it by coefficients of 0 (flat), 0.5 (half the grade), 1, and 2 (double the grade). The results indicate that assuming a flat profile in PHEM would result in an average underestimate of the segment emission by 2.7% for CO_2 and 7.0% for NO_x when calculated with road grade, and by 7.9% for CO_2 and 20.4% for NO_x were the road grade doubled.

The method developed in this study provides a simple methodology for calculating 1Hz road grade, and has been shown to improve the modelling of CO_2 emission for this data set. This

research suggest that using the PHEM model with a LiDAR-GIS calculated road grade provides a practical method for accurately estimating real-world micro-scale emission.

On-road emission monitoring by PEMS is scheduled to be introduced for Euro 6c type approval from September 2017. In order to accurately determine road load during the real-world test procedure it will be important to develop a suitable methodology for calculating a 1Hz road grade.

Introduction

The latest generation of emission models such as the US Environmental Protection Agency's MOVES (Koupal et al., 2004) and the Technical University of Graz's PHEM (Hausberger, 2003) generate emission estimates by referencing a calculated engine power output to a calibrated mass emission for each second of data.

An estimate of second-by-second engine power output can be determined from a 1Hz measure of vehicle speed and road grade along with specification data for the test vehicle. Equation 1 calculates Vehicle Specific Power (VSP) which is used as the measure of engine power output at each second in MOVES. PHEM employs a similar equation to determine engine power.

$$\mathrm{VSP} = \mathrm{v} \cdot [(1.1\mathrm{a}) + (\mathrm{g} \cdot \sin(\arctan(\mathrm{r}))) + (\mathrm{g} \cdot \mathrm{C_R})] + \left[(\rho_\mathrm{a} \cdot \mathrm{C_D} \cdot \mathrm{A})/(2\mathrm{m})\right] \cdot \mathrm{v}^3 \qquad (1)$$

Where v is vehicle speed (m/s); a is the vehicle acceleration (m/s^2); g is the acceleration due to gravity (m/s^2); r is the road grade (dimensionless); C_R is the coefficient of rolling resistance for the vehicle (dimensionless); ρ_a is the ambient air density (kg/m^3); C_D is the drag coefficient of the vehicle (dimensionless); A is the frontal area (m^3); and m is the vehicle mass (kg).

Engine power output has been shown to be highly correlated to the second-by-second exhaust emission of various species including CO_2 and NO_x (Coelho et al., 2009). Fig.1 shows the approximately linear increase in average CO_2 emission at each integer increase in VSP and the low rate of emission with negative VSP (where the vehicle is decelerating), recorded by the test vehicle used in this study.

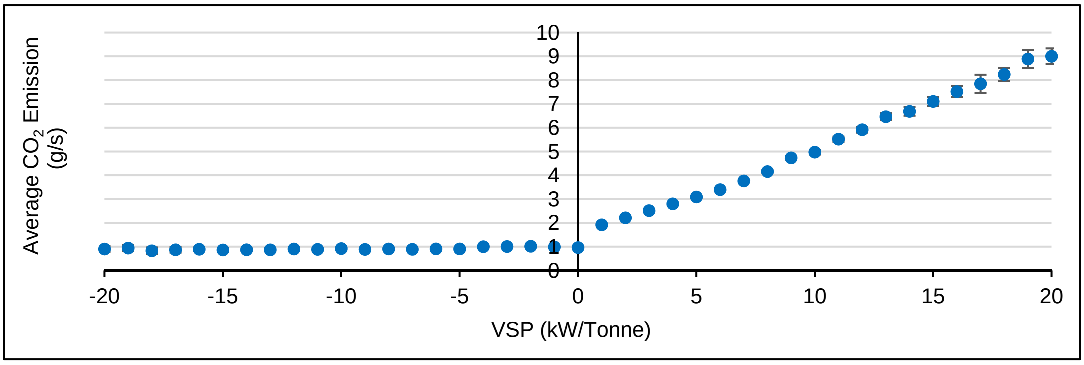

Figure1: Average CO_2 Emission at each VSP (EURO4 Passenger Car 57037s of data)

Based on the principle that a vehicles emission is broadly consistent at similar points of engine operation, power-based models employ engine maps, derived from second-by-second PEMS and chassis dynamometer testing, which describe the average fuel consumption and exhaust emission for each discrete engine power output, specific to the vehicle type and fuel. The discrete engine power modes are further stratified, in PHEM by engine speed and in MOVES by vehicle speed. Therefore in PHEM for each second of a real-world driving the combination of calculated engine power output and simulated engine speed can be used to interpolate, from engine maps specific to the test vehicle type, a rate of pollutant emission.

