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APPLICATION OF A SYNTHETIC POWER INDICATOR METHOD TO QUANTIFY CHEMICAL POLLUTION IN MOTOR VEHICLES

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Abstract: *This document discusses the estimation of vehicle emissions using traffic simulation software and specific power calculations. It explains the concepts of direct and inverse modeling for estimating vehicle parameters and powertrain operation. The document also presents equations for calculating the power required to move a vehicle and the factors affecting resistance to forward movement. It introduces the concept of Vehicle Specific Power (VSP) and how it can be used to estimate emissions and fuel consumption based on different driving scenarios. The document provides emission rates for different VSP intervals and discusses the impact of driving conditions on pollutant emissions. It also describes a case study of modeling the trajectory and analyzing emissions of a single vehicle using simulation software.*

Key words: *Vehicle emission, Vehicle Specific Power (VSP), Vehicle route, Vehicle simulation*

1. INTRODUCTION

Direct and inverse modeling are both highly effective methods for estimating the dynamic and energy parameters of vehicles [1].

Direct modeling utilizes various inputs including throttle position, gear selection, powertrain architecture, and auxiliary components. The inputs provided are crucial in the calculation of the powertrain's operation, enabling the determination of the required drive torque and engine speed. The outputs obtained are the speed and acceleration of the vehicle.

On the other hand, inverse modeling works by taking the vehicle's velocity and acceleration as inputs and then calculating the powertrain operation in reverse [2]. This allows for the determination of the optimal engine regimes to ensure efficient vehicle operation.

2. THEORETICAL CONSIDERATION

There are two approaches to modeling the dynamic and energy parameters of vehicles: direct modeling and inverse modeling. As everyone is aware, direct modeling takes into account various input parameters such as the position of the accelerator pedal, the gear, the powertrain architecture, and auxiliary components. By utilizing these inputs, the powertrain's operation is calculated, allowing for the determination of the necessary drive torque and engine speed. The results include the velocity and rate of change in velocity of the vehicle. Inputs in inverse modeling include vehicle velocity and acceleration. The operation of the powertrain is analyzed in reverse to determine the engine speeds necessary for optimal vehicle efficiency [1].

The formula that defines the power P_t required to move a motor vehicle of mass m with speed v is commonly found in the specialized scientific literature can be seen in equation 1 bellow.

$$P_t = F_t \times v = v(m \times a \times \delta + R_a + R_r + R_p) \quad (1)$$

$$\delta = 1 + \varepsilon_i \quad (2)$$

where:

- F_t is the wheel force
- δ is the coefficient of moving masses and can be calculated with the equation 2
- R_a is the air resistance

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- R_r is the rolling resistance
- R_p is the slope resistance

If we explore the terms on the right side of the equation 1, corresponding to the resistance to forward movement, we will uncover a more complete and detailed equation:

$$P_t = F_t \times v = v\left(C_r mg cos(\alpha) + mg sin(\alpha) + \frac{1}{2}\rho_{aer} C_x A v^2 + m \times \frac{dv}{dt}(1+\varepsilon_i)\right) = mv\left[g\big(C_r cos(\alpha) + sin(\alpha)\big) + \frac{dv}{dt}(1+\varepsilon_i)\right] + \frac{1}{2}\rho_{aer} C_x A v^3 \quad (3)$$

where:

- C_r is the drag coefficient of the driveway
- $\alpha[°]$ is the road slope
- h is the height of the slope
- l is the width of the slope
- $\rho_{aer}\left[\frac{kg}{m^3}\right]$ is the density
- C_x is the coefficient of aerodynamic drag
- A is the front area of the vehicle
- ε_i is the mass factor

ε_i can also be calculated with equation 4 bellow:

$$\varepsilon_i = 0.04 + 0.0025G^2 \quad (4)$$

The equation 4 includes the coefficient G, which represents the overall transmission ratio. This ratio considers both the gear ratio, i_{tr}, and the final transmission ratio, i_f. The overall transmission ratio G can be calculated with the equation 5.

$$G = i_{tr} \times i_f \quad (5)$$

Then the equation 4 can be rewritten:

$$\varepsilon_i = 0.04 + 0.0025(i_{tr} \times i_f)^2 \quad (6)$$

When it comes to electric vehicles, a torque multiplier gear is typically utilized, maintaining a consistent ratio throughout the journey.

