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A methodology to estimate real-world vehicle fuel use and emissions based on certification cycle data

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Abstract

This work presents a methodology to estimate vehicle fuel consumption and NO_x mass emission rates using only public certification data from individual vehicles. Using on-road data collected from 14 vehicles it was possible to establish trends of fuel use and emissions according with the power demand, using the Vehicle Specific Power methodology, which were further applied to estimate modal fuel consumption and NO_x emission rates on Diesel vehicles. Comparing with real-world operation, fuel consumption estimates presented average absolute deviations lower than 10%. Regarding NO_x estimates, average absolute deviation is around 22%. With this method it is possible to evaluate an individual vehicle using public data without have to measure it on-road and establishing links between certification and real-world vehicle operation.

*Keywords:*Vehicle certification; on-road vehicle monitoring; PEMS; fuel consumption; NO_x emission

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1. Introduction

Mobility of people and goods is assured by transportation sector, which is responsible for 30% of world's total energy delivered, accounting for road, rail, air, water and pipeline (U.S. Energy Information Administration, 2010) and within transportation sector, exhaust from road sources is responsible for the almost total NO_x and CO emitted and around 70% of $PM_{2.5}$ and 85% of NMVOC's (European Environment Agency, 2010). Therefore, it is important to develop tools that quantify the associated impacts regarding mobility, namely using vehicles.

The impacts of a vehicle trip can only be quantified in a rigorous way by doing on-road measurements using a portable emission monitoring system (PEMS) to collect vehicle dynamics, engine data, road topography and tailpipe gas concentration of pollutants during operation. However, it is not feasible to measure every vehicle technology performing selected driving cycles, therefore numerical tools are commonly used to simulate vehicle

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operation. Numerical tools can perform micro-simulation of vehicle use, such as Advisor, CMEM (Barth et al., 2000), EcoGest (Silva et al., 2006) or based on activity in a macro perspective, such as Copert.

Advisor is an example of micro-simulation numerical tool developed by National Renewable Energy Laboratory (NREL) of U.S. Department of Energy. It allows characterizing energy and emissions of a single vehicle, for a user-defined technology, performing a desired drive cycle. It is based on fuel consumption and emission maps, using a road load methodology based on vehicle speed, acceleration, aerodynamic and rolling resistance as well as topography to estimate the power demanding to the engine, defining the correspondent engine speed and load. To each point in the driving profile is assigned the correspondent power and consequently the engine operation point (RPM, Load) in fuel consumption and emission maps (Wipke et al., 1999). As a drawback, a correct analysis of vehicle energy use and emission outcomes implies a deep knowledge of the vehicle characteristics.

Copert is also a numerical tool that allows to determinate emissions associated to road transport. It has been developed by European Environment Agency and scientifically coordinated by Joint Research Center. The Copert methodology is based on a transport emission inventory included on EMEP/EEA guidebooks. It considers different typologies of motor vehicles - passenger cars, light duty vehicles, buses, mopeds and motorcycles – and uses emission factors to estimate pollutant emissions (CO, NO_x, VOC, PM, NH_3, SO_2, heavy metals) and greenhouse gases (CO_2, N_2O ,CH_4) (Ntziachristos et al., 2009; Gkatzoflias et al., 2007; Ntziachristos & Samaras 2012). This methodology is based on vehicle activity and uses as inputs average speed, distribution of time under urban, rural and highway environments, vehicle typology and engine displacement.

The use of emission factors (g/km of fuel or pollutants) is also common in traffic simulation models, such as $VERSIT^+$ by TNO, which is the base of traffic modeling tools like PTV VISSIM. $VERSIT^+$ is based on road measurements on different driving profiles and vehicle technologies and age (Smit et al., 2006; Smit et al. 2007). This tool evaluates the studied drive profile, which characteristics best fit with the measured and assigns the correspondent fuel use factor, CO_2, CO, HC, NO_x and PM_{10} emission factors. On-road measurements were used to calibrate the model, as the driving cycle used for type-approval test is a simplification of real-world driving patterns (Smit et al., 2006).