As described in Equation 1, road grade forms part of the engine power output calculation due to the influence of gravity on the vehicle. On downhill sections, with negative road grade, gravity acts to accelerate the vehicle, reducing the necessary power output from the engine, causing a concomitant decrease in fuel consumption and CO_2 emission. On uphill sections, the force of gravity acts to decelerate the vehicle requiring increased engine power to maintain a constant speed. As a result neglecting to include road grade or using an inaccurate grade can lead to an inaccurate estimate of engine power output and cause an erroneous over or underestimation of exhaust emission from the power emission model.

The 1Hz road grade required for second-by-second power calculation in PHEM, to generate emission estimates, is very difficult to determine accurately using GPS measurements from a PEMS. The GPS instrument in this study had an elevation measurement 95% Circular Error Probability (CEP) of 10 metres, meaning that the measured height is within 10 metres of the true position 95% of the time (Racelogic, 2008). The instrument imprecision, combined with measurement errors resulting from signal interference, rendered the raw recorded GPS height insufficiently accurate for 1Hz gradient estimation.

This paper proposes a simple LiDAR-GIS methodology (Wyatt et al., 2014) to calculate a road grade estimate for each second of PEMS data. Using this method, this reported work seeks to test the validity of using the PHEM model with LiDAR-GIS grade to estimate micro-scale emission by comparing the PHEM estimate of the total CO_2 emission through a real-world micro-scale section (utilising the PHEM estimates generated from the PEMS measured second-by-second vehicle speed and the corresponding LiDAR-GIS road grade) to the PEMS recorded section total CO_2 emission. Further, the study investigates the effect of omitting road grade from the PHEM calculation of vehicle emissions over a net flat (average road grade of 0) road segment.

Methodology

Test Vehicle. A EURO 4 compliant petrol Ford Mondeo was used as the test vehicle in this research. The vehicle had a port fuel injected 1.8 litre, 4 cylinder, 16 valve spark ignition engine with a maximum power of 92 kW (125 PS) at 6000 rpm, a 5-speed manual gearbox and a three way catalyst.

The vehicle specification data used in the power-emission modelling are a rolling resistance coefficient of 0.013 (Ehsani et al., 2009); a kerbweight (with 90% fuel levels, full fluid levels and a 75kg driver) of 1374kg (Li et al., 2008); an aerodynamic drag coefficient of 0.32 and vehicle frontal area of 2.3m^2 (Doucette and McCulloch, 2011); an idle engine speed of 850rpm; and a loading of 150kg for the PEMS equipment.

Study Design. The test route for this study was a 780m segment of single lane urban arterial road between the suburb of Headingley and the city of Leeds in the UK (Fig.2). The maximum speed limit in the test area is 48 km/h. The test route was completed 48 times with PEMS measurements taken on both the Headingley inbound (A) and outbound (B) lane during each test run.

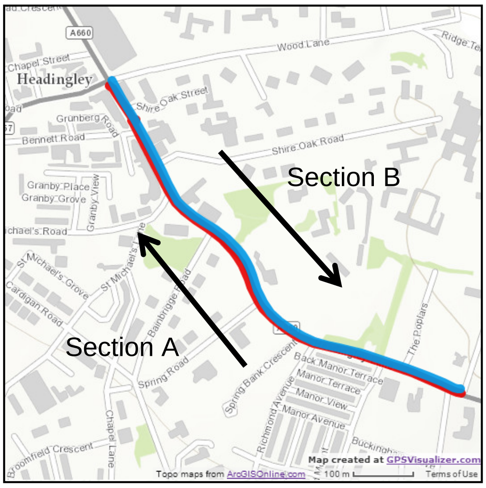

Figure 2: Headingley Test Sections (GPSvisualizer, 2014)

Test runs were conducted between 07:30 and 21:00 over a week long testing period from the 26th February 2007 to the 5th March 2007 in order to capture the complete range of traffic flow conditions for this network, from 'heavily congested' to 'free-flowing'. The tests were carried out in a variety of weather conditions with ambient temperatures from 1°C to 15°C. The variation in ambient conditions and different traffic situations encountered on each test run were uncontrollable factors which resulted in run-to-run variation in fuel consumption and exhaust emission during test data collection.

Test Vehicle Instrumentation. A Horiba On Board Emissions Measurement System (OBS-1300) with a Non-Dispersive Infra-Red analyser (HNDIR) was used to measure the exhaust mass flow rate and the air/fuel ratio and to record a volumetric measure of CO_2 exhaust emission, from which the mass emission of CO_2 could be calculated (Equation 2). A RaceLogic VBOX II GPS engine and data logger was used to record absolute position, vehicle speed and acceleration. The PEMS also included a dedicated power supply unit. All data were recorded at 1Hz.