Considering the impact of the gear utilized on the inertia of the masses during acceleration, the equation for the power of propulsion at the wheel can be written as the equation 7.

$$P_t = v\left(C_r mg cos(\alpha) + mg sin(\alpha) + \frac{1}{2}\rho_{aer} C_x A v^2 + m \times \frac{dv}{dt}(1+\varepsilon_i)\right) = mv\left[g\big(C_r cos(\alpha) + sin(\alpha)\big) + \frac{dv}{dt}(1+\varepsilon_i)\right] + \frac{1}{2}\rho_{aer} C_x A v^3 = \frac{1}{2}\rho_{aer} C_x A v^3 + mvg\big(C_r cos(\alpha) + sin(\alpha)\big) + mv\frac{dv}{dt}\ \delta_i = \frac{1}{2}\rho_{aer} C_x A v^3 + mvg\big(C_r cos(\alpha) + sin(\alpha)\big) + mv\frac{dv}{dt} \times (1.04 + 0.0025G^2) \quad (7)$$

For simplicity, we can use R_a and R_d:

$$P_t = v(R_a + R_d) + mv\frac{dv}{dt} \times (1.04 + 0.0025G^2) \quad (8)$$

3. CHEMICAL POLLUTION THROUGH VEHICLE SPECIFIC POWER

3.1 VSP (Vehicle Specific Power)

The approach utilizes simplified force calculations on the vehicle to analyse energy and environmental factors using data obtained from road measurements. This method allows for the estimation of power relative to mass across various speed [3, 4, 5], acceleration, and road inclination scenarios, resulting in more accurate emission rate predictions compared to models that rely on average speed.

By taking into account these variables, the model can provide more precise calculations on the energy consumption and emissions of a vehicle in real-world driving conditions. This detailed analysis allows for better understanding of the environmental impact of different driving scenarios, helping to inform policy decisions and promote the development of more sustainable transportation options. Ultimately, this approach can lead to more effective strategies for reducing emissions and improving energy efficiency in the transportation sector.

As an illustration, through analysing the mentioned parameters and employing standard values, Jimenez computed the precise power of every point of the journey on a second-by-second basis, based on equation [6].

$$VSP\left[\frac{W}{kg}\right] = v(1.1a + 9.81 \times \alpha + 0.132) + 3.02 \times 10^{-4} \times v^3 \quad (9)$$

3.1 Chemical pollution

The work groups together point with similar VSP through a modal analysis, which typically consists of 14 operating ranges for light vehicles. Each of these VSP modes has its own values for consumption and emissions [7,8,9]. Considering important vehicle factors like engine capacity and travel route, the emission rates of CO2, CO, HC, and NOX for the 14 VSP modes of various vehicle types can be calculated on the basis of equation 9 with the results presented in table 1.

The estimated emission rates offer valuable insights into how different types of vehicles impact the environment in various operating conditions. Researchers and policymakers can make well-informed decisions about mitigating the negative effects of transportation on air quality and climate change by gaining a comprehensive understanding of the emissions associated with each VSP mode. This data can be utilized to formulate strategies aimed at decreasing emissions and enhancing the overall sustainability of the transportation sector.

Table 1

Emission rates (e.r.) for different VSP

No	VSP interval	CO_2 e.r.	CO e.r.
1	VSP<-2	1.54369	0.01103
2	-2≤VSP<0	1.60441	0.00872
3	0≤VSP<1	1.13083	0.00468
4	1≤VSP<4	2.38626	0.01215
5	4≤VSP<7	3.21025	0.01673
6	7≤VSP<10	3.95773	0.02327
7	10≤VSP<13	4.75201	0.02932
8	13≤VSP<16	5.37422	0.03694
9	16≤VSP<19	5.94005	0.04951
10	19≤VSP<23	6.42751	0.06376
11	23≤VSP<28	7.06599	0.10538
12	28≤VSP<33	7.6177	0.24781
13	33≤VSP<39	8.32244	0.41307
14	39≤VSP	8.47503	0.62466

Table 2

Emission rates (e.r.) for different VSP

No	VSP interval	HC e.r.	NO_x e.r.
1	VSP<-2	0.000901	0.001014
2	-2≤VSP<0	0.000901	0.001042
3	0≤VSP<1	0.000835	0.000423
4	1≤VSP<4	0.001027	0.001613
5	4≤VSP<7	0.001253	0.002638
6	7≤VSP<10	0.001664	0.003793
7	10≤VSP<13	0.002089	0.005098
8	13≤VSP<16	0.002332	0.006373
9	16≤VSP<19	0.002818	0.007664
10	19≤VSP<23	0.002985	0.009913
11	23≤VSP<28	0.003786	0.012685
12	28≤VSP<33	0.004573	0.014384
13	33≤VSP<39	0.0057	0.015967
14	39≤VSP	0.007164	0.016717

A vehicle's fuel consumption and emissions can be estimated for different driving conditions using this methodology. Alternatively, a driving cycle can be characterized by the dynamic profile as a function of the time spent in each VSP mode. Then, any vehicle's VSP modal emissions (table 1 and 2) can be combined with this information to estimate fuel consumption and emissions for NEDC and WLTP cycles or any other travel pattern.

