Vehicle Specific Power: An Alternative to Evaluate the Dynamics of Real-Driving Tests

Andre Luiz Silva Forcetto (✉ aforcetto@gmail.com)

USP IAG: Universidade de Sao Paulo Instituto de Astronomia Geofisica e Ciencias Atmosfericas <https://orcid.org/0000-0001-8329-6377>

Orlando Salvo Junior

Universidade de São Paulo Escola Politécnica: Universidade de Sao Paulo Escola Politecnica

Francisco Fernando Maciel Filho

Universidade de São Paulo Escola Politécnica: Universidade de Sao Paulo Escola Politecnica

Maria de Fatima Andrade

USP IAG: Universidade de Sao Paulo Instituto de Astronomia Geofisica e Ciencias Atmosfericas

Flavio Guilherme Vaz de Almeida Filho

Universidade de São Paulo Escola Politécnica: Universidade de Sao Paulo Escola Politecnica

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Abstract

Vehicles are an important source of air pollutants and greenhouse gases. Their emissions are controlled since the 1970's by laboratory tests, but divergences are often found between the results and real-world emissions. Real Driving Emissions procedure was implemented in many countries, in order to evaluate the vehicle closer to actual operation. In order to reduce the dispersion of the results, some dynamic parameters, such as speed and acceleration, are controlled, but the influence of the road grade has not been taken into account. This paper presents an alternative for the dynamic metrics, based on the Vehicle Specific Power, that allows evaluating more accurately the vehicle dynamics and representing better both the up-and-downhill effect as well the low engine power driving requirement, even when the regulatory parameters are into their limits.

1. Introduction

More than half of urban population in the world is exposed to air pollution levels above the safety standard (WHO 2018). It has been estimated that in 2016 air pollution resulted in 4.2 million deaths worldwide; aside from this, there is a long list of adverse effects related to air pollution such as cardiovascular and respiratory diseases, cancer and adverse birth outcomes (WHO 2018, 2020).

Vehicles are a relevant source of greenhouse gases (GHG) like carbon dioxide (CO_2) and methane (CH_4) and primary pollutants: carbon monoxide (CO), nitrous oxide (NO_x), particulate matter (PM), unburned hydrocarbons and other volatile organic compounds (VOC). Vehicles emissions of VOC and NO_x play also an important role in the formation of ozone (O_3) and secondary PM, the main pollutants in many metropolitan areas worldwide (CETESB 2019; WHO 2020).

The vehicle emission measurement can be done in different methods, e.g., remote sensing, laboratory tests or in the real-world, like the Real Driving Emissions (RDE) test, where the vehicle is evaluated on the streets and roads; however, the results are subjected to an inherent uncertainty due to lack of precision in the instruments and variations in trip conditions such as traffic, accelerations, topography and temperature (Giechaskiel et al. 2018).

In order to reduce the dispersion of results, the European RDE procedure determines that some parameters must be kept under control, such as cumulative positive altitude gain, speed and acceleration. However, it is still possible that this procedure could be improved; e.g., the road grade is not considered, despite its influence in the CO_2 and pollutants emission (EU 2016a). As a practical example, during a RDE test it was witnessed that the driver was accelerating the vehicle mainly in downhill in order to accomplish more easily the dynamics requirements, but with lower power requested and reducing fuel consumption and emissions, and this behavior was not reflected in the parameters report.

The Vehicle Specific Power (VSP) is an interesting tool because it takes into account the road grade and it is already successfully applied in mathematic models for air pollution emission from vehicles and to evaluate vehicle dynamic in road tests (Frey et al. 2010; Khan and Frey 2016). This study has the objective of applying VSP to assess the dynamic of RDE tests in a more comprehensive way than the regulatory parameters from European RDE procedure.

2. Vehicle's Evaluation For Pollutants: From Laboratory To Real Driving Emission

2.1 The beginning: laboratory tests

In California, USA, the Air Resources Board (CARB) introduced, since 1970, air quality standards and settled programs to reduce the pollutant emissions, where auto manufacturers must meet the first standards for hydrocarbons and nitrogen oxides emissions (CARB 2017). A test cycle called Federal Test Procedure #75, or FTP-75 for short, was developed to evaluate light duty vehicles (LDV) in dynamometer under controlled conditions and verify their compliance to these standards. The FTP-75 reproduces a typical urban-rural trip in Los Angeles metropolitan area and it was adopted for type-approval in USA, Canada, Brazil and Australia (Dieselnet.com 2019). Europe introduced also, since the 1990's a procedure to measure fuel consumption, CO_2 and pollutants emission. At first, used to be the New European Driving Cycle (NEDC) but it was replaced after 2017 by the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). For the development of the WLTC, real world in-use data was collected by the UN body from Europe, India, Japan, South Korea and United States, in order to be a more realist cycle for global use (Tutuianu et al. 2014; Alphabet.com 2019). Besides Europe, WLTC is also used in Japan for type-approval proposals and it is being implemented in China, South Korea and Russia (Alphabet.com 2019).