Time alignment of the OBS and VBOX was conducted using the velocity data measured by each instrument and exhaust flow measurement drift was corrected where required (Ropkins et al, 2007).

CO_2 Mass Emission Calculation. In order to convert the OBS measured percentage concentration of CO_2 in the exhaust emission to CO_2 mass emission per second, the following equation was applied.

$$\mathrm{CO_{2\,MASS}} = [\mathrm{CO_2}]_{\mathrm{t=t+DT}} \times \mathrm{MWT_{CO2}} \times [\mathrm{Q_{EX}}]_{\mathrm{t=t}} \times (273.15/293.15) \times \mathrm{UCF} \qquad (2)$$

Where, $\mathrm{CO_{2\,MASS}}$ is the CO_2 mass emission rate in g/s, standardised to 20°C and 1atm (293.15K and 101.3kPa); $[\mathrm{Q_{EX}}]_{\mathrm{t=t}}$ is the exhaust flow rate in m^3/min at time t; $[\mathrm{CO_2}]_{\mathrm{t=t+DT}}$ is the percentage concentration of CO_2 associated with $[\mathrm{Q_{EX}}]_{\mathrm{t=t}}$, which is read after a measurement Delay Time (DT); $\mathrm{MWT_{CO2}}$ is the molecular weight of CO_2 (44.01 g/mol); and UCF are the required Unit Conversion Factors. The Unit Conversion Factors are a multiplication by 1/100 to correct the units of $[\mathrm{CO_2}]_{\mathrm{t=t+DT}}$ from a percentage volume to volume; a multiplication of 1/60 to change the units of $[\mathrm{Q_{EX}}]_{\mathrm{t=t}}$ from m^3/min to m^3/s; a multiplication of 1/22.415 to convert $\mathrm{MWT_{CO2}}$ from g/mol to CO_2 density using the ideal gas volume of 1 mole at Standard Temperature and Pressure (STP), with 273.15/293.15 amending the density of CO_2 to that at 20°C and 1 bar.

LiDAR-GIS Methodology for Elevation Profile and 1Hz Road Grade Estimation. This study developed a simple LiDAR-GIS method to calculate a road grade estimate for each second of PEMS data. The method uses a 5m resolution Digital Terrain Map (DTM) generated from LiDAR elevation data recorded by aircraft (Millin-Chalabi et al., 2011). The DTM and the PEMS recorded 1Hz GPS latitude and longitude for each test run are imported into the GIS software ArcGIS enabling the elevation at each recorded GPS position to be extracted from the DTM.

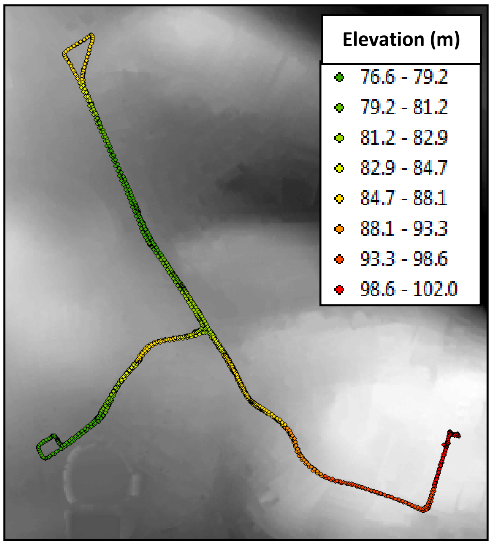

Figure 3: ArcGIS Image of DTM and GPS Positions with Extracted Elevation

The measurement of latitude and longitude with GPS systems can also incur measurement errors. The GPS system used in this study had an absolute positioning accuracy of 3m 95% CEP (Racelogic, 2008). These errors are most obvious when the test vehicle is stationary yet the vehicle latitude and longitude wanders. In these cases the vehicle can travel a negligible distance but the LiDAR-GIS elevation can change significantly, resulting in the calculation of an unfeasibly steep road grade. An algorithm is applied to alleviate this error. When the vehicle is travelling at greater than 10m/s the gradient is calculated from the change in elevation divided by the distance covered in that second. When the recorded vehicle speed is slower than 10m/s the gradient is instead calculated from the change in height and distance over the time period from where the vehicle was at least 5m before and 5m past the position of the measured second. The algorithm ensures that each road grade value is calculated over a distance of greater than 10m.