The New European Driving Cycle (NEDC) is recognized as a low load cycle, with only a small range of vehicle/engine operation being used (Farnlund & Engstrom, 2002). Hence, several studies have addressed the feasibility of NEDC comparing with on-road, real-world vehicle operation, regarding fuel use and pollutant outcomes (Tzirakis et al., 2006; Pelkmans & Debal, 2006; Weiss et al., 2011; Sturm et al., 1998; Keller et al., 2011; Rhys-Tyler & Bell, 2012). Discrepancies between real-world and standard cycle can go up to 20% regarding fuel use and a factor of 2 to 4 for NO_x emission.

Independently of its applicability under real-world conditions, every new vehicle sold in Europe must comply with the current EURO standards, which regulates CO, HC, NO_x and PM emission over a standard driving cycle (NEDC – New European Driving Cycle). Certification data includes regulated pollutant emission (in g/km) and fuel consumption (in liters/100 km), is public, easily available for all vehicles sold in Europe and is also used to guide potential vehicle buyers.

Therefore, under the motto of “can we do more with less resources?” this work presents a methodology that use only certification data as inputs to determine Vehicle Specific Power modal fuel and NO_x emission rates for specific vehicles that can be further applied on desired driving cycles.

Nomenclature

CI	Compression-ignition (diesel-fuelled)
ECE-15	Urban part of NEDC
EUDC	Extra-urban part of NEDC

NEDC	New European Driving Cycle
OBD	On-Board Diagnostic
SI	Spark-ignition (gasoline-fuelled)
VSP	Vehicle Specific Power

2. Experimental methods

On-road measurements were performed to evaluate different vehicle technologies using a PEMS to collect vehicle dynamics, engine parameters, tailpipe emissions and road grade, while the vehicle is being operated. The PEMS used includes the following equipment (Gonçalves, 2005):

- On-board diagnostics port reader from OBDKey to collect engine data
- Vetronix PXA 1100 gas analyzer to collect tailpipe gas concentrations
- GPS receiver Garmin GPSMap 76CSx to collect altitude using barometric altimeter

Using a PEMS it is possible to collect in a second-by-second basis vehicle dynamics (speed and acceleration), engine data (RPM, engine load, mass air flow, among others), tailpipe gas concentrations and road grade. This information is then analyzed using the Vehicle Specific Power (VSP) methodology to assign the correspondent power demand (in W/kg) due to a combination of speed, acceleration and road grade, as shown in (Jiménez-Palacios, 1999). Therefore, each second of driving is assigned the correspondent VSP and a modal analysis is used to group points of similar power per mass (W/kg) demand (Frey et al., 2003; Frey et al., 2007; EPA, 2002).

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot grade + 0.132) + 3.02 \cdot 10^{-4} \cdot v^3 \tag{1}$$

Fourteen EURO 5 vehicles, comprehending eleven CI vehicles and three SI vehicles were tested under on-road real-world conditions for an average of around 2 hours of driving in urban and extra-urban conditions to fully characterize VSP modes. Figure 1 presents a typical curve of fuel consumption rate according to the VSP, found for conventional technologies, derived from on-road operation. Hence, there are six unknown variables and three generic equations. Considering that NEDC fuel consumption results from the fuel consumption rate at each VSP mode and the time-distribution of each VSP mode, ECE-15 and EUDC global fuel consumption for each vehicle provide 2 equations. The remaining four equations result from physical assumptions of continuity in fuel consumption and continuity of the derivative, resulting in six unknown variables and six equations.

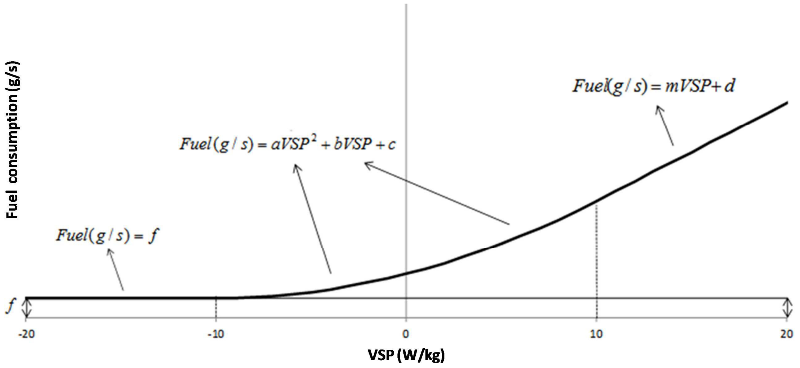

Fig. 1. Generic trend of fuel consumption as function of VSP mode, using three generic equations and six variables

