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Comparing emission rates derived from remote sensing with PEMS and chassis dynamometer tests - CONOX Task 1 report

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Preface

Understanding real driving (or on-road or real-world) emissions is crucial for taking cost-effective actions to reduce air pollution and improve air quality in urbanized areas all over the world. Remote sensing represents one means to monitor real driving emissions from large on-road fleets, and has been used in Europe in various applications already since the early 1990's to reach a better understanding of the European situation regarding real driving emissions. However, until present remote sensing has never been used in Europe for e.g. legislative or enforcement purposes, which instead have relied on other emission measurement approaches, providing results that are more or less representative for real driving emissions (e.g. chassis dynamometer or PEMS testing, idle tests). In light of "dieselgate", approaches capable of measuring the "real" real driving emissions, such as remote sensing, have gained an increasing interest, also for emission control purposes.

This report presents the outcome of a common European and US collaborative effort to analyse how large datasets from remote sensing measurements carried out in various locations and countries across Europe could be used as a complement to existing approaches to measure road vehicle emissions, in order to achieve a better understanding of the European issue of air pollution from road transport. The work presented in this report focuses on NO_x emissions from diesel passenger cars corresponding to the Euro 4, 5 and 6 standards.

This work was part of the CONOX project[1], which was carried out during 2017 under a contract from the Federal Office for the Environment in Switzerland, FOEN (www.bafu.admin.ch).

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[1] Study on comparing NO_x real driving emissions from Euro 5 and Euro 6 light-duty diesel vehicles as measured by remote sensing, PEMS and on chassis dynamometers

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Summary

Remote sensing measurements may present an important complement to conventional emission measurements, e.g. on-board vehicles by means of PEMS or on chassis dynamometers, mainly due to its ability to measure emissions from large samples of vehicles in a short time, typically in the order of thousands of vehicles per day. Thus, remote sensing has the potential to be used both for producing emission factors for use in mobile source emission inventory models and tools, as well as for emission control purposes and evaluation of various emission control policies.

Despite this, remote sensing has rarely been used for such purposes in Europe. In fact, very few attempts have been made even in trying to compare results from remote sensing measurements with those from the conventional and well-established emission measurement methods.

In this study – i.e. Task 1 of the CONOX project – a newly developed method is presented to enable improved comparisons of emission results from remote sensing measurements with those from PEMS routes or from chassis dynamometer standard driving cycles, which together will help us to corroborate measurements and better understand real-driving emissions of in particular NO_X and NO_2 from late model diesel light-duty vehicles, e.g. Euro 5 and Euro 6 passenger cars.

The method utilizes information and data commonly available from remote sensing measurements, such as driving (speed and acceleration), road (grade) and ambient (air temperature) conditions, together with crucial vehicle information, such as make, model, segment (weight and size), engine/fuel type and Euro classification. From this information the vehicle specific power (VSP) is calculated on an individual vehicle level, which is used as input to simulations with the TU Graz PHEM model to derive instantaneous fuel rates on an individual or aggregated vehicle level. The derived fuel rates are used to convert emissions expressed as gram pollutant emitted per kg fuel burned from the remote sensing measurements into gram pollutant emitted per vehicle distance driven (e.g. g/km) or per time unit (e.g. g/s).

By dividing large remote sensing datasets into a number of VSP bins, the proposed method can be used to convert remote sensing emission rates to any test cycle, such as the WLTP, for further comparisons.

The full method has not yet been applied to the huge dataset from remote sensing measurements carried out in Europe in a number of countries the last couple of years, which was compiled within Task 2 of the CONOX project (containing e.g. emission measurements on more than 200,000 diesel passenger cars, the majority of which belonging to Euro standards 4, 5 and 6). A slightly simplified version of the method was applied on Euro 5 and Euro 6 diesel passenger cars NO_X emissions within Task 2 of the CONOX project (separate report available), with the results showing a very good agreement between remote sensing emission averages and emission averages from PEMS on both a very aggregated level (whole fleet sample averages) and on a less aggregated level (e.g. engine family averages).

It is recommended that the method is further refined and applied more systematically, for e.g. real driving emissions market surveillance and for validation or provision of mobile source inventory models emission factors.

Introduction

Emission rates measured by remote sensing are instantaneous, usually under positive acceleration, and without idling. Their unit is typically gram (or mole) pollutant emitted per gram (or mole) CO_2 emitted, i.e. emission ratios, which - through the fuel combustion equation - can be directly converted to *gram pollutant emitted per mass or volume unit fuel burned*. Emission factors from type approval or RDE tests are typically cycle or trip averages, and thus include constant speeds, accelerations, decelerations and idling, and possibly also cold start extra emissions, and their typical unit for light-duty vehicles is *gram pollutant emitted per distance driven*. This means that the crucial link for enabling comparisons between emission rates as measured by remote sensing with those measured in conventional emission tests is the *fuel consumption in mass or volume unit per distance driven*.

The objective of the Task 1 of the CONOX project was to develop and demonstrate robust methods which allow comparisons of emission rates measured by remote sensing with those measured on chassis dynamometers or onboard vehicles by means of portable emission monitoring equipment such as PEMS (Portable Emission Monitoring System). The complementarity of the methods as well as the limits and uncertainties in the comparisons were evaluated within the study.

More specifically, the methods developed were applied to compare aggregated results from remote sensing measurements, carried out across Europe in several countries between 2011 and 2017, with the results from the official (governmental) "dieselgate" inquiries, conducted in France, Germany, the UK and Wallonia, involving measurements on mainly Euro 5 and Euro 6 diesel passenger cars. The results of these comparisons are presented in detail in the Task 2 CONOX report (Sjödin *et al.*, 2017).

The methods considered for comparing remote sensing data with PEMS and chassis dynamometer data in this study offer various levels of details depending on available data and modelling tools. The methods considered were:

1. *Unit conversion using results from type approval testing*

   Using fuel consumption (or CO_2 emission) data measured in the type approval test, to either convert remote sensing data into gram per km or type approval data into g per kg or liter fuel burned, would be beneficial since results from type approval testing are publically available and the fuel consumption and emissions (CO, HC, NO_X and PM) of each new engine family put on the market are measured. The main drawback of this approach, however, is that the driving cycle used in the type approval test, the NEDC, is far away from representing any real driving behavior, whereas remote sensing can be said representing real-world driving conditions per se. The gap between fuel consumption performance over the NEDC and that found in real driving has also been widening with over time (Tietge et al., 2016), so no constant conversion factor for a specific marque and model of passenger car for example can be established.

2. *Unit conversion by modelling the specific remote sensing driving conditions with PHEM*

   Models of vehicle dynamics, like the TU Graz PHEM model[2], are capable of reproducing the fuel economy for an average vehicle of any category, e.g. Euro 5 diesel passenger cars, with high accuracy. The input data that are required for such simulations are typically available in the remote sensing data – e.g. vehicle speed and acceleration, road grade, vehicle characteristics such as mass, size, engine technology, Euro classification, etc. In this way emission rates derived from remote sensing measurements can be converted into gram pollutant emitted per distance driven.

3. *Comparison of emission rates per vehicle specific power (VSP) and convertibility to random test cycles*

   Remote sensing emission rates are associated with the driving condition of the vehicle expressed as vehicle specific power (VSP). Likewise, the emission rates measured by PEMS or on a chassis dynamometer as well as the instantaneous fuel economy can be associated with the driving condition. Thus, emission rates per VSP can be compared with each other – or aggregated over a succession of VSP states. In this way the average instantaneous remote sensing emission rates per VSP can also be used to simulate any driving cycle that is given as a succession of VSP rates.

After initially having carefully reviewed the three different approaches above, a combination of the suggested approaches 2 and 3 was considered to have the greatest potential to compare emission rates derived from remote sensing measurement with emission rates according to PEMS and chassis dynamometer measurements. The combined method is described in detail in this report.

It should be noted here that a full application of the developed method on the pan-European analysis within Task 2, involving e.g. comparisons of agglomerated remote sensing datasets with datasets from the official enquiries, was out of scope of the CONOX project. Instead a slightly simplified method was used for this analysis. It is anticipated that the conclusions drawn from the outcomes of Task 2 would not have changed significantly from using the more sophisticated method presented in this report.

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[2] PHEM (Passenger car and Heavy duty vehicle Emission Model) is a vehicle simulation tool capable of simulating vehicle hot and cold emissions for different driving cycles, gear shift strategies, vehicle loadings, road gradients, vehicle characteristics (mass, size, air resistance, etc.), see e.g. http://www.ermes-group.eu/web/system/files/filedepot/14/P03-Presentation_TUG_V1.pdf

Method description

General

Remote sensing (RS) emission rates are associated with the driving condition of the vehicle expressed as vehicle specific power (VSP), which is the engine power divided by the vehicle mass. Likewise, the emission rates measured by PEMS or on a chassis dynamometer as well as the instantaneous fuel economy can be associated with the driving condition. Thus, emission rates per VSP can be compared with each other – or aggregated over a succession of VSP states. In this way the average instantaneous RS emission rates per VSP can also be used to simulate any other driving cycle that is given as a succession of VSP rates.

Since remote sensing measures emissions as a ratio to CO_2, i.e. to fuel consumption, it is necessary to estimate the instantaneous rate of fuel consumption in order to project grams of pollutant per second or per km driven.

The first section (*VSP and fuel consumption*) of this method description describes the development of PHEM-based VSP estimates and fuel consumption estimates for use with remote sensing.

The second section (*Convert remote sensing emission rates to any test cycle*) illustrates the method used to transform RS emissions into estimated test cycle equivalent values.

The third and final section discusses related issues such as:

a. What is the necessary number of RS measurements per VSP bin for a robust RS emission rate?

b. Applicability of the PEMS/chassis dyno/modelled instantaneous emission factor to single vehicles or a sub-group of vehicles? What parameters to use for the characterization of vehicle groups?

c. When is the time alignment between emission measurement result and vehicle speed and acceleration signal sufficient to correlate emissions and VSP?

d. The issue of NO_X and NO_2 in remote sensing measurements, until recently only including NO.

VSP and fuel consumption

VSP

The VSP can be computed for a given driving situation (velocity and acceleration) from a standardized VSP equation. The equation is elaborated from the basic longitudinal dynamics equations below.

The engine power necessary during a driving cycle can be computed from the main power consumers quite accurately as follows:

$$P = P_{accel.} + P_{roll} + P_{air} + P_{grad} + P_{transmission} + P_{aux}$$

For a simple approach the following assumptions are made:

- The power to accelerate rotational accelerated mass is equivalent to 4% of the power for translational accelerated mass.
- The losses in the transmission are 8% of the power at the driven wheels (acceleration, rolling resistance, air resistance, gradients go through transmission system). In the case of energy flow from the wheel to the engine (braking by the engine) the losses also would change the direction. As simplification this effect is not considered here since it is only relevant in VSP areas below zero.
- The auxiliaries' power demand in real driving is on average 2.5 kW.