These laboratory procedures have good repeatability but all of them are just an average of traffic condition, vehicle load, accelerations and speeds, without up and down hills and running under a more restrict environment temperature conditions that in real world. Other factors not considered in the laboratory tests include vehicle's mileage, variations in the quality of the fuel, actual driver's behavior, traffic jams and air conditioning usage (AVL 2015; Blumberg and Posada 2015; Pouresmaeili et al. 2018; Khan and Frey 2018). Divergences between CO_2 emissions from laboratory to real world are also discussed within some governmental programs that tax vehicles by its efficiency (May et al. 2014; Duarte et al. 2016; Tietge et al. 2017; Tsiakmakis et al. 2017).

Due these matters, laboratory tests are criticized for lacking representativeness; in fact, many studies point to Diesel passenger cars emitting NO_x in real world from 2 to 25 times higher than the regulatory limits and CO_2 up to 50% higher than in the laboratory tests; gasoline vehicles show problems related to cold start emission and CO_2 up to 90% higher. And more, divergences can be found in some vehicles due the presence of fraudulent resources, for example the presence of an ECU software for the type approval process and another completely different program for running on the roads (May et al. 2014; Tutuianu et al. 2014; Blumberg and Posada 2015; German 2016; Kadijk et al. 2016; Marnier 2016; Takai and Ishii 2016; Khan and Frey 2018).

2.2 The Real Driving Test

In USA, on-road measurement is done since 2005 to evaluate heavy-duty vehicles emissions; for LDV, real world emission is used for monitoring (EPA 2005; Engeljehring 2019). The European Union developed a procedure for vehicle's real-world measurement called Real Driving Emissions (RDE), which it was made effective after 2016 for monitoring and since 2018 for regulatory proposals (EU 2016a). RDE is being also adopted, even partially, in many other countries, like South Korea, Japan and Australia (Engeljehring 2019). China is preparing itself to apply a similar RDE test like Europe in a regulatory phase called China 6, that will take effect after July/2020 (He and Yang 2017) and a RDE international procedure, based on the European and Japanese methods, is under development by the United Nations Economic Commission for Europe (UNECE) (UNECE 2020). As European and UNECE RDE are very similar and the international method is still on the way to be implemented, in this study the EU procedure was adopted as reference for the RDE test.

2.2.1 EU RDE procedure

When Europe defined Regulation 715/2007 (EU 2007), it pointed to the need of ensuring that real world emissions correspond to the measurements in laboratory tests, recommending the introduction of a specific procedure to this. The European RDE procedure have a combination of trips that represents a regular drive at local and express roads and highways (EU 2016a, b), the vehicle is coupled to a Portable Emission Measurement System (PEMS), that is able to measure CO₂, CO, NO_x, PN, PM and HC (AVL 2016; EU 2016a; Horiba 2016).

According to the EU RDE requirements (EU 2016a, b), the test must have three phases, divided by speed: urban, up to 60 km/h, rural, between 60 to 90 km/h, and motorway, over 90 km/h; each one driving at least 16 km; the cumulative positive elevation gain limit is 1200 m / 100 km; altitude difference between the start and finish must be lower than 100 m; moderate environment conditions are when altitude is below 700 m and temperature between 0 to 30°C.

The RDE Brazil is based on EU RDE and will be made effective after 2022, in a new type-approval phase called PROCONVE L7 (CONAMA 2018). The main difference between EU and Brazilian procedures is that, in Brazil, there are just two driving phases, urban and rural; the urban trip is about 30 to 40 km long and rural trip has about 16 to 20 km.

The traveled distance and engine data come from vehicle on-board diagnosis (OBD) and the PEMS built-in GPS provides both horizontal and vertical position which results also in distance, as well as speed and altitude. The GPS accuracy in the horizontal plan is about 3 meters; however, vertical measurement is subject an inherent higher dispersion (Garmin 2020); for example, Drosos and Malesios (Drosos and Malesios 2012) notice an error up to 7 meters in a free field study.