Modelling in PHEM. PHEM (Hausberger, 2003) is a comprehensive power-instantaneous emission model for the EU vehicle fleet. PHEM requires 1Hz speed and road grade, along with specification data for the test vehicle to calculate the engine speed and power output of the vehicle for each second of test data. The engine speed and power values for each second are then referred to an engine emission map, specific to the certified EU emission standard and fuel type of the test vehicle, to estimate the mass per second vehicle fuel consumption and emission (g/s).

This research used the PEMS measured 1Hz speed profile from each test run and the corresponding LiDAR-GIS estimated road grade for each second. The specific test vehicle specifications were input into PHEM and the emission engine map used during the modelling was for a EURO 4 petrol vehicle.

Results and Discussion

LiDAR-GIS Elevation and Road Grade Calculation for Sections A and B. Figure 4 is a plot of the elevation profile for Sections A and B, generated using the LiDAR-GIS method, from one test run. The figure shows the extracted DTM elevations at each 1Hz PEMS recorded latitude and longitude. The LiDAR-GIS method was found to produce consistent elevation profiles for each test run, without the same measurement and interference errors that afflict PEMS recorded GPS elevation.

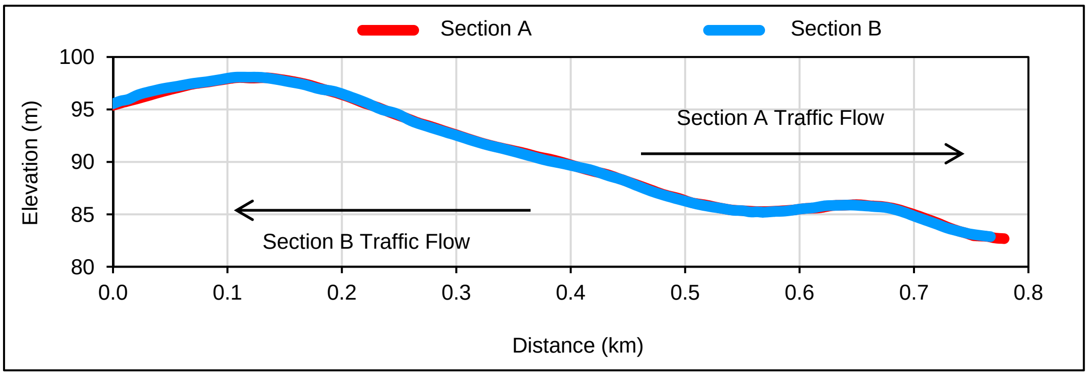

Figure 4: Section A and B Elevation Profile from the LiDAR-GIS Method

There is a 12.5m change in elevation over the road Segment AB, with a maximum elevation of 98m and a minimum elevation of 83m. The average road grade over the segment is ±1.6% with Section A being predominantly downhill and Section B predominantly uphill.

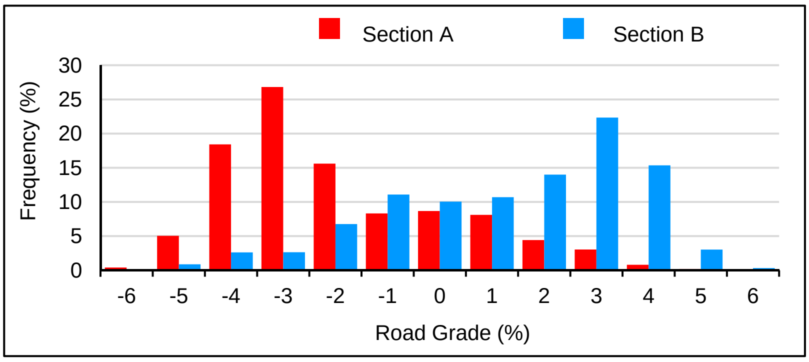

Figure 5: Sections A and B Road Grade Frequency Distribution from LiDAR-GIS Method

Figure 5 presents the average road grade frequency distribution for Sections A and B, calculated from the LiDAR-GIS 1Hz road grade data, over the 48 test runs. As the PEMS recorded GPS positions are different in each test run, the road grade frequency distributions for each run vary considerably. For example, for test runs with substantial congestion and long stationary periods, the road grade at those stationary points will consequently provide a greater fraction of that runs frequency distribution. The results in Fig.5 are therefore an average road grade frequency distribution over all 48 test runs. For Sections A and B 99.5% of the 1Hz LiDAR-GIS road grade estimates were within the range of ±5%.