The engine power demand is then in [W]:

$$P = [m * a * 1.04 + R_0 + R_1 * v + Cd * A * 0.6 * v^2 + m * g * Grad] * 1.08 * v + 2500$$

The "Gradient" is defined as altitude[m] / distance [m].

For the VSP in kW/ton follows:

Equation 1: $$\boldsymbol{VSP} = \frac{\mathbf{2500+(R_0*v+R_1*v^2+C_d*A*0.6*v^3)*1.08}}{\boldsymbol{m}\mathbf{*1000}} + \frac{\mathbf{v*1.08*(1.04*a+g*Grad)}}{\mathbf{1000}}$$

with:

VSP ....vehicle specific power [kW/ton],
m ....vehicle mass including loading in [t],
the vehicle mass in real driving conditions may be approximated from the vehicles empty weight: $m = m_{DIN} * 1.2$,
m_{DIN} ....vehicle empty mass according to DIN (in running order, without driver) in [kg][3],
GVW..................maximum allowed gross vehicle weight in [kg],
a..........................vehicle acceleration [m/s²],
v ....vehicle speed [m/s],
C_d ($=C_w$).............aerodynamic drag coefficient of the vehicle in [-],
R0, R1................ road load coefficients of the vehicle in [N] and [N/(m/s)] from rolling resistance and from friction losses in bearings.

Consequently with a known speed, acceleration and gradient from the remote sensing measurements the actual VSP of a vehicle can be calculated. Vehicle input data from the PHEM model provides parameters for the European average vehicle used in HBEFA 3.3[4]. The generic values shown in Table 1 are available as input for VSP calculation. Default values for average vehicles as well as for different vehicle segments are provided. Table 1 also includes the function to calculate the normalized fuel flow from the VSP as shown in Equation 2 further below.

Table 1 also shows values normalized per ton of vehicle mass. On a per ton basis R0 and R1 are quite similar across vehicle segments. The most important differentiating parameter for individual vehicle types within a segment is likely to be C_w*A. On demand the user consequently could simplify Equation 1 by implementing the normalized generic data per ton vehicle mass.

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[3] Attention: the vehicle reference mass in the NEDC test is mDIN + 100kg, you should check which values you have as basis.

[4] Keller, M.; Hausberger, S.; Matzer, C.; Wüthrich, P., Notter, B., Philipp Wüthrich, Benedikt Notter (2017) HBEFA Version 3.3 http://www.hbefa.net/e/documents/HBEFA33_Documentation_20170425.pdf

Table 1. Generic data suggested to be used per vehicle segment or for average diesel passenger cars and vans if no specific vehicle information is available.

	Real world settings				Real world settings/ ton			
Vehicle Segment	Test mass [k	R0 [N]	R1 [Ns/m]	cw*A [m²]	Test mass [k	R0 [N/t]	R1 [(Ns/m)/t	cw*A [m²/t]
SegA+B	1381	120	0.77	0.537	1	0.087	0.00055	0.000389
SegC	1678	151	0.93	0.617	1	0.090	0.00055	0.000368
SegD	1841	166	1.02	0.665	1	0.090	0.00055	0.000361
SegE+F+J	2181	204	1.18	0.915	1	0.094	0.00054	0.000420
VanI	1355	122	0.73	0.529	1	0.090	0.00054	0.000391
VanII	1684	152	0.89	0.765	1	0.090	0.00053	0.000454
VanIII	2360	213	1.24	1.307	1	0.090	0.00052	0.000554
Average car	**1732**	**157**	**0.95**	**0.660**	**1**	**0.090**	**0.00055**	**0.000380**
Averag Van	**1923**	**174**	**1.02**	**0.965**	**1**	**0.090**	**0.00053**	**0.000485**
Average all	**1751**	**158**	**0.96**	**0.690**	**1**	**0.090**	**0.00055**	**0.000390**

Table 2. Generic data suggested to be used per vehicle segment or for average gasoline passenger cars and vans if no specific vehicle information is available.

	Real world settings				Real world settings/ ton			
Vehicle Segment	Test mass [kg]	R0 [N]	R1 [Ns/m]	cw*A [m²]	Test mass [kg]/ton	R0 [N/t]	R1 [(Ns/m)/t]	cw*A [m²/t]
SegA+B	1227	106	0.67	0.538	1	0.087	0.00055	0.000439
SegC	1545	139	0.85	0.618	1	0.090	0.00055	0.000400
SegD	1702	154	0.94	0.689	1	0.090	0.00055	0.000405
SegE+F+J	1869	175	1.01	0.810	1	0.094	0.00054	0.000433
VanI	1227	106	0.67	0.538	1	0.087	0.00055	0.000439
VanII	1607	145	0.84	0.853	1	0.090	0.00053	0.000531
VanIII	2196	198	1.14	1.158	1	0.090	0.00052	0.000528
Average car	**1428**	**127**	**0.78**	**0.598**	**1**	**0.089**	**0.00055**	**0.000421**
Averag Van	**1303**	**114**	**0.71**	**0.601**	**1**	**0.087**	**0.00054**	**0.000457**
Average all	**1422**	**127**	**0.78**	**0.598**	**1**	**0.089**	**0.00055**	**0.000423**

Fuel consumption

To be in the position to produce fuel consumption values representative for a specific, short driving situation, the PHEM results for average passenger cars can be used. PHEM has representative vehicle data sets as input data compiled from hundreds of real world vehicle measurements. PHEM simulates fuel consumption and emissions from vehicles in any driving situation based on engine maps and vehicle longitudinal dynamics simulation. Thus, PHEM can produce representative fuel consumption values for various driving conditions with a 1Hz resolution. More detailed descriptions are given in e.g. Rexeis (2013) and Hausberger (2012) and in the PHEM model user manual.

An example for 1Hz fuel consumption values simulated by PHEM for the average EURO 6 diesel passenger car, belonging to segment C is shown below. In Figure 1 the result is plotted over the actual engine power as basis for the elaboration of a simple method to calculate the actual vehicle fuel flow.

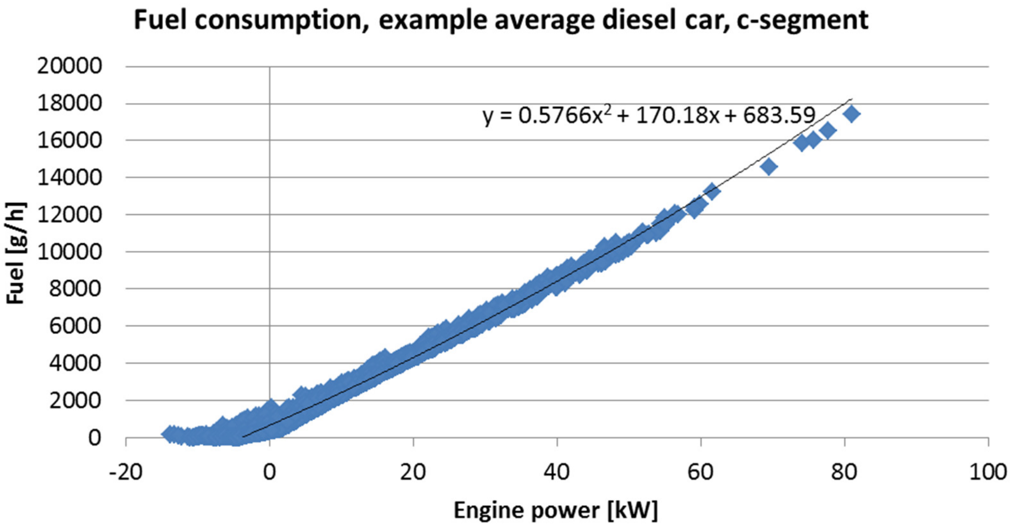

Figure 1. **Fuel consumption characteristics for the average Euro 6 diesel passenger car, C-segment, from the 1Hz CADC PHEM simulation (each dot represents one second in the cycle).**

The fuel consumption characteristic curve is quite similar in different test cycles for a given vehicle (Figure 2). This meets the expectations since the engine efficiency mainly depends on engine power and engine speed. The effect of the engine power is fully reflected by the VSP on the x-axis. The influence of engine speed is defined by the gear shift logics. In real driving the gear shift behaviour of drivers follows typically a function of torque demand and actual engine speed and thus gives similar engine speed levels over VSP for different real word cycles. The average gear shift behaviour of European drivers however, is not known. PHEM uses a gear shift model developed from various drivers in various vehicles described in Zallinger (2010). The lower fuel flow values for the NEDC points in Figure 2 can be explained by the rather early gear shifts in the NEDC test provisions to maximize fuel economy. The gear shifts in WLTP are different but rather below the NEDC shift points. With increasingly sophisticated automatic transmission systems now more common it is becoming increasingly important that measurement and analysis techniques do not prescribe gear shift behaviour. Instead approaches such as normalization to VSP that can be applied to passenger cars with both manual and automatic transmission systems are used.

The data can be normalized to VSP to be applicable for the remote sensing evaluation which frequently uses VSP classes. This normalization also reduces the differences in the parameters between vehicle segments. The x-axis in Figure 1 can be normalized by division by the vehicle test weight in the cycle used to determine the fuel consumption characteristic curve (here 1.65 t) to have the VSP unit expressed as kW/ton. Consequently the fuel mass flow is also normalized by division of the vehicle mass [tons]. Thus the power axis and the fuel flow axis in Figure 1 are simply divided by the vehicle mass. Figure 2 shows the normalized characteristic fuel consumption curve for the diesel passenger car C-segment gained from three different driving cycles. For gasoline passenger cars the same calculations were made as for diesel passenger cars. Figure 3 compares the normalized fuel flow curve for different real world cycles for the average Euro 6 gasoline car of the C-segment in PHEM. As for diesel cars the normalized curves are quite similar over the cycles. Thus the use of one curve for all cycles is a good simplification. Due to the different fuel density and the different engine characteristics, the normalized fuel characteristic curves however, differ between diesel and gasoline. Thus separate functions for these engine types shall be used if possible. Otherwise the parameters from Table 1 and Figure 3 may be averaged according to average shares of the vehicles in the fleet.