EU RDE accepts data from GPS for evaluation of positive cumulative altitude gain, but due to the noise in altitude the values must be smoothed, where a two-step interpolation is done over 400 meters segments (EU 2016a). According to Zhang and Frey (Zhang and Frey 2006) and Sandhu (Sandhu and Frey 2013), a single-step interpolation on 160 meters segments is enough to represent accurately the road grade; on the other hand, the 400 meters criterion is accepted worldwide, even though it produces a less variable profile and enlarges the confidence intervals.

There are other two alternative methods to measure altitude that are cost-effective and with good precision: by digital elevation maps (DEM) and by barometric altimeter. Other costly options are the use of LIDAR in an airplane traveling over the region to be analyzed, inertial sensors and high frequency GPS (Zhang and Frey 2006). Many DEM are available in the internet, providing altitude values for latitude/longitude coordinates with a horizontal resolution between 30 to 90 meters (GPSvisualizer.com 2019). For the Brazilian topography, for example, the DEM is based on the Shuttle Radar Topography Mission (SRTM-3), developed by NASA that gather altitude data between parallel 56°S and 60°N at 90 meters resolution for all South America (NASA 2021).

Barometric altitude can be come from an atmospheric air pressure sensor and calculated by the Eq. 1 (Grimm 1999). Usually, all PEMS models have this sensor available.

$$Z = 8 \cdot (1013 - P) \quad (1)$$

Where Z is the altitude (m) and P is the atmospheric pressure (hPa or milibar).

2.2.2 RDE dynamic parameters

Since the driver's behavior has direct effect on emission, EU RDE settles limits for vehicle's dynamic (EU 2016b). There are two parameters under control: Relative Positive Acceleration (RPA) and v*a[95]. RPA, in m/s², is measured every time when the vehicle accelerates more than 0.1 m/s²; instants with acceleration lower than 0.1 m/s² or negative are not taken on account. The EU RDE procedure defines a minimal value to RPA; to be under this limit means that the driver is requiring such a low power from the vehicle that will introduce a bias in the results, because the vehicle will have a very low consumption and pollutants emissions than in comparison to the laboratory test.

In a similar way, v*a[95], measured in m²/s³ or W/kg, is the percentile 95 of vehicle speed times positive acceleration for which one-second time steps (EU 2016b). This parameter represents how much kinetic energy is required to accelerate the vehicle; a v*a[95] above the limits shows that the driver is requiring more power than compared to laboratory test cycle and it also may distort the emissions results (Fontaras et al. 2014; Wyatt et al. 2014; Pouresmaeili et al. 2018).

2.3 VSP as dynamic parameter

VSP is defined as the energy consumption of a vehicle to overcoming the rolling resistance and aerodynamic drag, expressed in kW/ton or W/kg; the main parameters are speed, acceleration and road grade (Jiménez-Palacios 1999; Rodríguez et al. 2016). In this study, VSP calculation is based on Eq. 2 proposed by Jiménez-Palacios (Jiménez-Palacios 1999) that is a simplification from the Specific Power equation used by EPA, because it is based in average values for rolling resistance, aerodynamic drag and air density:

$$VSP = v * (1.1 * a + 9.81 * grade + 0.132) + 3.02 * 10^{-4} * (v + v_w)^2 * v$$

Where v is vehicle instant speed (m/s); a is vehicle instant acceleration (m/s²); $grade$ is the vertical rise by distance (%) and v_w is wind speed (m/s); the VSP result is expressed in W/kg.

VSP is being applied in mathematic models to evaluate vehicular emissions as well to evaluate the deviations among on-road and laboratory measurements, as shown by Frey et al. (Frey et al. 2002, 2010). Although a direct correlation cannot be determined, many studies show that VSP, emissions and consumption are linked with one another in RDE tests and remote monitoring (Faria et al. 2019; Murena et al. 2019; Varella et al. 2019; Yuan et al. 2019; Yang et al. 2020).

3. Methods

The analysis of VSP as criteria to evaluate the dynamics of RDE tests is based on four steps: i) calculate VSP from laboratory cycles; ii) define equations to determine maximum and minimum VSP for these cycles; iii) calculate VSP from RDE tests and iv) analyze these data under VSP max/min criteria and comparing with $v * a$ and RPA results.