One major drawback of this method is that it becomes distorted when different combinations of speed, acceleration, and road angle produce the same amount of power. This method is tailored to the complicated features that are produced by dependencies, namely consumption, load, and speed. However, it remains a useful tool for capturing the effects of driving in real time, and MOVES (developed by the EPA) expresses the instantaneous emission rate as a function of vehicle speed and VSP mode [5,8,10].

4. MODELING THE TRAJECTORY AND ANALYZING EMISSIONS OF A SINGLE VEHICLE

4.1 Vehicle trajectory

For the study of the emissions of an individual vehicle, a simulation was made in the Aimsun platform in an urban street network, figure 1. This simulation aimed to assess the impact of the vehicle on the environment and to identify areas with high pollution potential by taking into account the acceleration and speed of the vehicle in relation to the route traveled.

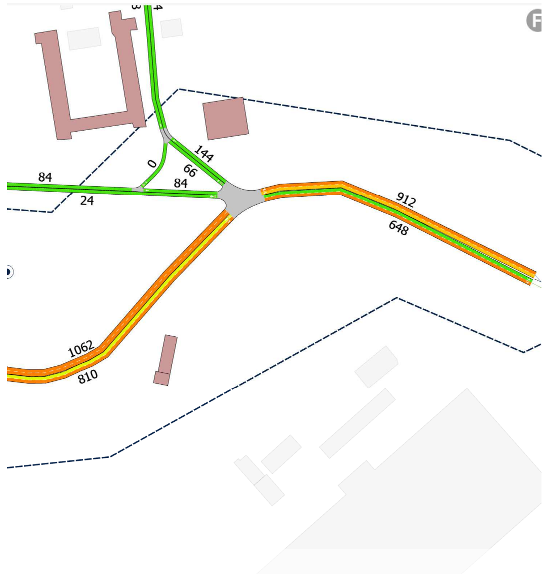


Fig. 1. Urban street network for vehicle path.

To model the vehicle's route, a new vehicle class (VSP Vehicle) was generated, Figure 2, and this class was used in an Origin-Destination (O/D) matrix in which a single vehicle was entered, Figure 3. Thus, using this new class of vehicles, it was possible to calculate the optimal route of the vehicle from the point of origin to its destination. The implementation of the O/D matrix with a single vehicle facilitated the detailed analysis of the route, thus allowing the exact identification of the vehicle's position on the established route (approximately 2 km) as well as the dynamic parameters in relation to the travel time.

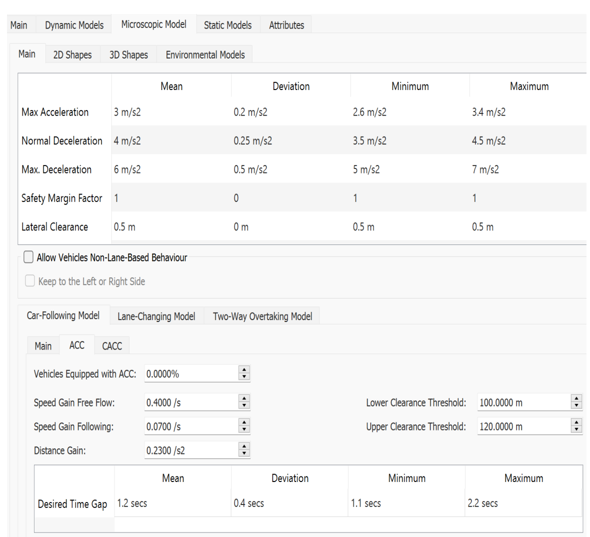


Fig. 2. The generated VSP Vehicle class.