A similar approach was established for NO_x emission, dependent of VSP mode and vehicle properties. From NEDC only a global value is available, hence using 11 CI vehicles, a method was developed based on a typical emission trend according with VSP found under on-road measurements. Vehicle properties, such as weight, engine power and displacement and certification emission factor were used to assign the correspondent emission rate value.

$$\frac{Ratio\ NO_{x,i}}{Average\ positive\ Ratio\ NO_x} = \frac{\frac{NO_{x_{On-road}}[g/s]}{NO_{x\_NEDC}[g/s]}}{Average\left[\frac{NO_{x_{On-road,Positive\ VSP}}[g/s]}{NO_{x\_NEDC}[g/s]}\right]}\ , i = VSP\ mode \tag{2}$$

Figure 2a) presents the generic NO_x emission trend found for 11 CI vehicles under real-world operation, as defined by (2). Figure 2b) presents how the Average Positive Ratio NO_x is affected by the vehicle characteristics, as was found using 10 vehicles tested under on-road measurements.

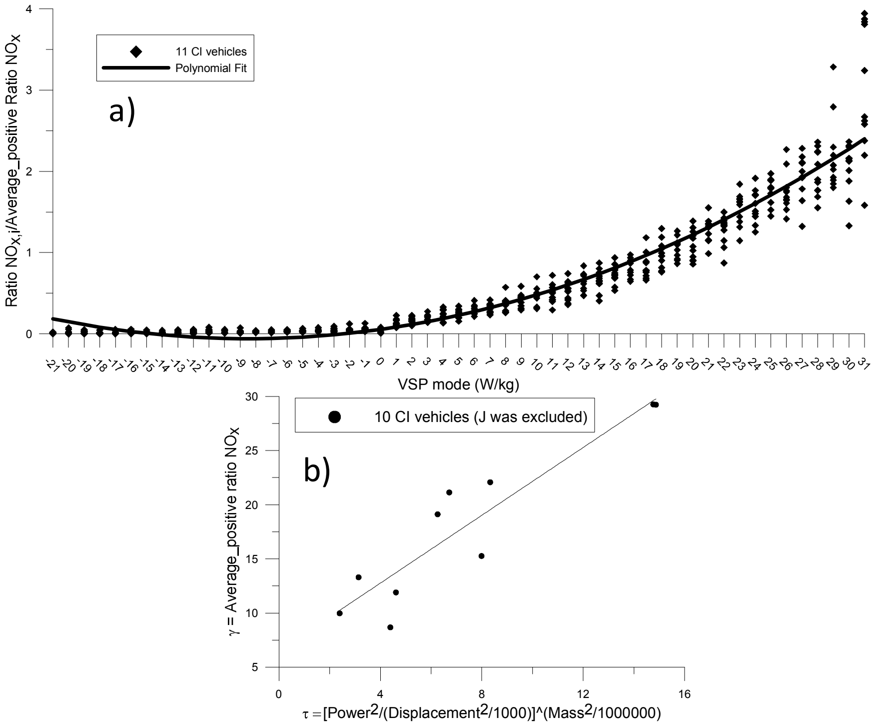

Fig. 2. (a) Ratio between on-road and certification NO_x adimensionalised by the average positive value, according with (2) for 11 CI vehicles; (b) Average positive Ratio NO_x (γ) as a function of engine power, displacement and vehicle mass (τ) for 10 vehicles

3. Results

3.1. Fuel consumption

Using the approach developed, fuel consumption estimates provided by the methodology and measured under on-road conditions can be compared. Two approaches were followed: using only certification data to obtain the estimates of fuel consumption and using on-road data to correct estimates provided when using only certification values. The last approach is intrinsically related with the issues described by several authors about representativeness of certification cycle (Tzirakis et al., 2006; Pelkmans & Debal, 2006; Weiss et al., 2011; Sturm et al., 1998; Keller et al., 2011; Rhys-Tyler & Bell, 2012).