3.1 Calculating VSP from laboratory test cycles

WLTC and FTP-75 laboratory test cycles are the baseline of the RDE test because they are planned to reproduce a typical driving trip under controlled parameters and the regulated pollutants are measured firstly through these tests.

In order to have VSP results able to be compared with RPA and $v * a$, it is important to follow a similar method to calculate VSP from those used for them. The step-by-step to this calculation is: i) set the speed x time from the cycle in an Excel sheet; ii) calculate acceleration, second by second; iii) calculate VSP according to Eq. 2 and iv) sort the results by acceleration; selecting only points with positive acceleration higher than 0,1 m/s². It is important to consider here why it has gotten just positive acceleration data: first, European procedure evaluates just positive acceleration and it was important to keep the same criteria here and, secondly, no acceleration or negative acceleration means that the vehicle is running at constant speed, coasting or breaking, requiring very low or even no power and producing almost no pollution. So, since all VSP values in this study are related to positive acceleration, henceforward the parameter under analysis will be referred as VSP+.

3.2 Maximum and minimum VSP + equations

The second step is to define equations that can embrace the VSP + points from the laboratory cycles. Since WLTC covers a broader speeds range than FTP-75, they are developed to the first one and afterwards verified about the coverage of the second cycle.

The process to define them to maximum and minimum VSP+, or VSP + Max and VSP + Min for short, is: i) aggregate VSP + results from WLTC cycle in 13 speed bins: 0–10 km/h; 10,01–20 km/h and so on, up to 130 km/h. The binning is useful to make easier settling the percentiles 5 for VSP + Min and 95 for VSP + Max; 10 km/h bins was chosen because it is the smallest range able to be analyzed without introduce so much noise; on the other hand, bin ranges of 20 km/h or larger did not produced better results than 10 km/h; ii) determine the percentiles 5 and 95 for each bin, to analyze data tendency. Percentiles are important to avoid influence from extreme VSP + points that could distort or blur results. Once more, the values 5–95 are arbitrary, however other values, such as 10–90, were tested and produced similar results, thus the first choice shows to be adequate; iii) create equations to define VSP + Min and Max and iv) verify how many VSP + points are inside the area covered by the curves that represents VSP + Max and Min. The target here is the curves embracing more than 90% of VSP + points of each cycle.

3.3 RDE tests runs

3.3.1 Vehicles

This step used ten tests developed with five different cars, that were driven on different altitude gains. These vehicles were chosen due to their close characteristics: compact models for 4 or 5 passengers, aspirated 4-cylinders Otto engine and similar weight, engine displacement, engine power and power-to-mass ratio (PMR), as shown in Table 1. Since it was request confidentiality by the manufacturers about sharing data from their models, all vehicles evaluated in this study are just named as #1, #2, etc.

Table 1
– Vehicles' characteristics

CAR ID.	EMISSION STD.	FUEL	GEARBOX	ENGINE DISPL. (cm ³)	POWER (kW)	WEIGHT (kg)	PMR (W/kg)
#1	Euro 4	E100	Manual	1600	90	1040	86,5
#2	Euro 6	E10	Manual	1242	51	1015	50,3
#3	Euro 6	E10	Manual	999	51	940	54,3
#4	Euro 6	E10	Manual	999	77	1273	60,5
#5	Euro 6	E10	Manual	999	70	1110	63,1

Vehicle #1 has two important particularities: First, the software used in its ECU is not OEM but it was developed by engineer students from Sao Paulo University (USP); because this, the vehicle is not compliant for CO emission, according to limit of 2.0 g/km for Brazilian phase L5, similar to Euro 4. However, the test data is still useful for comparing VSP + data and the increase or decrease of CO₂ and pollutants emissions in different altitude gains. Secondly, the vehicle #1 engine is flexfuel, what means it is able to burn gasoline, ethanol or a mix of both in any proportion; so, its emission profile, even high, is interesting to be evaluated and compared with only gasoline-fueled vehicles.

3.3.2 Instruments

The PEMS is, as the acronym means, a portable system to measure vehicle's emissions and dynamic data from RDE tests. It is composed of compact laboratory-grade gas analyzers, exhaust flow meter, ECU connection by OBD port, a high frequency GPS (5 Hz or higher), a computer to gather data at least at 1 Hz and batteries to power supply. All results are saved in a *.csv file to be post-processed after the test. A PEMS weighs about 100 to 150 kg and can be assembled into the trunk or on an external support (AVL 2016; Horiba 2016).