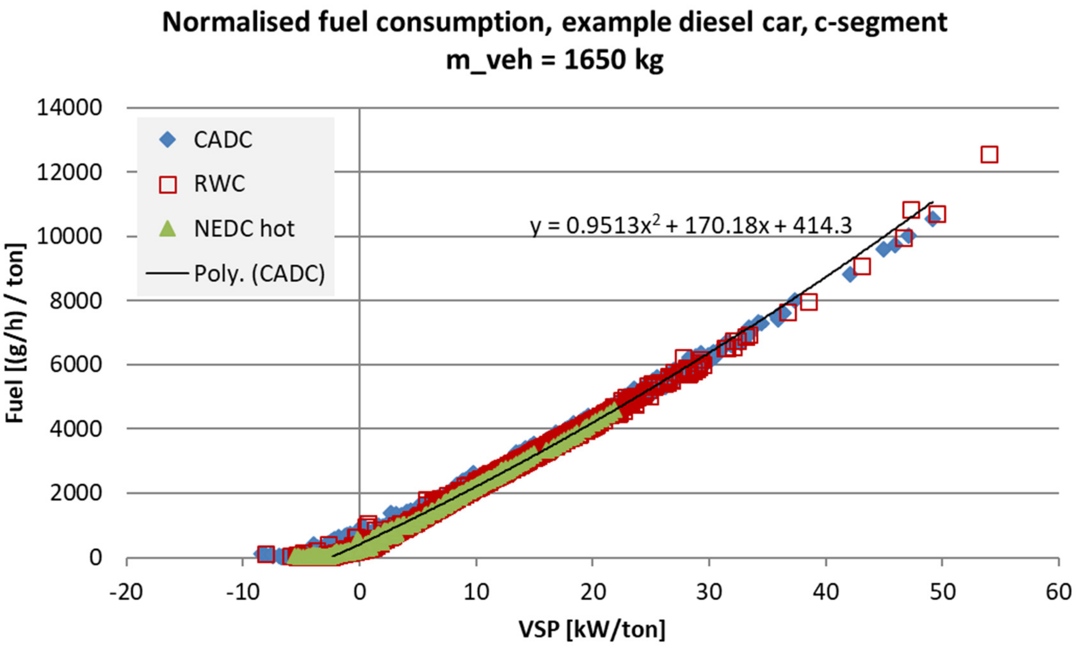

Figure 2. Fuel consumption characteristic curve for the average Euro 6 diesel passenger car, C-segment, from the 1Hz CADC PHEM simulation.

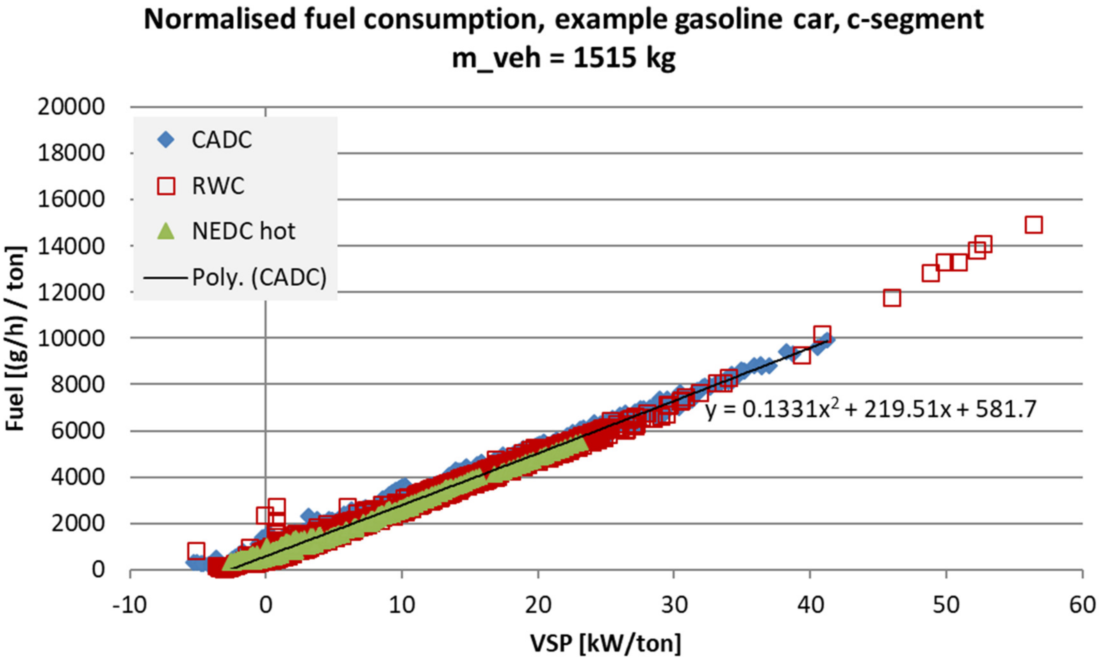

Figure 3. Normalised fuel consumption characteristic curve for the average Euro 6 gasoline car, C-segment, from the 1Hz CADC PHEM simulation.

Due to the normalization of the characteristic fuel flow curves the curves are quite similar for different vehicle segments, as shown in Figure 4 for diesel passenger cars. Figure 5 shows the curves for the gasoline passenger car segments.

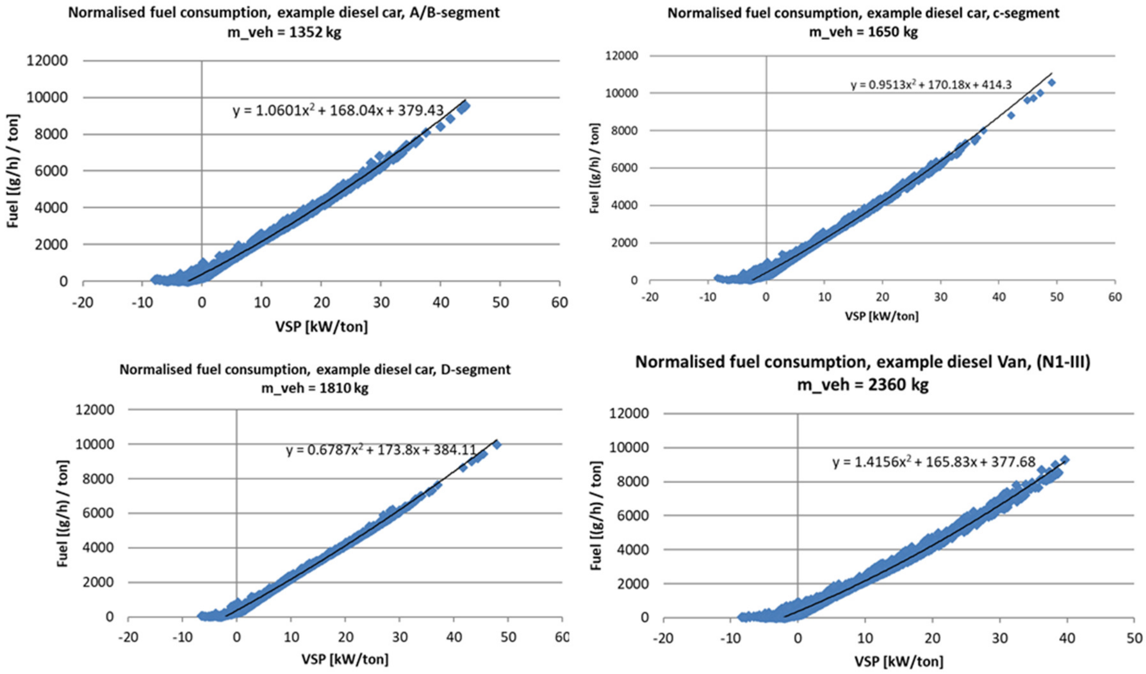

Figure 4. Normalised fuel consumption characteristic curve for the average Euro 6 diesel passenger cars, different segments from the 1Hz CADC PHEM simulation.

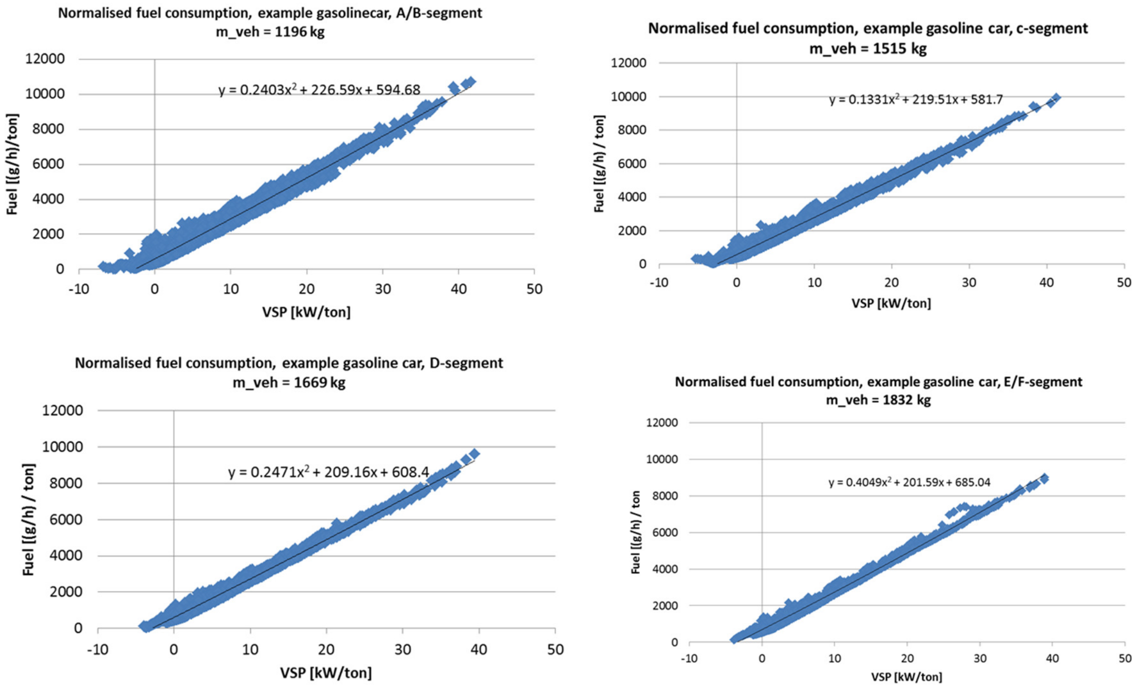

Figure 5. Normalised fuel consumption characteristic curve for the average Euro 6 gasoline passenger cars, different segments from the 1Hz CADC PHEM simulation.

Table 3 summarizes the parameters necessary for application of the fuel consumption model.

Table 3. Generic data suggested to be used per vehicle segment or for average diesel and gasoline passenger cars and vans if no specific vehicle information is available.