PEMS Measured Average Speed and CO_2 Emission. Testing between the hours of 07:30 and 21:00 over a week long test period, captured the likely spectrum of traffic flow conditions through Sections A and B. Figure 6 highlights the frequent congestion experienced in Section A, caused by a traffic light controlled junction at the end of the section, with an average section speed over the 48 test runs of only 10.2 km/h. The fastest run through Section A took 74s and the slowest 756s, with 50% of the run times between 143s (average speed 20 km/h) and 396s (7 km/h).

Section B remained relatively free flowing even in the morning and evening rush hours as the only traffic management measure that could obstruct traffic flow in the section is a pedestrian crossing, and the nearest traffic light controlled junction is 500m past the end of the section. The average speed through the section was 29.4 km/h. The run times were much more consistent than Section A's, with the fastest run taking 62s and the slowest 128s, with 50% of the runs between 84s (33 km/h) and 106s (26 km/h).

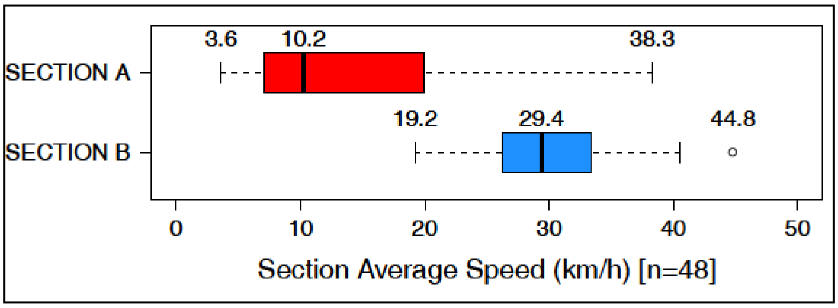

Figure 6: Box plot of PEMS Measured Average Section Speed in km/h [n=48 runs]

The CO_2 emission box plot (expressed in g/km) presented in Fig.7 for Section A demonstrates the wide range of possible CO_2 emission values for the same vehicle, over the same section, depending on traffic flow conditions. The highest measured emission over Section A was 1082 gCO_2/km, recorded during the slowest test run. That test run was completed in 756s and the vehicle was stationary for 406s during the run (54% of the total time). Whilst idle CO_2 emission per second is relatively low, this stationary time resulted in the emission of 321 gCO_2, which was 39% of total CO_2 emission in the section (822 gCO_2). Significant periods of stationary time can have a large impact on the calculated section gCO_2/km value, as, whilst stationary the vehicle travels no distance but, as the engine ticks over, the total CO_2 emission continues to increase. The lowest measured gCO_2/km emission over Section A was 226 gCO_2/km; this was the run with the highest average speed at 38.3 km/h and the vehicle did not have to stop in the section. On average in Section A the vehicle was stationary 40% of the measurement time, whilst in Section B the average stationary time was only 4%.

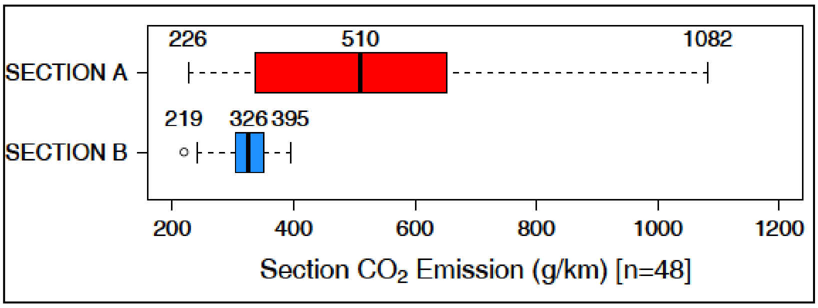

Figure 7: Box plot of PEMS Measured CO_2 g/km Emission [n=48]

In 18 of the 48 test runs through Section B, the test vehicle did not stop; through Section A this only occurred in 2 of the 48 test runs. With considerably less congestion in Section B, the test vehicle was able to maintain a consistent speed close to the speed limit for the road and, as a result, the measured CO_2 emissions through the section were generally much lower than those in Section A, and over a much narrower range. The inter-quartile range of emission for Section A was between 337 gCO_2/km and 652 gCO_2/km compared with between 305 gCO_2/km and 352 gCO_2/km in Section B.

PHEM Model Estimate of PEMS Measured Emission. To investigate the ability of the PHEM emission model to generate micro-scale section emission estimates, each of the 48 test runs through Section A and B was modelled in PHEM using the PEMS recorded 1Hz vehicle speed for each run and the associated LiDAR-GIS 1Hz grade ($PHEM_G$). A CO_2 emission estimate was generated for each run and then compared with the PEMS measured on-road CO_2 emission.