Vehicle #1 was evaluated with a Horiba OBS-ONE model; vehicle #2 with a Sensors SEMTECH and the others with an AVL MOVE. All PEMS accomplish EU regulation (EU 2016a) and were validated by comparing their results against a vehicular laboratory; Table 2 shows the main parameters evaluated. All models take altitude data from the GPS but their vertical accuracy is not clearly defined in the OEM datasheets. For the Horiba OBS-ONE and the AVL MOVE is available also the barometric pressure with good resolution, in millibars with more than 3 significant algarisms after the decimal point; Sensors SEMTECH express it in millibars but rounded to no algarisms after the decimal point, what is not enough precision to calculate the road grade as required by VSP.

Table 2
– Validation requirements

Parameter	Accuracy (difference of laboratory reference)
Distance (km)	< 250 m/test
CO	< 150 mg/km or 15%, whichever is larger
CO ₂	< 10 g/km or 10%, whichever is larger
NOx	< 15 mg/km or 15%, whichever is larger
Exhaust mass flow	+/- 3 kg/h, standard error < 10%, r ² > 0.9

3.3.3 Tests conditions and characteristics

The analysis in this study is focused on the urban phase, because the environmental parameters and execution methods are similar in all RDE tests, with exception of the altitude gain, which is a key factor for VSP. It was evaluated emissions of CO, NOx and CO₂. Keeping in mind the 1,200 m / 100 km limit of altitude gain, in this study were used, for each vehicle, one trip close to or above this limit, named as high altitude gain, and another trip with about half limit, or 600 m / 100 km, named as medium altitude gain. Tests #1 and #2 were made in Sao Bernardo do Campo, Brazil; tests #3, #5, #7 and #9 in Esperia, Italy and #4, #6, #8 and #10 in Sacromonte, Italy. These locations are relevant to this study because they represent more than only one region or country and they are also close to important big cities as Sao Paulo and Milan, although far enough to avoid heavy traffic. Table 3 shows the trips conditions and Figs. 1 and 2 have their topographic profiles.

Table 3
– Test conditions

Car ID.	Test #	Amb. Temp. (°C)	Trip length (km)	Urban trip duration (s)	Avg. Speed (km/h)	Avg. Altitude (m)	Altitude gain (m/100km)
#1	1	30,5	28,2	4873	22,0	766,5	579
	2	22,7	28,8	4986	21,1	774,1	1159
#2	3	24,6	31,6	3576	32,0	240,8	631
	4	20,0	60,9	6520	33,7	437,4	1713
#3	5	12,2	32,5	4146	28,8	238,8	649
	6	5,3	63,0	6806	33,7	440,1	1614
#4	7	23,6	31,8	3733	31,4	239,5	640
	8	18,7	61,2	6138	36,3	438,6	1653
#5	9	19,6	31,9	4009	29,3	236,6	677
	10	17,8	61,8	6551	34,0	448,7	1632

3.4 Analyzing RDE tests

The method used to calculate VSP + from RDE tests is similar to the VSP + calculation from WLTC exposed in 3.1, however, the influence of altitude gain must be considered, which requires a specific care with it.

3.4.1 Altitude measurement

The main data for altitude comes from the PEMS built-in GPS, second by second, that also provides latitude and longitude coordinates, which are processed in the website < www.gpsvisualizer.com > to add altitude from point to point, based on the available DEM (GPSvisualizer.com 2019). Barometric data comes from the PEMS atmospheric air pressure sensor.

GPS, DEM and barometric pressure are fully available only for tests #1 and #2 but lack some information for the others tests; hence these three datasets from tests #1 and #2 are compared one each other in order to determine GPS precision, as well the need of smooth.

3.4.2 Calculating and analyzing VSP+

The method to calculate VSP + from RDE tests is: i) import speed and altitude data from PEMS; ii) smooth the GPS altitude variation by mobile media filter; iii) calculate distance traveled second by second for points with speed higher than 1 km/h; iv) calculate the road grade, in percent variation of altitude per distance; v) calculate acceleration, second by second; vi) calculate VSP + according Eq. 2, second by second and vi) select the points with acceleration greater than 0,1 m/s².