Diesel engines	Normalised fuel flow function (FC_norm = A *VSP^2 + B * VSP + C)		
Vehicle Segment	A	B	C
SegA+B	1.0601	168	379
SegC	0.9513	170	414
SegD	0.6787	174	348
SegE+F+J	0.6041	176	397
VanI	1.3333	165	368
VanII	1.3313	166	357
VanIII	1.4156	166	378
Average car	**0.8570**	**171**	**389**
Averag Van	**1.3741**	**166**	**371**
Average all	**0.9087**	**171**	**387**

Gasoline engines	Normalised fuel flow function (FC_norm = A *VSP^2 + B * VSP + C)		
Vehicle Segment	A	B	C
SegA+B	0.2403	227	595
SegC	0.1331	220	582
SegD	0.2471	210	609
SegE+F+J	0.405	202	685
VanI	0.2403	227	595
VanII	0.7031	209	472
VanIII	0.8764	201	390
Average car	**0.2102**	**221**	**596**
Averag Van	**0.3329**	**223**	**570**
Average all	**0.2163**	**221**	**595**

The following steps for the computation process of the fuel flow are necessary when using normalized characteristic fuel flow functions:

1. Calculate the VSP according to Equation 1.
2. With the VSP the normalized fuel consumption has to be calculated using the polynomial equation for the fuel consumption characteristic curve (parameters A, B, C as defined in Table 3). Multiplication of the normalized fuel consumption with the vehicle weight m [tons] gives the de-normalized (g/h) fuel flow:

   EQUATION 2: $FC\left[\frac{g}{h}\right] = [A * VSP^2 + B * VSP + C] * m$

3. Negative fuel flow values gained from the calculation shall be set to zero (VSP values which are below the motoring curve of the vehicle need in reality engagement of the mechanical brake of the vehicle. Mechanical braking leads to extrapolation of the fuel consumption into non existing negative power ranges of engines[5]), i.e. if FC < 0 → FC = 0.
4. Division by the actual speed yields the fuel flow in g/km:

   EQUATION 3: $FC\left[\frac{g}{km}\right] = \frac{FC\left[\frac{g}{h}\right]}{v\left[\frac{km}{h}\right]}$

Users of the method can either use the data fitting to the single vehicles or average, generic values for a fleet average as outlined in Table 1 and Table 2. Using the generic data for average passenger cars for calculation of VSP and for the fuel consumption gives two rather simple equations.

Remote sensing emission rates at a specific VSP in g/kg of fuel can be converted in g/h using the result from Equation 2:

RS g/s = (RS g/kg) * (FC g/h) / 3,600,000

Consequently remote sensing emission rates in g/kg fuel in can be converted into g/km using the fuel flow computed according to Equation 3:

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[5] In reality the engine brake power is limited by the motoring curve. This limit is not considered here, thus negative power due to mechanical braking causes negative results for the fuel flow which shall be set to zero assuming the engine to be in motoring condition in such cases

RS g/km = (RS g/kg) * (FC g/km) / 1,000

The equations to convert remote sensing raw data into g pollutant emissions per kg fuel burned are presented in Appendix 1.

Discussion

Investigations by state entities, e.g. the UK Department for Transport (DfT 2016), have demonstrated large differences in fuel economy between NEDC conformity tests conducted in the laboratory and NEDC conformity tests conducted on-road. The PHEM model and the method above account for this effect:

- The VSP calculation is based on real-world road load and vehicle mass values which are higher than the type approval NEDC values,
- The fuel consumption maps used for elaborating the fuel flow functions with the model PHEM are real-world results,
- The energy consumption from auxiliaries like alternator, air conditioning etc. is considered in the VSP function.

Thus, the known reasons for deviations between NEDC fuel consumption and real world fuel consumption are corrected in the VSP based approach developed here. Additional differences, such as test tolerances, not balanced battery state of charge over NEDC tests etc., are not relevant here.

Converting remote sensing emission rates to any test cycle

Instantaneous remote sensing emission rates are often reported as concentrations of CO_2 and CO as % and HC, NO and NO_2 as ppm by volume. With knowledge only of the fuel being used, these can be restated as grams of emissions per kilogram of fuel. The equations for the conversions are presented in Appendix 1.

The typical vehicle specific power (VSP kW/t) distribution from remote sensing sites in the US is illustrated in Figure 5 together with the time distribution of positive VSP in the US06, WLTP and NEDC test cycles. The power distribution from the US remote sensing sites, which are mostly on-ramps to highways, approximates the US06 driving cycle used in the US Supplemental Federal Test Procedure (SFTP). This is a higher power distribution than found in WLTP or NEDC. Therefore the aggregate remote sensing emission rates do not reflect the driving conditions of WLTP without some transformation.

Figure 6 plots emissions of US diesel passenger cars as measured by remote sensing vs. VSP. The vehicles are divided into two age groups: 2009 and newer models, and pre-2009 models, respectively.

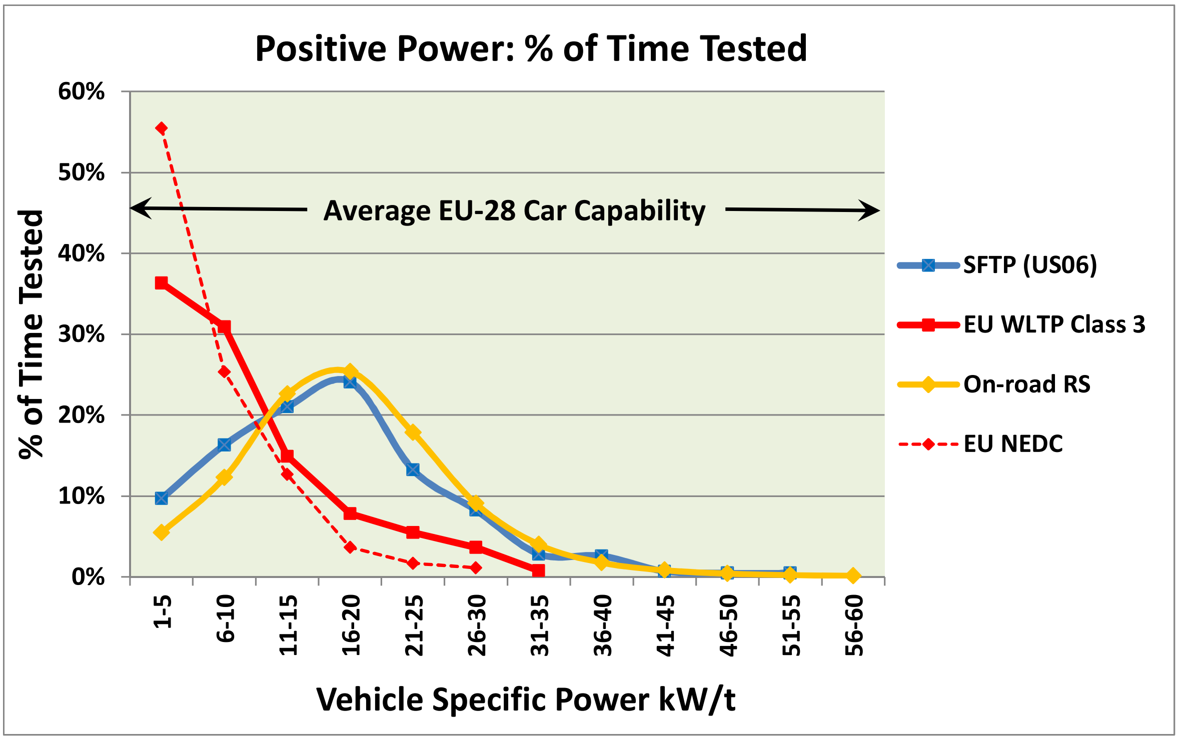

Figure 5. VSP distribution of remote sensing measurements of diesel passenger cars at survey sites in the US.

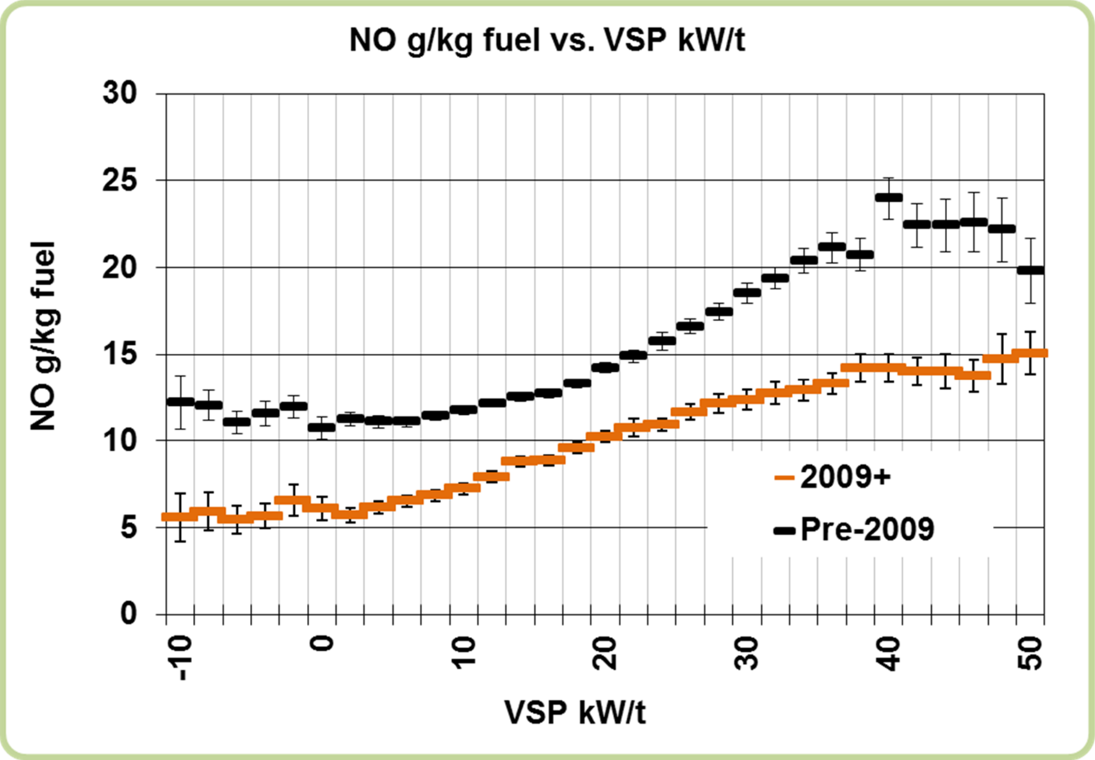

Figure 6. RSD US diesel passenger car NO emissions vs. VSP (2009+ = 2009 and newer models).