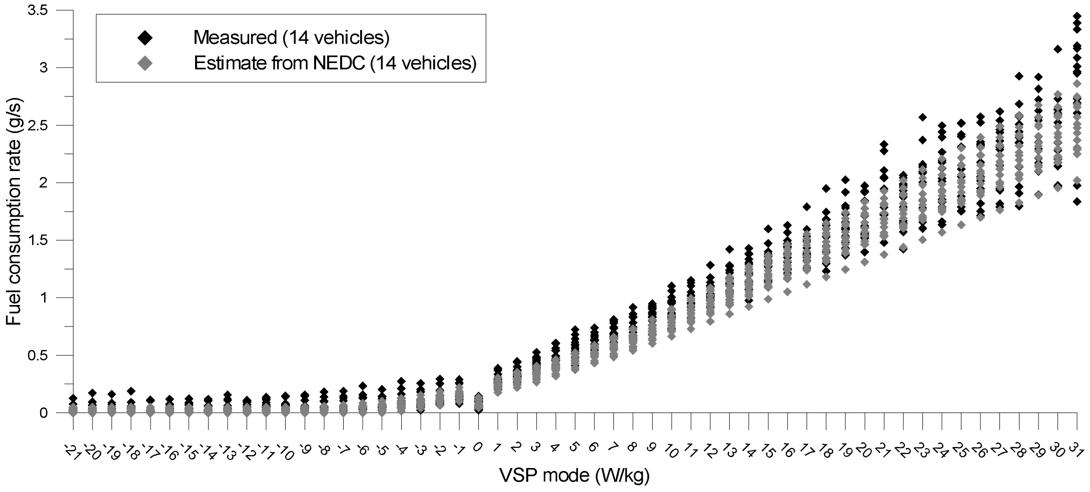

Fig. 3. Comparison of fuel consumption rates for each VSP mode between estimates from certification and on-road measurements

Figure 3 presents the estimates of modal fuel consumption rates using only each vehicle certification values. It can be seen that the model is sensible to the inputs (public, easily available ECE-15 and EUDC fuel consumption data). It also can be seen that it follows the trend and magnitude of on-road measurements (black dots). Table 1 presents the coefficients of determination between modal fuel consumption estimates and measurements using only certification data and correcting these estimates using on-road data, which accounts for real-world operation and off-cycle conditions. On average, the R^2 values are higher than 0.9, showing good agreement between estimates and measurements. Both approaches presents similar R^2 values, however, if vehicles C and D were excluded (monitored for shorter periods), R^2 would increase to 0.960 and 0.967 using certification input only and correcting certification with on-road data, respectively. The last approach, combining certification and on-road corrections to cope with off-cycle conditions, will be further referred as Model.

Table 1. Summary of R^2 for the 14 vehicles studied, comparing certification based estimates versus on-road measurements and certification based corrected estimates versus on-road measurements

Vehicle	A	B	C	D	E	F	G	H	I	J	K	L	M	N	**Av.**
R^2 Certification	0.974	0.976	0.788	0.709	0.948	0.979	0.983	0.968	0.910	0.920	0.971	0.983	0.986	0.925	**0.930**
R^2 Cert+On-road	0.989	0.961	0.645	0.784	0.978	0.964	0.992	0.986	0.950	0.961	0.985	0.988	0.968	0.881	**0.931**

Table 2. Comparison of integrated second-by-second measured fuel consumption with modal VSP approach using estimates provided by certification data (Cert. Based) and estimates provided by certification corrected by on-road data (Model)