The following parameters from these data were evaluated:

- % points above VSP + Max curve
- % of these points (above VSP + Max curve) that occurred with the vehicle running on positive road grade
- % points below VSP + Min curve
- % of the points below VSP + Min curve that occurred with the vehicle running on negative road grade
- % of negative VSP + points

PEMS data from all vehicles were processed with the freeware EMROAD version 6.03, which is developed by Joint Research Centre (JRC) – Italy (JRC 2020) and the following data were picked up from EMROAD reports:

- v*a[95] and the regulatory maximum value for v*a[95]
- RPA and the regulatory minimum value for RPA
- Cumulative positive elevation gain
- CO₂, CO and NO_x specific emissions in g/km

4. Results And Discussion

4.1 Calculating VSP + from WLTC and FTP-75 cycles

The VSP + from WLTC and FTP-75 cycles were calculated by Eq. 2 and according to the method described in item 3.1; the results are summarized in the Table 4 and Fig. 3.

Table 4
– WLTC and FTP-75 VSP + results

Cycle	Cycle duration (s)	Positive accel. points (s)	Positive accel. points (%)	Urban (< 60 km/h) points (s)	Urban positive accel. points (s)	Urban positive accel. points (%)
WLTC	1800	610	34%	983	423	43%
FTP-75	1874	611	33%	1284	537	42%

It is important to observe that in both cycles the percentage ratios of positive acceleration points are very similar, as well as the area covered by VSP + points up to 60 km/h, however, at medium and higher speeds WLTC covers a greater range.

4.2 Definitions of VSP + Max and Min equations

Following the method defined in 3.2, VSP + points from WLTC resulted in the Eq. 3 for VSP + Max and Eq. 4 for VSP + Min; they produced two curves that embrace 94.4% of all VSP + WLTC points and 90.3% of FTP-75 points, as seen in Figs. 4 and 5.

$$\text{VSP + Max} = -0.0019 * X^2 + 0.472 * X + 0.6 \quad (3)$$

$$\text{VSP + Min} = 0.00128 * X^2 + 0.0028 * X + 0.57 \quad (4)$$

Where X is the instantaneous speed (km/h).

4.3 Analyzing RDE tests

4.3.1 Altitude's accuracy

The comparison of the three raw datasets, GPS, DEM and barometric altitude, brings a high correlation for altitude but there is a very poor correlation for road grade. It shows that main parameter, altitude, is accurate, but can have small variations, or noise, in the road profile which can lead to high differences in the road grade. Since this noise affects the VSP + values, it is necessary to smooth the gathered data, regardless of which instrument is supplying it. Figures 6 and 7 display a small sample of the altitude and road grade profiles from test #2, where it is possible to see the irregularities in the profile and their effect in the road grade; Table 5 shows the correlation for altitude and Table 6 for the road grade.

Table 5
– Correlation between altitude sources (raw data)

Test #1 – cumulative altitude gain: 579 m / 100 km	
Source of data	R ²
DEM x GPS	0.967
DEM x Barometric	0.917
GPS x Barometric	0.915
Test #2 – cumulative altitude gain: 1159 m / 100 km	
DEM x GPS	0.899
DEM x Barometric	0.926
GPS x Barometric	0.938

Table 6
– Correlation between road grades (raw data)

Test #1 – cumulative altitude gain: 579 m / 100 km	
Source of data	R ²
DEM x GPS	0.447
DEM x Barometric	0.017
GPS x Barometric	0.062
Test #2 – cumulative altitude gain: 1159 m / 100 km	
DEM x GPS	0.003
DEM x Barometric	0.013
GPS x Barometric	0.005

The smoothing in the EU RDE procedure is based on distance; however, in this study, all data from tests are indexed by time and not by distance. In order to smooth the altitude data in 160 meters segments as recommended by Sandhu (Sandhu and Frey 2013), the average speed of the urban trip was taken from EMROAD to calculate how many seconds are needed to travel 160 m. In the tests #1 and #2 the average urban speed is about 21.5 km/h or 5.97 m/s, consequently it is necessary approximately 27 seconds to travel 160 m; so, in this study the smooth was done by moving average in segments of 30 s. Figures 8 and 9 display the same small sample of altitude and road grade profiles from test #2 after smoothing and Table 7 shows the correlation for altitude and Table 8 for the road grade. The GPS data after smooth presented good correlation with DEM and barometric altitude for road grade, thus able to be used in the VSP + analysis.