Three sets of data can now be combined:

- the VSP time distribution of a target test cycle, for example, WLTP,
- the remote sensing emission rate [g/kg] at each VSP, and
- the fuel rate [kg/s] at each VSP

to project emissions over the WLTP test cycle in g/km:

$$\{\sum_{vsp=-m}^{n} wltp\ seconds_{vsp}\ x\ rsd\ emissions\ g/kg_{vsp}\ x\ fuel\ kg/s_{vsp}\ \}/test\ distance\ km$$

Speed bins in addition to VSP

Figure 7 is a set of charts derived from the PHEM modal output for CADC example Euro 5 diesel passenger car, segment C, of emissions grams per kg of fuel vs. VSP kW/t. In this case VSP is the PWheel kW divided by the vehicle test mass of 1650 kg on CADC binned into 2 kW/t bins. These charts are similar to those derived from the remote sensing data.

In Figure 7, the PHEM modal output was split into two speed bins; 0-50 km/h and >50 km/h to take an initial look at the question of whether VSP alone is sufficient to categorize emissions. For example, the gradient of the main remote sensing site in Switzerland (Zürich-Gockhausen) is around 9 degrees (>4 %), which makes the vehicle power demand equivalent to highway driving (Chen and Borken-Kleefeld, 2014). However, the actual driving conditions are different, e.g. lower gears used on the gradient, immediate driving history of the vehicle, etc. The PHEM CO chart suggests there are significant variations at lower speed.

Whether there is a need for two or more speed bins to project emissions will be examined further using the on-road data. The US EPA MOtor Vehicle Emission Simulator (MOVES), the model used to project US mobile source emissions inventories, uses VSP bins and three speed bins; 1-40km/h, 40-80km/h and over 80 km/h[6].

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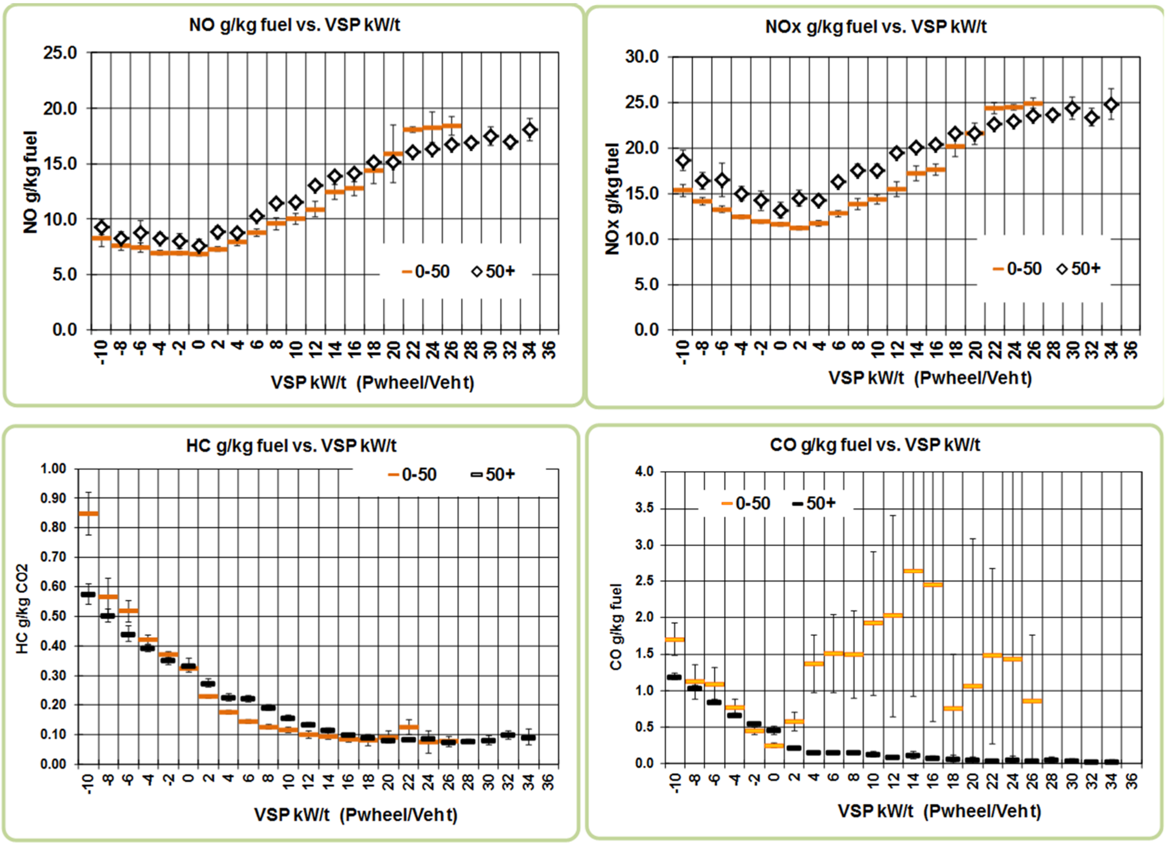
[6] EPA-420-B-12-037 'MOVES Operating Mode Distribution Generator Documentation Report' May 2012


NO g/kg fuel vs. VSP kW/t

NOx g/kg fuel vs. VSP kW/t

HC g/kg fuel vs. VSP kW/t

CO g/kg fuel vs. VSP kW/t

Figure 7. PHEM CADC Euro 5 diesel passenger car og segment C emissions vs. VSP (P-wheel).

Emission rates at idle and negative VSP

Remote sensing instruments measure emissions of vehicles driving on-road typically at speeds above 15 km/h. It also requires a certain minimum exhaust plume. The exhaust plume may become insufficient as VSP approaches zero.

Depending on the data collection sites it may be necessary to use an interpolated remote sensing emission rate in g/kg of fuel, i.e. start at the emissions level at the lowest reliable VSP value and then interpolate the remote sensing emission rates to match the shape of the PHEM g/kg fuel emission curve vs. VSP. The calculated mass of emissions [g/s] will approach zero as the fuel rate approaches zero.

Alternatively, one can compare PHEM and remote sensing emissions over an abbreviate test cycle using only positive VSP and make a reasonable assumption about the missing section. It is anticipated the covered section will include 80% of the total emissions with a large part of the missing 20% being idle emissions that are relatively easily obtained from other sources.

Related issues

Remote sensing measurements per VSP bin for a robust remote sensing emission rate

Opus has used a set of 4 million US remote sensing records to characterize emissions by vehicle type, where vehicles type was defined by vehicle class, weight class, fuel, make, engine size and model year. A simple estimate of 95% confidence interval of the emissions for each vehicle type was calculated as +/- $1.96\sigma/\sqrt{N}$ from measurements within a VSP range. Figure 8 shows the average confidence interval as a percentage of the mean emissions of each type vs. the square root of the number of measurements.

From this chart one can estimate average confidence intervals depending on the pollutant:

- 100 measurements +/- 35 to 80% (NO: +/- 45%);
- 400 measurements +/- 20 to 45% (NO: +/- 27%);
- 900 measurements +/- 15 to 30% (NO: +/- 22%);
- 1600 measurements +/- 12 to 24% (NO: +/- 17%);
- 2500 measurements +/- 10 to 20% (NO: +/- 14%).

The actual confidence interval for a particular vehicle type depends on the range of emissions within the type.

A reasonable goal would be to have at least 400 measurements in each Type bin. For plotting emissions vs. VSP for a Type or Segment, a suggestion would be at least 100 measurements per bin. The variability between successive bins will indicate the stability of the results.

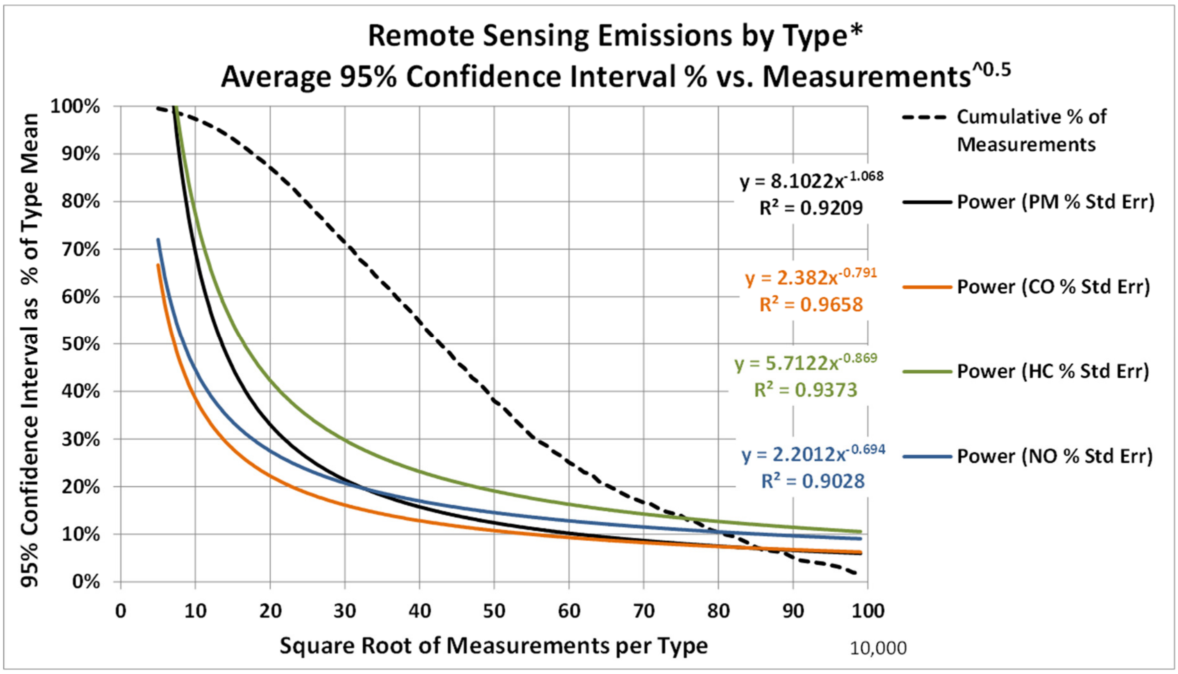


Figure 8. 95% confidence interval vs. number of measurements by Type.

What parameters to use for the characterization of vehicle groups

While RSD emissions measurements are fewer than 100,000 it makes sense to limit the number of vehicle segment bins, e.g. by fuel and the vehicle class segments in Table 1: A&B, C, D, EF&J and vans I, II and III.

In a study on cost and well-to-wheel implications of CO_2 regulations in the EU vehicle segments are characterized (Thiel *et al.*, 2014). Market and diesel shares for passenger cars and a chart of vehicle segment mass presented in this study are shown in Table 4 and Figure 9, respectively.