Figure 8 plots the $PHEM_G$ (N.B. PHEM with the LiDAR-GIS grade) calculated total CO_2 emission as a percentage of the real-world PEMS recorded total CO_2 emission for each of the 48 test runs through Sections A and Section B. $PHEM_G$ appears to yield a slight underestimate the real-world emission, with median estimates of 91% and 93% through Sections A and B respectively.

The underestimation of the real world emission is possibly the result of test vehicle discrepancy from the average EURO 4 vehicle described in PHEM, as the PHEM EURO 4 petrol engine emission maps are not specific to the test vehicle. Alternatively there may be some disparity between the timing of the real-world and PHEM modelled gear changes, which would influence the calculation of engine speed in PHEM and therefore the calculated CO_2 emission. Possible inaccuracy of the modelled vehicle weight could also have influenced the PHEM calculated rate of CO_2 emission, as the total weight of the test vehicle and loading was not directly measured and may vary from the kerbweight and loading estimate.

It is likely that much of the difference between the PHEM calculated and PEMS measured CO_2 emission, and the spread of estimate values, is due to parameters not included in the modelling such as run-to-run variation in ambient temperature (between 1°C and 15°C) the state of charge of the starter battery and use of the vehicles air conditioning and heating systems, each of which could have an influence on the test vehicle's CO_2 emission (Mock et al., 2012).

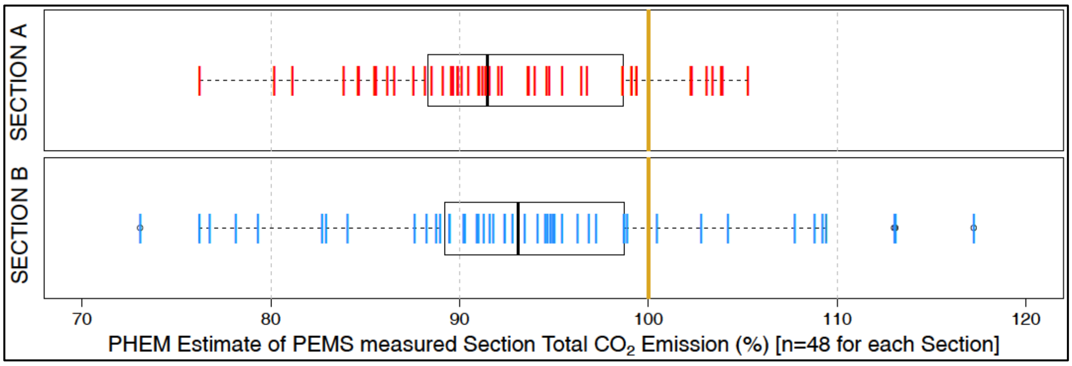

Figure 8: Box plots of the percentage $PHEM_G$ estimate of the PEMS measured section CO_2 Emission through Sections A and B [n=48]

Figure 9 is a scatter plot of the $PHEM_G$ calculated total CO_2 emission against the PEMS measured total CO_2 emission for each of the 96 test runs through Sections A and B. In total 49% of the $PHEM_G$ estimates were between 90% and 100% of the real-world emission; 27% were between 80% and 90%; and 15% between 100 and 110%. The figure highlights some discrepancy between the modelled and real-world CO_2 emission. However, given the variety of traffic conditions encountered (encompassing long stationary periods of idle emission; stop-start congested travel; and free flow driving), differences between the test vehicle and the average EURO 4 vehicle described in PHEM, and the run-to-run influence of factors outside the scope of the model, PHEM does provide accurate and reliable estimates of CO_2 real world emission.

This research demonstrates that using the PHEM model with a LiDAR-GIS calculated 1Hz road grade provides a practical method for accurately estimating micro-scale on-road CO_2 emission.

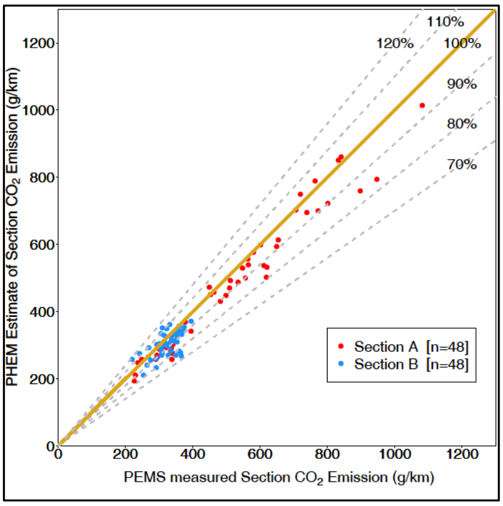

Figure 9: Plot of the PHEM Estimate versus the PEMS Measured Section CO_2 Emission [n=96]

PHEM Modelling of Section CO_2 Emission With and Without Road Grade. To ascertain whether road grade is important to the modelling of micro-scale section emissions in PHEM, the test area was also modelled as if it were flat. CO_2 emission estimates were calculated in PHEM with the road grade set to zero ($PHEM_0$) for each of the 48 runs through sections A and B.