Table 7
– Correlation between altitude sources (after smooth)

Test #1 – cumulative altitude gain: 579 m / 100 km	
Source of data	R ²
DEM x GPS	0.977
DEM x Barometric	0.928
GPS x Barometric	0.915
Test #2 – cumulative altitude gain: 1159 m / 100 km	
DEM x GPS	0.912
DEM x Barometric	0.942
GPS x Barometric	0.946

Table 8
– Correlation between road grades (after smooth)

Test #1 – cumulative altitude gain: 579 m / 100 km	
Source of data	R ²
DEM x GPS	0.889
DEM x Barometric	0.874
GPS x Barometric	0.927
Test #2 – cumulative altitude gain: 1159 m / 100 km	
DEM x GPS	0.588
DEM x Barometric	0.676
GPS x Barometric	0.767

4.3.2 VSP + in comparison with v*a[95] and RPA from RDE tests

The dynamic parameters found in the ten tests, according to the European RDE procedure, are summarized in Table 9 and the VSP + calculated according to the method described in 3.4.2 is shown in Table 10.

Table 9
– Dynamics according RDE EU procedure

Car ID.	Test #	Altitude gain (m/100km)	RPA min	RPA in the test	v*a[95] max	v*a[95] in the test
#1	1	579	0.14	0.21	14.6	9.9
	2	1159	0.14	0.17	14.7	8.9
#2	3	631	0.12	0.17	14.8	11.2
	4	1713	0.12	0.15	15.0	8.3
#3	5	649	0.13	0.20	15.1	13.9
	6	1614	0.12	0.14	15.3	7.4
#4	7	640	0.13	0.19	15.4	14.2
	8	1653	0.12	0.18	15.5	10.6
#5	9	677	0.13	0.18	15.7	13.9
	10	1632	0.12	0.15	15.8	9.3

Regarding the dynamic parameters RPA and v*a[95], all tests fulfill the regulatory limits, even if the altitude gain is high or low, and both parameters are lower for tests with high altitude gain.

Table 10
– VSP + results

Car ID.	Test #	# VSP + points	% VSP + <i>above</i> max	% VSP + <i>above</i> max in pos. road grade	% VSP + <i>below</i> min	% VSP + <i>below</i> min in negative road grade	% VSP + <i>negative</i>
#1	1	1400	6.0%	78.6%	9.8%	69.3%	2.4%
	2	1424	6.6%	91.5%	21.2%	79.8%	9.0%
#2	3	1231	2.8%	44.1%	11.1%	80.3%	0.3%
	4	2433	8.1%	96.5%	22.3%	94.6%	10.6%
#3	5	1253	8.5%	65.4%	13.0%	81.0%	0.5%
	6	2463	6.1%	98.0%	24.2%	96.6%	10.9%
#4	7	1152	10.2%	53.4%	10.2%	90.6%	0.1%
	8	2343	12.5%	90.8%	21.5%	97.2%	9.4%
#5	9	1188	9.0%	68.2%	12.2%	87.6%	1.5%
	10	2308	10.0%	97.4%	25.5%	95.9%	11.9%

In these graphic examples, Fig. 10 represents VSP + results from test #9, with the vehicle being driven on a trip with medium altitude gain of 677 m / 100 km and Fig. 11 shows VSP + from test #10, with the same vehicle running a trip with high altitude gain of 1632 m / 100 km.

About the VSP + results, it is important to highlight:

- Several points are above VSP + Max curve, with the driver requiring more vehicle power than in the WLTC and FTP-75 cycles;
- The positive road grade (uphill) has more influence in VSP + points above Max curve for high altitude gain; on the other hand, for medium altitude gain, many points occurred even when driving on negative road grade (downhill);
- Several points are under VSP + Min curve, thus the driver is requiring less power than in the laboratory test, due to lower accelerations and/or accelerating on downhill;
- An average of 87.3% of VSP + points below Min curves occurred when driving on negative road grade;
- The concentration or position of the clusters of VSP + points higher or lower in relation to VSP + Max / Min curves indicates respectively more or less power requirement;
- The scattering of VSP + points is higher for high altitude gain in comparison to the medium altitude gain. This higher dispersion is due to the RDE requirement of the altitude difference between trip start and finish must be less than 100 m; because of this, when the vehicle is being driven on high altitude gain, half of the trip is done in high positive road grade but the other half of the trip is in high *negative* road grade. There is higher VSP + demand above Max curve to drive on uphill; however, in the other half of the trip, downhill, both VSP + below Min and VSP + negative are bigger due to the low power required;
- One important issue is that, *even considering only positive v*a[95] points, there are negative VSP + points*; thus, vehicle is increasing speed at negative road grade with low or no power required and the accelerator is off or almost off; sometimes the driver must break the vehicle to avoid the increasing of speed. In these cases, it is common that the ECU cuts the fuel injection in rotational speeds over than 1,500-2,000 RPM, resulting in zero or close to zero consumption and emissions;
- All negative VSP + points occurred on negative road grade.