Table 4: Vehicle segments with market and diesel shares in the EU in 2010-2011 (Thiel *et al.*, 2014).

Segment	Segment name	Examples	Market share (%)		Diesel share (%)	
			2010	2011	2010	2011
A	Mini cars	Fiat 500, Smart Fortwo	10.0	8.7	7	7
B	Small cars	Opel Corsa, Peugeot 207	27.6	26.0	34	36
C	Medium cars	Volkswagen Golf, Renault Megane	24.1	23.3	55	58
D	Large cars	Ford Mondeo, BMW 3-series	10.4	11.0	77	80
E	Executive cars	Audi A6, Lexus GS	2.9	3.3	81	86
F	Luxury cars	Mercedes S-class, Maserati Quattroporte	0.3	0.3	61	70
J	Sport utility cars	Toyota RAV 4, Hyundai Santa Fe	10.3	12.9	75	75
M	Multi purpose cars	Citroen C4 Picasso, Honda F-RV	13.2	13.1	72	73
S	Sport coupes	Mazda MX-5, Porsche 911	1.2	1.3	24	28
Total					51	55

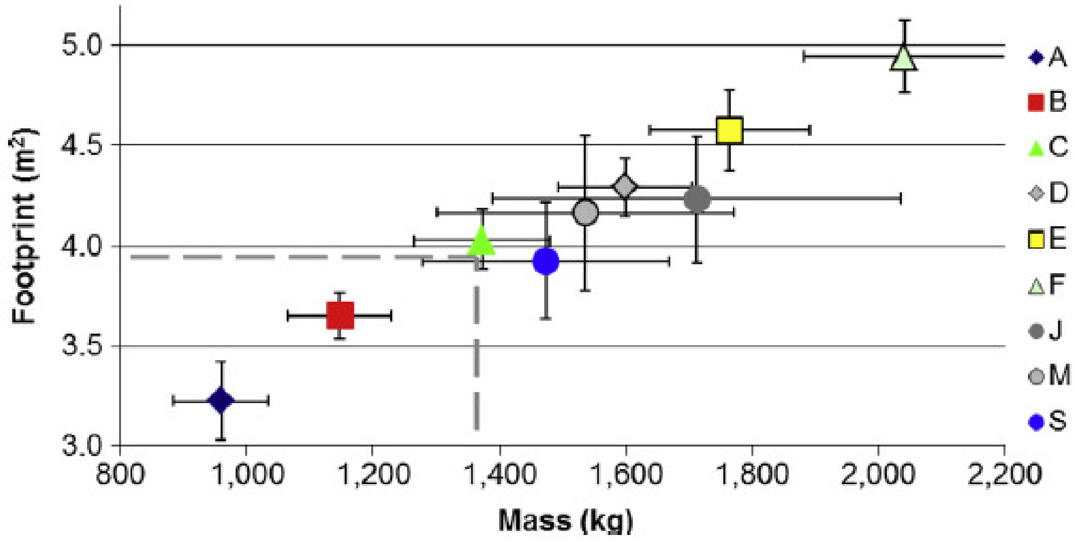


Figure 9. Vehicle Segment Mass based on Table 4 (Thiel *et al.*, 2014).

Multi-purpose cars could be combined with large cars or sport utility cars. This scheme creates seven vehicle classes across two fuel bins for a total of 14 bins. These will be further sub-divided by Euro standard.

As the number of measurements increases it will be possible to further segment vehicles by manufacturer and popular vehicle types.

Vehicle segments as currently defined are not entirely satisfactory because they overlap and there is no rigorous definition as to which segment a vehicle type belongs. In the long run it may be easier to categorize vehicles by fuel, vehicle class, weight class and engine size. These parameters can be automatically decoded from the unique vehicle identification number (VIN).

Time alignment between emission and vehicle speed & acceleration measurements

Remote sensing instruments measure the plume of tailpipe emissions behind a passing vehicle. Emissions created in the engine are subsequently reduced by the emissions control system after treatment and then emitted from the tailpipe. The time lag and the distance travelled by the vehicle between the time the emissions are created and their exit from the tailpipe depends on the exhaust system volume capacity, the exhaust rate proportional to the engine power output and the vehicle speed.

Jimenez (1999) estimated the distance travelled by a Jeep Cherokee while the exhaust travelled from the engine to the tailpipe. For typical remote sensing conditions this could vary from 5 to 15 meters.

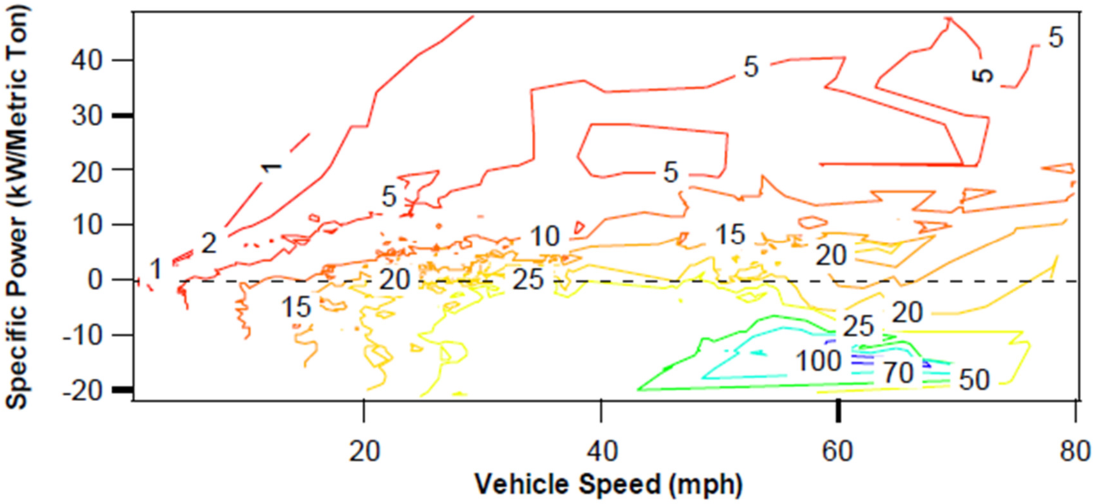


Figure 10. Vehicle distance traveled during exhaust transit (copied from Jimenez, 1999).

For practical reasons remote sensors typically have the speed and acceleration measurement coincident with the RS I/R and U/V measurement beams. Sites are selected where vehicles will be in a relatively steady operating mode as they approach and pass the remote sensing unit. The positioning of traffic cones is important to encourage this. Cones are placed well ahead of the measurement point so that any slowing occurs well in advance. By the time the vehicle enters within 20 meters of the RSD unit the clear road ahead is visible and the vehicle is accelerating.

It is not possible to say the VSP is always precise with respect to the emissions. However, emission rates in g/kg of fuel are not sensitive to small changes in VSP. Variations should also tend to average out with multiple measurements.

The issue of NO_X and NO_2

Most of the remote sensing data in the CONOX database, presently hosting about 700,000 records (=vehicle passages), do not include NO_2, since the NO_2 capability rather recently has become a feature of remote sensing. Therefore, a dedicated study and application of the developed method was done based on a subset of the CONOX dataset containing both NO and NO_2 (and thus NO_X) remote sensing measurements. This dataset was collected in 2013, and contained measurements on 8,300 diesel passenger cars from four locations in London, with slopes ranging from 0 to 3.75 % (Carslaw et al., 2015 and 2016). The diesel passenger car dataset was distributed as 1,058 Euro 3, 3,495 Euro 4, 3,494 Euro 5 and 65 Euro 6. The developed method was applied for each of the three car segments AB, C and D (cf. Table 1).

Based on the remote sensing dataset (e.g. speed and acceleration measurements) VSP was calculated for Euro 3 to Euro 5 diesel cars. The distribution over VSP bins is presented in Figure 11. Their average VSP was 7.9 kW/ton.

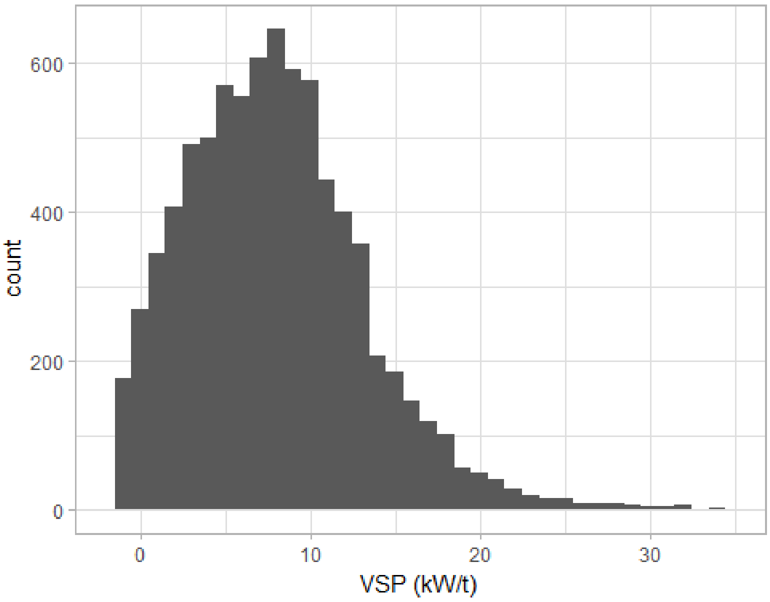


Figure 11. VSP distribution (number of cars measured by VSP bin) for Euro 3 to Euro 5 diesel passengers cars according to remote sensing measurements in London in 2013.

NO_X emissions as measured by remote sensing in London in 2013 as a function of VSP for Euro 5 diesel passenger cars, overall and split by vehicle segment, are presented in Figure 12. There is a good consistency across different car segments, i.e. the segment does not seem to matter when plotted in this way.

The same plot as in Figure 12, but for NO_2 emissions, is given in Figure 13. It seems clear that larger vehicles tend to be associated with higher NO_2 emissions.