Figure10 displays box plots of the $PHEM_G$ and $PHEM_0$ percentage estimates of the PEMS measured section CO_2 emission, for each of the 48 test runs through Section A and B. The $PHEM_0$ estimates are determined from the same PEMS vehicle velocity data used in the $PHEM_G$ calculation, but with a road grade of zero for each second of data rather than the LiDAR-GIS calculated values.

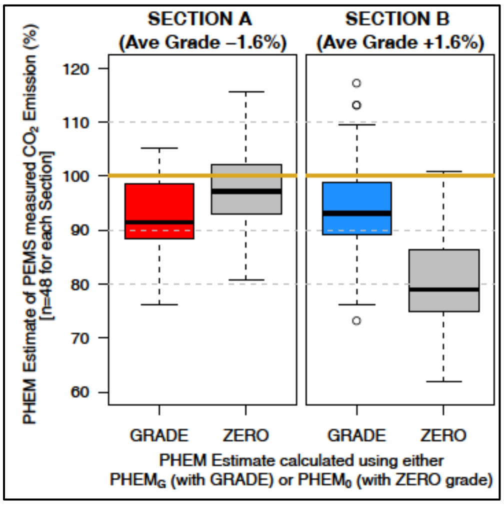

Figure 10: PHEM Estimate of PEMS Section CO_2 Emission with and without Road Grade (%)

The $PHEM_0$ calculated section CO_2 emission values in Section A appear to provide a more accurate estimate of the real-world section emission than $PHEM_G$, with a median section total CO_2 emission estimate of 97% from $PHEM_0$ and only 91% from $PHEM_G$. However in Section B, the $PHEM_G$ values are much closer to the measured on-road emission than the $PHEM_0$ estimates, with a median estimate of 93% from $PHEM_G$ and 79% from $PHEM_0$.

The variability of the $PHEM_0$ estimates in predicting the PEMS real-world CO_2 emission demonstrates why it is vital to incorporate an accurate 1Hz road grade when calculating micro-scale emission estimates from power based models. $PHEM_0$ overestimates CO_2 emission on downhill sections (such as Section A), where the force of gravity aids acceleration of the vehicle, which decreases the necessary power output from the engine, and reduces fuel combustion and CO_2 emission. $PHEM_0$ also underestimates CO_2 emission on uphill sections (such as Section B) where extra power from the engine must be supplied to overcome the opposing force of gravity. $PHEM_G$ consistently provides estimates between 90% and 100% of the measured section emission irrespective of section average grade.

Sensitivity Analysis of CO_2 and NO_x Emission to Road Grade. To investigate the importance of road grade to modelling micro-scale sections where there is undulation in the elevation profile over the section, but an overall net flat road grade (i.e. the section begins and ends at the same elevation), Section A and B were combined to form Segment AB. As Section B ends where Section A begins, combining the two sections into one segment created a segment with an average road grade of zero.

The CO_2 and NO_x emission through Segment AB were modelled in PHEM using the PEMS measured vehicle speeds for each of the 48 test runs, without road grade and with three road grade scenarios. The road grade scenarios were formed by multipling the calculated 1Hz LiDAR-GIS road grade, for each test run, by three coefficients. In the first scenario, $PHEM_{0.5G}$, the LiDAR-GIS grade was multiplied by 0.5, halving the grade at each second. The second scenario, $PHEM_G$, used the 1Hz LiDAR-GIS grade (coefficient of 1) and the third scenario, $PHEM_{2G}$ muliplied the LiDAR-GIS grade by 2, doubling the grade at each second of data.

The Segment AB road grade distribution under $PHEM_G$ (as show in Fig. 5) has 99.90% of the 1Hz road grade values between ±6% road grade with 94.59% between ±4%. For $PHEM_{0.5G}$, 98.15% of the 1Hz road grade values were within the range ±2%, with 99.94% between ±3%. With a doubling of the LiDAR-GIS road grade, the $PHEM_{2G}$ road grade distribution for Segment AB has 68.58% of the 1Hz road grade values between ±6% and 99.09% within the range of ±10%.