4.3.3 Emissions comparison between VSP + and v*a[95] and RPA

According to Suarez-Bertoa (Suarez-Bertoa et al. 2019) the driving behavior and the road grade are the main influence in CO₂, CO and NOx emissions. However, the catalyst design, its dimensions and noble metals concentration have a great influence in the emissions (Brück et al. 1995; Koltsakis and Stamatelos 1997). The results in the Table 11 show a CO increase of about 200% for vehicles #2 and #3, which are those with lower PMR, and high NOx emission for vehicle #4, the vehicle with highest VSP + above Max curve, as seen in Table 10. It is important to remember that during downhill in high altitude gain the car's accelerator is off and the final CO₂ emission can be lower than in low or medium altitude gain, what happened for vehicles #2, #3 and #5.

Table 11
– Emissions – Urban trip

Car ID.	Test #	PMR (W/kg)	Altitude gain (m/100km)	CO ₂ (g/km)	Δ %	CO (g/km)	Δ %	NOx (g/km)	Δ %
#1	1	87	579	179.3	10%	16.776	-22%	0.032	-20%
	2	87	1159	197.6		13.117		0.026	
#2	3	50	631	151.6	-8%	0.353	197%	0.008	-4%
	4	50	1713	140.1		1.047		0.008	
#3	5	54	649	179.8	-10%	0.130	236%	0.019	-8%
	6	54	1614	161.1		0.435		0.018	
#4	7	60	640	149.3	12%	0.362	-45%	0.119	142%
	8	60	1653	167.5		0.198		0.288	
#5	9	63	677	166.1	-6%	0.147	13%	0.073	-23%
	10	63	1632	156.0		0.167		0.056	

5. Conclusions

The regulatory parameters RPA and v*a[95] are not so effective to evaluate dynamics in RDE test in higher altitude gains because they tend to present lower values even if more power is being required. VSP + presents to be a more comprehensive tool to analyze the vehicle power requirement, especially in high accelerations and altitude gain. These two factors have crossed influence on CO₂ and pollutants emissions, although this correlation happens in a complex and not direct way. As VSP + evaluation of a RDE test dynamic requires similar effort for post-processing calculation and its results are more accurate than v*a[95] and RPA, there is a potential for introducing VSP + as regulatory parameter of RDE procedure, for development tests and vehicle homologation.

The tests analyzed here cover some specific situations; it is still necessary to extend this analysis to broader conditions such as diverse altitude gains, different driver behaviors and PMR, as well as requiring as much power available or, in the contrary, under slow accelerations and so on, in order to define more clearly the boundaries for VSP + demand in real world driving and comparing it with laboratory cycles. Future improvements in the altitude measurement can also contribute to more exact VSP + values.

6. Declarations

Ethical approval and consent to participate

Not applicable

Consent for publication

Not applicable.

Available data

The datasets generated and/or analyzed during the current study are available

in the Mendeley Data repository at: Forcetto, Andre (2021), "VSP dataset", Mendeley Data, V1, doi: 10.17632/bv7kjn5crj.1, <<http://dx.doi.org/10.17632/bv7kjn5crj.1>>

Competing interests

The authors declare that they have no competing interests.

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Authors' contribution

The contribution from the authors to this study are: conceptualization, methodology, formal analysis and the final written manuscript performed by ALSF; the first manuscript drafts written by ALSF, OSJ and FFMF. The validation of research data and results, as well the supervision performed by MFA and FGVAF. All authors approved the final manuscript.

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Figures

Figure 1

Sao Bernardo do Campo/Brazil

Figure 2

Esperia and Sacromonte / Italy

Figure 3

VSP+ from WLTC and FTP-75 cycles

Figure 4

VSP+ Max / Min x WLTC

Figure 5

VSP+ Max / Min x FTP-75

Figure 6

Test #2 – Altitude profile (raw data)

Figure 7

Test #2 – Road grade profile (raw data)

Figure 8

Test #2 – Altitude profile (after smooth)

Figure 9

Test #2 – Road grade profile (after smooth)

Figure 10

Test #9 – VSP+ for low altitude gain

Figure 11

Test #10 – VSP+ for high altitude gain

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