	Inputs		On-road Trip (g)			Deviation (%)		
	ECE-15 (l/100)	EUDC (l/100)	Measured	Cert. Based	Model	Cert. Based	Model	
Vehicle A	7.3	5	10413.6	8926.2	9798.2	-14.3%	-5.9%	5.9%
Vehicle B	5.1	3.9	9121.6	8272.2	9090.3	-9.3%	-0.3%	0.3%
Vehicle C	5.9	4.3	2786.1	3025.1	3391.4	8.6%	21.7%	21.7%
Vehicle D	5.2	3.7	3707.6	2234.7	2478.2	-39.7%	-33.2%	33.2%
Vehicle E	4.3	3.4	2424.6	1938.0	2153.7	-20.1%	-11.2%	11.2%
Vehicle F	5.1	4	2372.2	2300.6	2549.9	-3.0%	7.5%	7.5%
Vehicle G	5.9	4.3	2377.6	2163.3	2433.4	-9.0%	2.3%	2.3%
Vehicle H	5.2	3.8	4084.3	3758.0	4185.7	-8.0%	2.5%	2.5%
Vehicle I	5.3	3.7	4435.6	3589.2	3984.9	-19.1%	-10.2%	10.2%
Vehicle J	3.9	3.3	3152.7	2378.4	2650.6	-24.6%	-15.9%	15.9%
Vehicle K	5.4	3.9	4305.3	3888.2	4309.5	-9.7%	0.1%	0.1%
Vehicle L	5.1	3.6	3444.2	3369.6	3759.9	-2.2%	9.2%	9.2%
Vehicle M	5.4	3.8	3795.4	3619.8	4019.0	-4.6%	5.9%	5.9%
Vehicle N	5.8	4.3	3290.7	2864.7	3186.4	-12.9%	-3.2%	3.2%
					Average	**-12.0%**	**-2.2%**	**9.2%**
					St. Dev.	11.6%	13.1%	9.2%
				Excluding C and D	Average	**-11.4%**	**-1.6%**	**6.2%**
					St. Dev.	7.0%	7.9%	4.8%

Table 2 presents the comparison between the integral of fuel use for each vehicle measured under on-road conditions and estimates provided by the model. It can be seen that using estimates provided only by certification data there is an underestimation of fuel consumption of -12% (or -11.4%, excluding vehicles C and D). Using certification estimates corrected by on-road data (Model), there is an improvement on average deviation (-2.2±13.1% or -1.6±7.9%, excluding vehicles C and D) and on average absolute deviation, which does not exceed 10% (or 6.2±4.8% excluding vehicles C and D).

3.2. NO_x emission

Regarding NO_x estimates there are less certification inputs available, therefore other vehicle properties were used as complement. Also, due to the disparity found between certification and on-road NO_x emission found during the development of this work and in-line in other studies (Tzirakis et al., 2006; Pelkmans & Debal, 2006; Weiss et al., 2011; Sturm et al., 1998; Rhys-Tyler & Bell, 2012), on-road corrections were included from the beginning of the development of the model.

Table 3. Summary of R^2 for the 11 CI vehicles studied comparing modal model estimates versus on-road measurements

Vehicle	B	C	E	F	G	H	I	J	K	L	M	**Av.**
R^2	0.915	0.809	0.964	0.856	0.945	0.925	0.952	0.586	0.854	0.889	0.512	**0.837**

Table 3 summarizes the R^2 between modal estimates and on-road measurements. On average, the R^2 is higher than 0.8, presenting a good agreement. The vehicles with lower R^2 are one very particular three-cylinder, 1.1 liter of engine displacement, that shows very high on-road emissions (vehicle J) and vehicle M, that shows constantly very low mass emission rates under real-world operation.

Table 4. Comparison of integrated second-by-second measured NO_x emission with modal VSP estimates provided by the model

	Inputs				**On-road Trip (g)**		**Deviation (%)**	
	NEDC NO_x (g/km)	**Power (kW)**	**Displacement (cm^3)**	**Mass (kg)**	**Measured**	**Model**	**Model**	
Vehicle B	0.142	105	1995	1225	101.4	111.6	10.1%	10.1%
Vehicle C	0.139	70	1248	1360	58.4	40.9	-30.0%	30.0%
Vehicle E	0.137	96.9	1686	1503	59.0	56.3	-4.5%	4.5%
Vehicle F	0.162	82	1560	1430	35.5	43.8	23.4%	23.4%
Vehicle G	0.137	80.5	1461	1285	30.2	23.8	-21.1%	21.1%
Vehicle H	0.104	77.2	1598	1499	54.9	42.3	-23.0%	23.0%
Vehicle I	0.129	84.3	1685	1713	92.0	88.2	-4.1%	4.1%
Vehicle J	0.149	55.2	1120	1191	62.3	31.4	-49.6%	49.6%
Vehicle K	0.125	85	1995	1385	44.9	36.5	-18.7%	18.7%
Vehicle L	0.173	55.2	1248	1140	34.4	38.1	10.8%	10.8%
Vehicle M	0.150	79.8	1796	1475	33.4	46.3	38.5%	38.5%
						Average	**-6.2%**	**21.3%**
						St Dev	**25.6%**	**14.1%**
					Excluding Vehicle J	**Average**	**-1.9%**	**18.4%**
						St Dev	**22.3%**	**11.1%**