Figure 11 shows the percentage change in emission over Segment AB, with PHEM modelled at each of the three road grade coefficients relative to the $PHEM_0$ modelled Segment AB emission, for each of the 48 test runs.

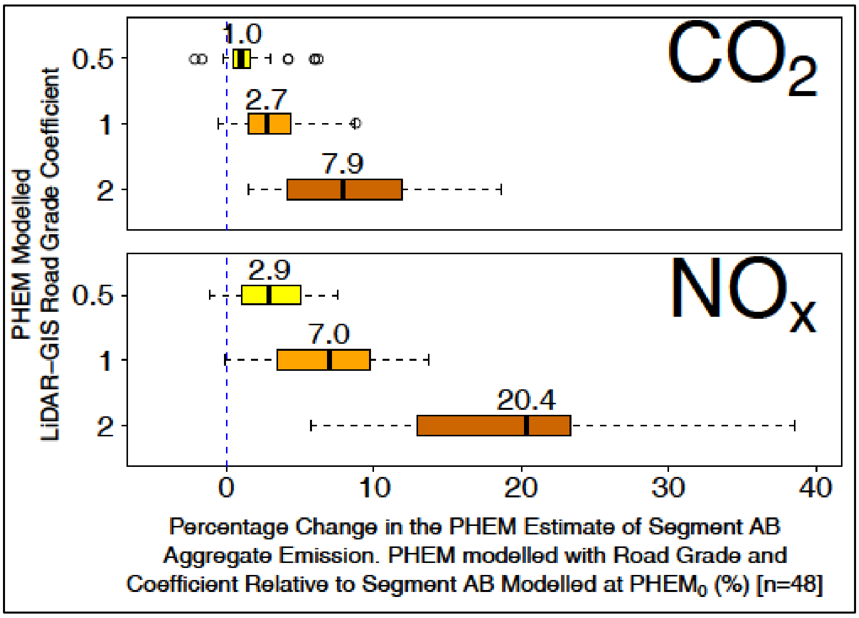

Figure 11: Percentage Change in PHEM Estimate of Net Flat Segment AB Emission Modelled without Road Grade versus with Road Grade Under Three Scenarios

Comparing the output of the $PHEM_G$ scenario, over the 48 runs, to Segment AB modelled with zero grade, reveals that assuming a flat profile in PHEM on average would result in an under-estimation of the segment emission by 2.7% for CO_2 and 7.0% for NO_x. From the $PHEM_{0.5G}$ calculated emissons, modelling the segment as flat would on average under-estimate CO_2 emission by 1% and NO_x emission by 2.9%, and had the road grade been twice as steep at each second, the average under-estimate would be 7.9% and 20.4% for CO_2 and NO_x emssions respectively.

Therefore with even quite modest undulation in elevation, the topography can have an important influence on vehicle emission. It is incorrect to assume that over a net flat road profile increased emission uphill will be offset by decreased emission downhill. The PHEM modelling indicates that NO_x is especially sensitive to road grade. This research suggests that in order to calculate accurate micro-scale estimates of vehicle emission using a power-emission model, a reliable 1Hz road grade must be included in the modelling process.

Conclusion

The real-world CO_2 emission of a petrol EURO 4 passenger car were recorded by PEMS during 48 test runs on the inbound and outbound lanes of a 780m segment of urban commuter road. The recorded range of emission was between 219 and 1082 gCO_2/km.

This study employed a simple LiDAR-GIS method for determining a 1Hz road grade from second-by-second PEMS measured latitude and longitude. The LiDAR-GIS grade was shown to improve the emission model PHEM's estimates of the on-road PEMS measured section CO_2 emissions, compared with PHEM estimates generated without road grade.

Despite variation in traffic flow and ambient weather conditions between test runs, 91% of the $PHEM_G$ CO_2 section emission estimates were between 80 and 110% of the PEMS measured value. This research demonstrates that using the PHEM instantaneous emission model with LiDAR-GIS calculated 1Hz road grade presents a feasible method for generating accurate real-world vehicle emission estimates at a micro-scale.

This research highlights that even on a road section with a modest average gradient (±1.6%) the road grade can have important influence on exhaust emission. NO_x emission was shown to be especially sensitive to road grade. It was also shown to be incorrect to assume that over a net flat profile increased emission uphill are offset by decreased emission downhill. Therefore to calculate accurate micro-scale estimates of vehicle emission using a power-emission model a reliable 1Hz road grade must be incorporated.

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