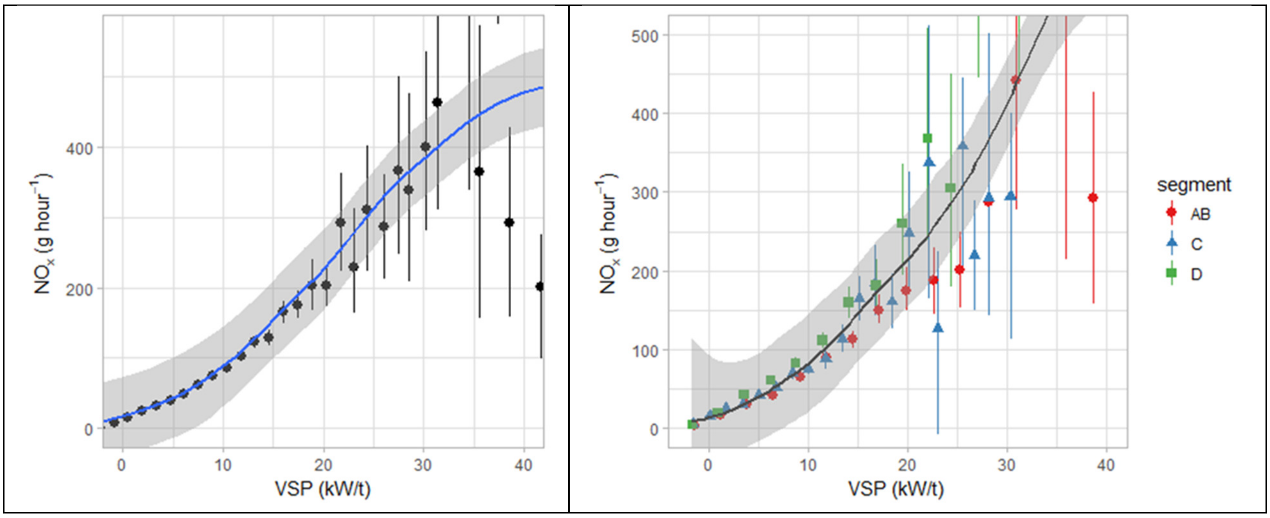


Figure 12. NO_x emission rates (in g/hr) vs VSP for Euro 5 diesel cars according to remote sensing measurements in London in 2013. The plot to the left represents all Euro 5 diesel cars, in the plot to the right the Euro 5 diesels have been split up into the three passenger car segments AB, C and D.

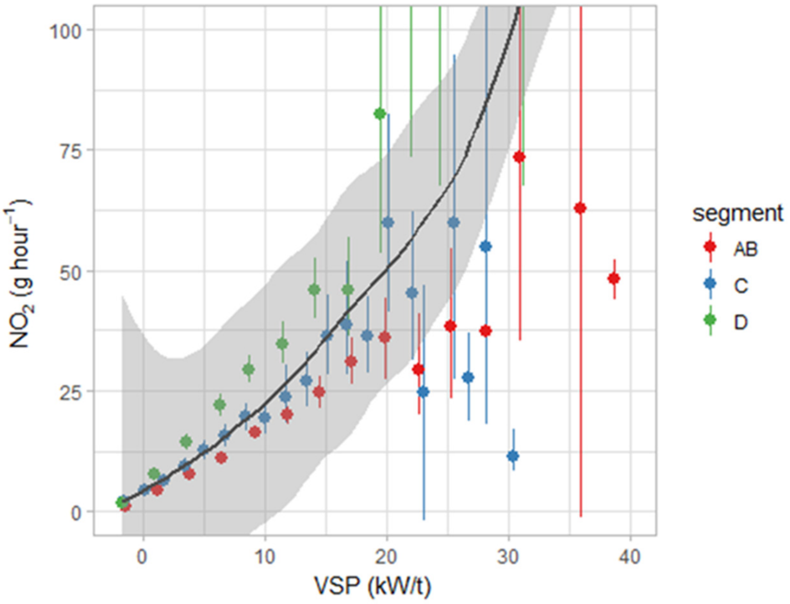


Figure 13. NO_2 emission rates (in g/hr) vs VSP for Euro 5 diesel cars according to remote sensing measurements in London in 2013, split by segment.

A further application of the developed method was undertaken to analyse NO_x and NO_2 emissions by vehicle manufacturer, as presented in Figure 14. There is roughly a factor of three difference between the lowest and the highest, with more detail available on specific models. Regarding emissions of NO_2, several manufacturers seem to have relatively high emissions from Euro 3 to Euro 5 (Volvo, Mercedes, Land Rover).

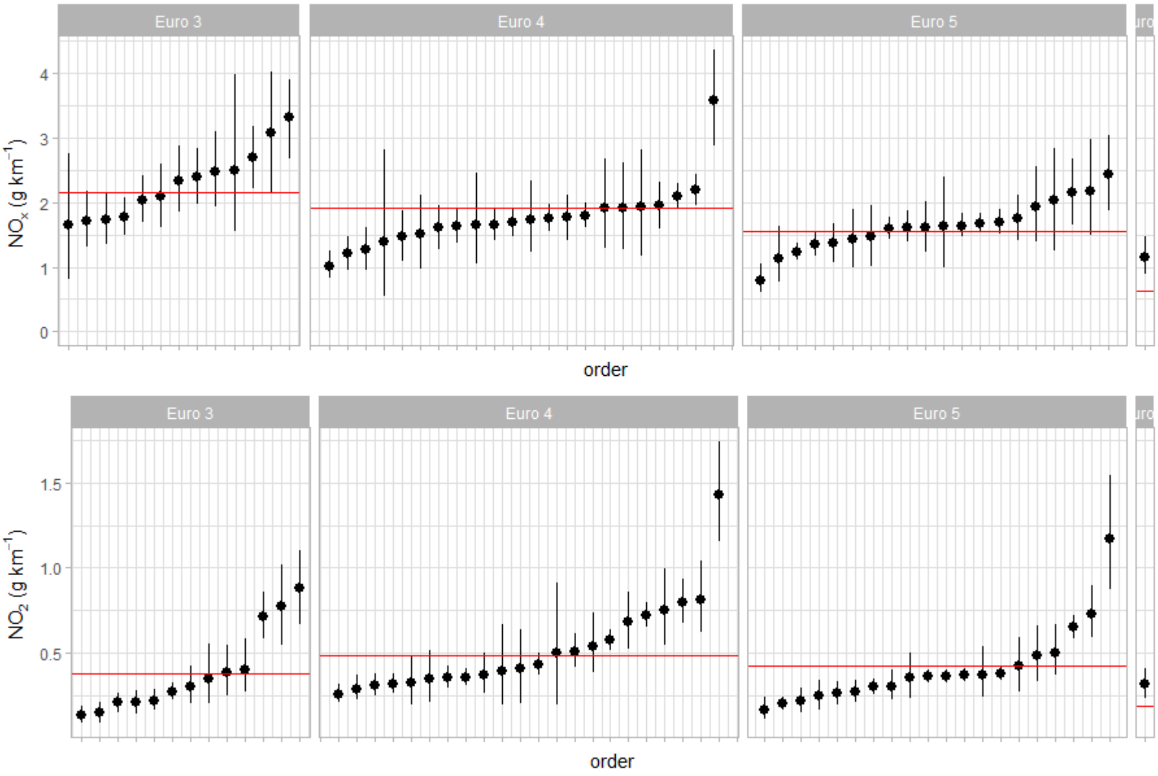


Figure 14. Average NO_x (top) and NO_2 (bottom) emissions for diesel passenger cars of Euro 3, 4 and 5 by vehicle manufacturer, ranked from left to right from the lowest to the highest (each point in the plots represents a vehicle manufacturer) . The red line represents the mean for each Euro standard.

Rather than VSP binning, a GAM smooth fit can be used as shown in the VSP plot in Figure 15, which provides a continuous function and can be directly applied to any 1 Hz VSP data (Ref David's TAP paper?). This relationship between NOx and VSP can be used to calculate NOx emissions over any other drive cycle where VSP is available.

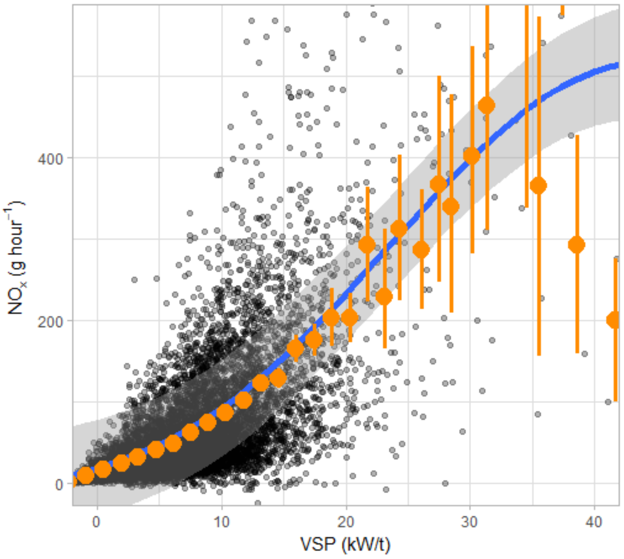


Figure 14. NO_x emissions (in g/hr) vs VSP from remote sensing measurements in London. Black points are individual remote sensing measurements, orange points are VSP-binning and the blue line represents the GAM fit.

Predicted NOx emissions in g/km for the Common Artemis Driving Cycle (CADC), a real-world driving cycle often used in chassis dynamometer measurements for generation of emission factor inputs to emission models, e.g. HBEFA, based on the London remote sensing measurements are presented in Table 5. Emissions over the CADC tend to be lower than the base London emissions (about 22% based on Euro 5 segment C). For a more precise evaluation it is probably useful to separately consider the urban, rural and motorway parts of the CADC.

Table 5. Predicted emissions of NOx (in g/km) for the CADC (Common Artemis Driving Cycle) based on the remote sensing measurements in London. Generic data suggested to be used per vehicle segment for average diesel passenger cars.

Euro standard	Vehicle segment	Estimated NOx (g/km) for the CADC
3	AB	1.34
	C	1.58
	D	1.78
4	AB	1.06
	C	1.30
	D	1.50
5	AB	0.85
	C	1.09
	D	1.29
6	AB	0.26
	C	0.50
	D	0.70

Conclusions and recommendations

In this study a method was developed to enable direct comparisons between real driving emission rates derived from remote sensing measurements and emission rates derived from measurements using more established (conventional) methods, e.g. for legislative emission testing, such as PEMS and chassis dynamometers.

The method relies on the ability of remote sensing measurements directly providing (by definition) instantaneous emission rates in gram pollutant per kilogram or liter fuel burned. As speed and acceleration measurements on an individual vehicle level today are an integral part in remote sensing measurements, the vehicle specific power (VSP) and thus instantaneous fuel flow (consumption) rates in kg or l fuel per unit distance travelled can be calculated. For the method these calculations were carried out by means of the PHEM model (Passenger Car and Heavy Duty Emission Model), developed and hosted by the Technical University of Graz. PHEM simulates fuel consumption and emissions from any vehicle in any driving situation based on engine maps and vehicle longitudinal dynamics simulation. PHEM modelling was used to produce representative fuel consumption values for various driving conditions for the most common segments of diesel and gasoline passenger cars by Euro standard with a 1Hz resolution. The calculated instantaneous fuel consumption data can be normalized to VSP to be applicable for the remote sensing evaluation which frequently uses VSP classes. This normalization also reduces the differences in the parameters between vehicle segments. In any case the method can be used to convert more aggregated as well as more disaggregated emission rates from remote sensing measurements into units such as gram pollutant emitted per unit distance driven (e.g. g/km) or per time unit (e.g. g/s).

