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# Establishing bonds between vehicle certification data and real-world vehicle fuel consumption – A Vehicle Specific Power approach

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ABSTRACT

A method to perform the energy characterization of a vehicle according to the specific power required while driving was developed using public vehicle certification data. Using a portable emission measurement system, fuel consumption was quantified in a second-by-second basis under on-road conditions for 19 vehicles (spark-ignition, compression-ignition and hybrids). This data allowed building generic curves of fuel consumption as a function of the specific power, according to Vehicle Specific Power methodology. Comparing on-road measurements and the model estimates, a $R^2$ higher than 0.9 for conventional and hybrid vehicles was obtained regarding modal fuel consumption. Comparing the fuel consumption measured on the drive cycles performed by each vehicle and the correspondent estimates, an absolute deviation of 9.2% ± 9.2% was found for conventional vehicles and 4.7% ± 1.8% for hybrids vehicles. This methodology was validated and applied to estimate the energy impacts of the best-selling vehicles in Portugal for different driving cycles. This prompt method, that does not require vehicle monitoring, can estimate curves of fuel consumption in g/s, as a function of specific power, which allows quantifying the absolute fuel use for any driving cycle.



## 1. Introduction

In Europe, vehicle certification data regarding fuel consumption, $CO_2$ and regulated pollutant emissions is public, easily available and is obtained from vehicle testing on a standard driving cycle (the New European Driving Cycle – NEDC). However, NEDC is recognized as a low load cycle and hardly representative of real world driving patterns, where vehicles may be optimized to the test driving conditions [1]. The gaps between laboratorial tests and on-road measurements have been addressed in a study carried by the European Commission Joint Research Center using a portable emission monitoring system (PEMS) on 12 vehicles ranging from EURO 3 to EURO 5 [2], concluding that $CO_2$ emissions are over 21 ± 9% higher on-road tests on typical rural and highway routes when comparing with NEDC. Moreover, performing NEDC under laboratory conditions, $CO_2$ values exceeded 15 ± 10% compared to certification values.

The European Commission Joint Research Center has also compared type-approval certification data and real-world fuel consumption from several sources (including studies from ADAC organization in Germany, Artemis project, automotive journals and vehicle owner's data), in order to establish correlations between these two indicators [3]. This study confirms that certification data underestimates fuel consumption by 10–15% on gasoline vehicles and 12–20% on diesel vehicles. Correlations were developed to predict real-world fuel consumption (in l/100 km) based on vehicle characteristics, such as engine displacement, vehicle mass and fuel consumption on certification cycle, but these do not consider the driving cycle.

A study carried in England by Rhys-Tyler and Bell [4] used data from remote sensing surveys carried in 2008 as input to fill Vehicle Specific Power (VSP) modal bins with real vehicle operation emission rates and use them to reconstruct the New European Driving Cycle and provide pollutant emissions estimates. Vehicle Specific Power methodology consists of a road load modal analysis based on vehicle dynamics and road topography, which groups experimental data points with similar power conditions, allowing the comparison of fuel and emission rates, independently of the driving cycle [5].

*Abbreviations:* CO, carbon monoxide; $CO_2$, carbon dioxide; HC, hydrocarbons; ICE, internal combustion engine; NEDC, New European Driving Cycle; NO, nitrogen oxide; $O_2$, oxygen; OBD, on-board diagnostic port; PEMS, portable emission monitoring system; SAE, Society of Automotive Engineers; SFC, specific fuel consumption; SOC, state-of-charge; TTW, Tank-to-Wheel; VSP, Vehicle Specific Power; WTT, Well-to-Tank; WTW, Well-to-Wheel.

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**Table 1**
VSP binning and ranges of W/kg for each mode.

| VSP mode | W (kg) | VSP mode | W (kg) | VSP mode | W (kg) | VSP mode | W (kg) | VSP mode | W (kg) | VSP mode | W (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| −21 | VSP < −20 | −12 | −12 ⩽ VSP < −11 | −3 | −3 ⩽ VSP < −2 | 6 | 5 < VSP ⩽ 6 | 15 | 14 < VSP ⩽ 15 | 24 | 23 < VSP ⩽ 24 |
| −20 | −20 ⩽ VSP < −19 | −11 | −11 ⩽ VSP < −10 | −2 | −2 ⩽ VSP < −1 | 7 | 6 < VSP ⩽ 7 | 16 | 15 < VSP ⩽ 16 | 25 | 24 < VSP ⩽ 25 |
| −19 | −19 ⩽ VSP < −18 | −10 | −10 ⩽ VSP < −9 | −1 | −1 ⩽ VSP < 0 | 8 | 7 < VSP ⩽ 8 | 17 | 16 < VSP ⩽ 17 | 26 | 25 < VSP ⩽ 26 |
| −18 | −18 ⩽ VSP < −17 | −9 | −9 ⩽ VSP < −8 | 0 | VSP = 0 | 9 | 8 < VSP ⩽ 9 | 18 | 17 < VSP ⩽ 18 | 27 | 26 < VSP ⩽ 27 |
| −17 | −17 ⩽ VSP < −16 | −8 | −8 ⩽ VSP < −7 | 1 | 0 < VSP ⩽ 1 | 10 | 9 < VSP ⩽ 10 | 19 | 18 < VSP ⩽ 19 | 28 | 27 < VSP ⩽ 28 |
| −16 | −16 ⩽ VSP < −15 | −7 | −7 ⩽ VSP < −6 | 2 | 1 < VSP ⩽ 2 | 11 | 10 < VSP ⩽ 11 | 20 | 19 < VSP ⩽ 20 | 29 | 28 < VSP ⩽ 29 |
| −15 | −15 ⩽ VSP < −14 | −6 | −6 ⩽ VSP < −5 | 3 | 2 < VSP ⩽ 3 | 12 | 11 < VSP ⩽ 12 | 21 | 20 < VSP ⩽ 21 | 30 | 29 < VSP ⩽ 30 |
| −14 | −14 ⩽ VSP < −13 | −5 | −5 ⩽ VSP < −4 | 4 | 3 < VSP ⩽ 4 | 13 | 12 < VSP ⩽ 13 | 22 | 21 < VSP ⩽ 22 | 31 | VSP > 30 |
| −13 | −13 ⩽ VSP < −12 | −4 | −4 ⩽ VSP < −3 | 5 | 4 < VSP ⩽ 5 | 14 | 13 < VSP ⩽ 14 | 23 | 22 < VSP ⩽ 23 | | |