Table 4 compares integration of second-by-second on-road NO_x emission with estimates provided by the model. It can be seen that average deviation is -6.2±25.6% (or -1.9±22.3% excluding vehicle J). Absolute average deviation is -21.3±14.1% (or 18.4±11.1% excluding vehicle J). Although the deviations can be seen as high, the inputs are very limited and based on each vehicle properties.

4. Summary and Conclusions

As a result of the present study, the methodology proposed in this work is able to start from certification data to define modal emission rates of fuel consumption and NO_x emission according to VSP mode. This data can be further used in any other driving cycle, using the correspondent VSP time distribution, to estimate fuel use and emission outcome in a given vehicle or a fleet of vehicles. Figure 4 presents a schematics of the inputs necessary and the procedures to calculate fuel and emission on any desired drive cycle.

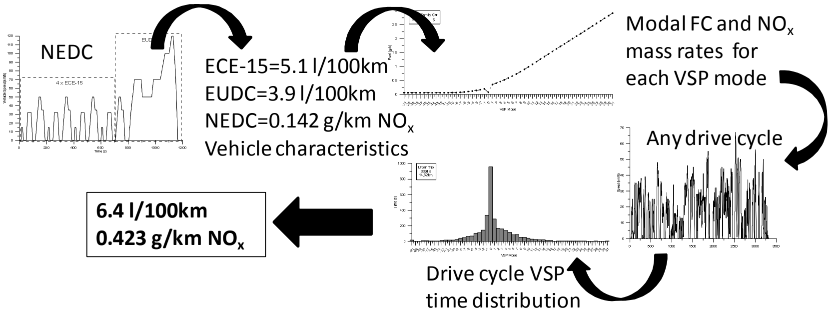

Fig. 4. Schematics of algorithm of the methodology proposed

Summarizing, using a portable emission measurement system, fuel consumption and emissions were monitored under on-road conditions on 14 conventional vehicles (SI and CI). With this data a generic fuel consumption curve was built as function of the specific power due to road topography and vehicle dynamics - speed and acceleration -, according to the Vehicle Specific Power (VSP) methodology. Using the certification cycle VSP modal time distribution and considering that each VSP mode has a fuel consumption rate (in g/s) associated, the finding of the coefficients that compose the generic curve is the result of the integration of these inputs. On-road data was used to correct the estimates provided by certification. Comparing on-road measurements and estimates, a R^2 value was found higher than 0.9 regarding modal fuel consumption rates. Comparing the measured drive cycles for each vehicle and using the estimates on the same cycle, an absolute deviation of 9.2%±9.2% (6.2%±4.8% if two suspicious vehicles were not considered) was found for conventional SI and CI vehicles.

A method was also developed to estimate NO_x mass emissions on Diesel vehicles. Mass emission rate of NO_x (in g/s) as function of VSP was obtained using a typical emission curves found using on-road data from 11 CI vehicles and a relation between the ratio of NO_x measured on-road and certification data. This ratio was found to be function of engine displacement, maximum power and vehicle weight. The comparison of real-world measurements and estimates provided by the model show an average R^2 value higher than 0.8. Comparing measured, real-world, drive cycles of each vehicle and the estimates for the same drive cycle resulted in an absolute deviation of 21.3%±14.1% or 18.4%±11.1% if the only 3 cylinder vehicle tested was excluded.

With this method, without the need to monitor the vehicle and in a fast way, it is possible to estimate curves of fuel consumption and mass emission rates of NO_x, in g/s, as a function of Vehicle Specific Power. With this information it is possible to find the absolute fuel use and NO_x emission for any driving cycle.

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