By dividing large remote sensing datasets into a number of VSP bins, the proposed method can be used to convert remote sensing emission rates to any test cycle, such as the WLTP, for further comparisons.

The possibility of extending/refining the method to add also speed bins, in addition to VSP bins, and to take into account emissions at idle or negative VSP, for the comparison of remote sensing emission rates with emission rates from PEMS measurements or from chassis dynamometer measurements on real-world driving cycles has also been investigated.

Related issues that were also highlighted in the study were the number of remote sensing measurements per VSP bin for a robust remote sensing emission rate, what parameters to use for the characterization of vehicle groups and the influence of the time alignment between emission and vehicle speed & acceleration measurements

A slightly simplified version of the method was applied on Euro 5 and Euro 6 diesel passenger cars NO_X emissions within Task 2 of the CONOX project (>70,000 remote sensing measurements and >300 PEMS measurements), with results showing a very good agreement between remote sensing emission averages and emission averages from PEMS measurements on both on a more aggregated level (overall fleet samples) and on a more disaggregated level (e.g. comparing engine families).

It is recommended that the method is further refined and applied more systematically, for e.g. real driving emissions market surveillance and for validation or provision of mobile source inventory model emission factors.

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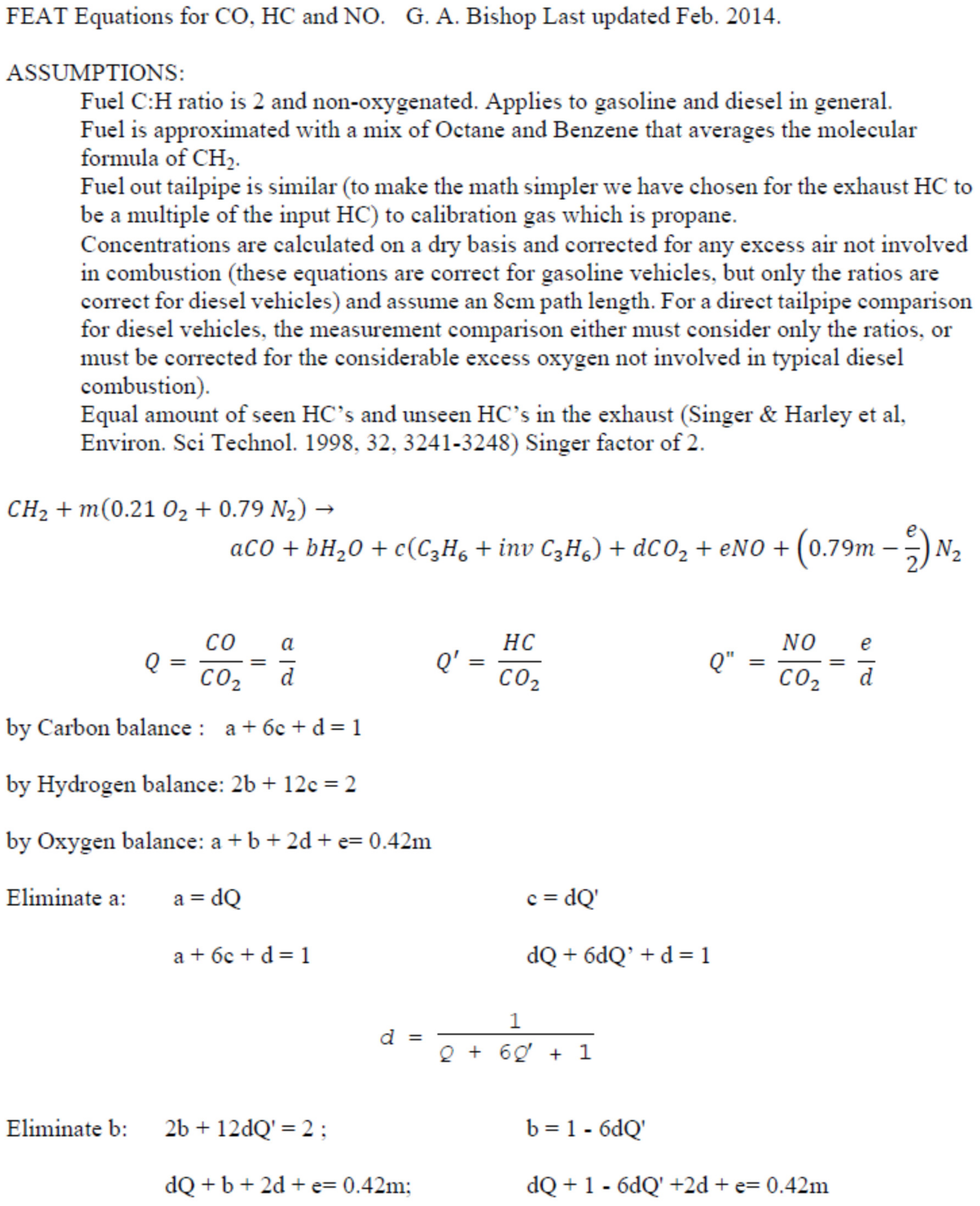
Appendix 1. Conversion of remote sensing data into gram pollutant emitted per kg fuel burned

The following text is copied from a dedicated document available at the Denver University Fuel Efficiency Automobile Test Data Center at:

http://www.feat.biochem.du.edu/assets/reports/FEAT_Math_II.pdf



FEAT Equations for CO, HC and NO.   G. A. Bishop Last updated Feb. 2014.

ASSUMPTIONS:

Fuel C:H ratio is 2 and non-oxygenated. Applies to gasoline and diesel in general.

Fuel is approximated with a mix of Octane and Benzene that averages the molecular formula of CH_2.

Fuel out tailpipe is similar (to make the math simpler we have chosen for the exhaust HC to be a multiple of the input HC) to calibration gas which is propane.

Concentrations are calculated on a dry basis and corrected for any excess air not involved in combustion (these equations are correct for gasoline vehicles, but only the ratios are correct for diesel vehicles) and assume an 8cm path length. For a direct tailpipe comparison for diesel vehicles, the measurement comparison either must consider only the ratios, or must be corrected for the considerable excess oxygen not involved in typical diesel combustion).

Equal amount of seen HC's and unseen HC's in the exhaust (Singer & Harley et al, Environ. Sci Technol. 1998, 32, 3241-3248) Singer factor of 2.

$$CH_2 + m(0.21\,O_2 + 0.79\,N_2) \rightarrow$$
$$aCO + bH_2O + c(C_3H_6 + inv\ C_3H_6) + dCO_2 + eNO + \left(0.79m - \frac{e}{2}\right)N_2$$

$$Q = \frac{CO}{CO_2} = \frac{a}{d} \qquad Q' = \frac{HC}{CO_2} \qquad Q" = \frac{NO}{CO_2} = \frac{e}{d}$$

by Carbon balance : $a + 6c + d = 1$

by Hydrogen balance: $2b + 12c = 2$

by Oxygen balance: $a + b + 2d + e= 0.42m$

Eliminate a: $a = dQ$ $c = dQ'$

$a + 6c + d = 1$ $dQ + 6dQ' + d = 1$

$$d = \frac{1}{Q + 6Q' + 1}$$

Eliminate b: $2b + 12dQ' = 2$; $b = 1 - 6dQ'$

$dQ + b + 2d + e= 0.42m$; $dQ + 1 - 6dQ' +2d + e= 0.42m$

substituting d from above:

$$0.42\,\frac{m}{d} = Q + \frac{1}{d} - 6Q' + 2 + Q'' = Q+Q+6Q'+1-6Q'+2+Q'' = 2Q + 3 + Q''$$

From the combustion equation the mole fraction of CO_2 is:

$$fCO_2 = \frac{d}{a + 2c + d + e + 0.79m - \frac{e}{2}}$$

divide numerator and denominator by d:

$$fCO_2 = \frac{1}{\frac{a}{d} + 2\frac{c}{d} + 1 + 0.5\frac{e}{d} + 0.79\frac{m}{d}}$$

substituting from above for a/d, c/d and e/d to get:

$$fCO_2 = \frac{1}{Q + 2Q' + 1 + 0.5Q'' + 0.79\frac{m}{d}}$$

multiply numerator and denominator by 0.42:

$$fCO_2 = \frac{0.42}{0.42Q + 0.84Q' + 0.42 + 0.21Q'' + (0.79)(0.42\frac{m}{d})}$$

substituting from above (0.42 m/d = 2Q + 3 + Q”) leads to:

$$fCO_2 = \frac{0.42}{2.79 + 2Q + 0.84Q' + Q''}$$

from which follows:

$$\%CO_2 = \frac{42}{2.79 + 2Q + 0.84Q' + Q''} = \frac{100}{6.64 + 4.76Q + 2Q' + 2.38Q''}$$

$$\%CO = Q * \%CO_2 \qquad \%HC = Q' * \%CO_2 \qquad \%NO = Q'' * \%CO_2$$

Some useful conversions are:

For grams/gallon assume fuel density of 726 g/l, a fuel carbon fraction of 86%, 3.79 l/gallon and for CO 28g/mole; for HC (propane, C_3H_8) 44g/mole for NO 30g/mole; for C 12g/mole:

$$\frac{gmCO}{gal} = \frac{28*Q*0.86*726*3.79}{(1+Q+6Q')*12}$$

$$\frac{gmHC}{gal} = \frac{2*44*Q'*0.86*726*3.79}{(1+Q+6Q')*12}$$

$$\frac{gmNO}{gal} = \frac{30*Q''*0.86*726*3.79}{(1+Q+6Q')*12}$$

We now prefer to use grams of pollutant/kg of fuel because it requires no assumption about the fuel density:

$$\frac{gmCO}{kg} = \frac{28*Q*860}{(1+Q+6Q')*12}$$

$$\frac{gmHC}{kg} = \frac{2*44*Q'*860}{(1+Q+6Q')*12}$$

$$\frac{gmNO}{kg} = \frac{30*Q''*860}{(1+Q+6Q')*12}$$

If you want to express the measured ratios in the units of other molecules, for example $gmNO_2/kg$ since all emitted NO will eventually oxidize in the atmosphere to NO_2, you only have to change the molecular weight of the species in the appropriate equation.

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