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 and, as a result, numerical tools are commonly used to simulate vehicle operation. Numerical tools can perform micro-simulation of vehicle use, such as Advisor [6], CMEM [7], EcoGEST [8] or based on activity in a macro perspective, such as Copert [9,10]. Some of the numerical tools referred are too complex, in order to account for the exact vehicle characteristics and driving profile, but some are too simple and too generic to provide an accurate analysis.

Considering that all new vehicles are certified over a standard driving cycle, homologation data should intrinsically reflect both vehicle technology, as well as properties, such as mass, aerodynamics and powertrain characteristics. As stated, it is not feasible to characterize all vehicles under real-world usage. Therefore, this research work main purpose was to develop a methodology that, using individual public certification data, could provide fuel consumption and pollutant emissions profiles, independently of vehicle technology (spark-ignition, compression-ignition, hybrids). Using this information as input, it is possible to evaluate driving cycles without the need to perform field measurements and establish links between real-world usage of vehicles and certification data, but also between laboratorial and simulation fields of scientific application.

## 2. Materials and methods

Fuel consumption was assessed for 19 EURO 5 vehicles sold in the European market, covering the most representative segments in vehicle sales, comprising the following vehicle technologies: conventional gasoline spark-ignition; conventional diesel compression-ignition; gasoline parallel hybrid; and gasoline parallel/series hybrid.

Fuel consumption was measured through on-road measurements, performed in the Lisbon Metropolitan Area, Portugal, using a portable emission measurement system (PEMS) collecting data at 1 Hz. Two types of routes were chosen: a primary itinerary which includes urban, extra-urban and highway roads; and a secondary itinerary almost exclusively in urban driving context.

### *2.1. PEMS description*

A PEMS system was installed in all vehicles to collect data in a second-by-second basis, namely engine parameters, exhaust gas composition, road topography and vehicle dynamics. This portable laboratory was already used in previous studies [11]. On-road data is collected from the numerous equipment installed on-board the vehicle and acquired by a laptop, using developed Labview software to receive, integrate, synchronize and record the data along the trips.

The information provided by the vehicle sensors is collected via the OBD port reader including, vehicle speed, engine speed and load, manifold absolute pressure, airflow mass, intake air temperature, coolant temperature and throttle position.

A GPS receiver with an integrated barometric altimeter is also used to collect vehicle position and altitude along the trip for subsequent calculation of road grade. Tailpipe emissions were measured continuously with a portable five gas analyzer, which provides simultaneous information on carbon dioxide ($CO_2$), carbon monoxide (CO), hydrocarbons (HC), nitrous monoxide (NO) and oxygen ($O_2$). The data collected allows estimating ICE fuel consumption and mass of pollutants in the exhaust gas in a second by second basis [11].

### *2.2. Data analysis – Vehicle Specific Power methodology*

The Vehicle Specific Power (VSP) methodology is based on a simplification of the forces applied to a vehicle. Hence, data collected during on-road measurements is analyzed using VSP methodology to perform an energy and environmental characterization of the vehicle monitored [5,12,13]. This analysis provides an estimate of the power per mass unit due to a combination of vehicle dynamics (speed, acceleration, rolling and aerodynamic resistance) and road grade. To each point of the trip, the correspondent specific power is assigned according to Eq. (1) [5].

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

where $v$, vehicle speed (m/s); $a$, vehicle acceleration (m/s$^2$); grade, road slope.

A modal analysis is used to group points of similar power per mass demand (W/kg). For light-duty vehicles, VSP is commonly divided in 14 modes [14,15]. However, in the scope of this work, to obtain a higher level of resolution of the specific power demand, VSP was divided in modes consisting of 1 W/kg, according to Table 1.

### *2.3. Vehicles description*

Using the portable laboratory, 14 EURO 5 vehicles with conventional gasoline and diesel technologies were measured under on-road conditions, as well as 5 EURO 5 hybrid vehicles (3 with parallel/series configuration and 2 with parallel configuration). Table 2 presents the summary of the characteristics of the conventional vehicles measured and the total data collected (in seconds). The average measurement time was of around 6900 s (almost 2 h of on-road data). Table 3 summarizes the characteristics of the hybrid vehicles studied, with an average measurement time of around 9700 s.