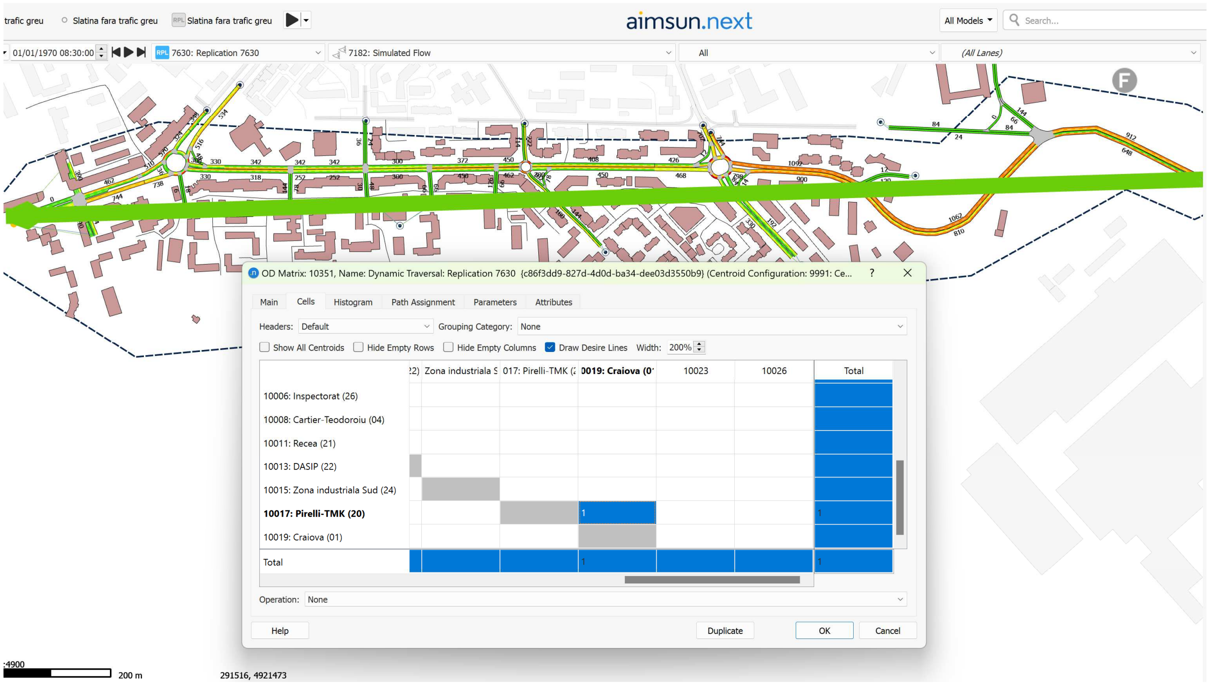


Fig. 3. O/D matrix and vehicle trajectory.

4.2 VSP calculation

The simulation presented above was carried out in real traffic conditions (the volumes of vehicles were measured and calibrated for the virtual network in relation to 07:30 for one hour), and the VSP Vehicle class vehicle was introduced into this network so that the dynamic values, acceleration and speed, were simulated in a way that was as real as possible and as close to reality as possible.

Table 3

Export sample for the studied vehicle

Simulation Time	Acceleration	Speed
08:11:05	1.66775	1.33420
08:11:06	1.59208	1.27366
08:11:07	1.28363	1.02691
08:11:08	0.61686	0.49349
08:11:09	0.10766	0.08612
08:11:10	0.00000	0.00000
08:11:22	0.60931	0.48745
08:11:23	1.89178	1.51342
08:11:24	1.04350	0.83480

Following the simulation, the collected data were exported (Table 3) and analysed to group them and convert them into a format that can be used in the equations presented above.

The car followed a path of two kilometres in 21 minutes, and every second acceleration and speed were recorded.

Regarding chemical pollution, this knowledge is absolutely essential for deciding the general performance and efficiency of the vehicle on this given path.

Using equation 9 on the table 3 we were able to established the corresponding VSP interval for each second of the travel cycle, after which they obtained the total durations of time spent in each of these 14 intervals, see table 4. Because of the exporting format and particularities from the Aimsun platform we have encountered in the 21 minutes a number of 1073 measurements.

Table 4

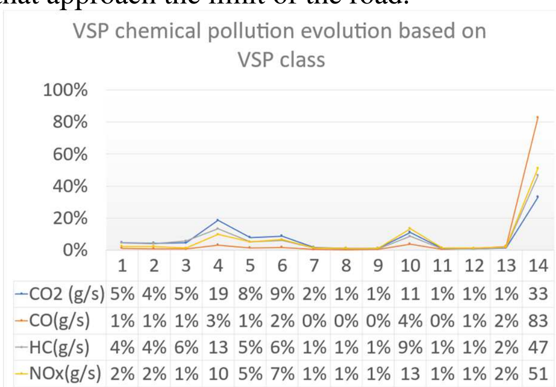
Calculated VSP intervals

VSP Class	Intervals	VSP Class	Intervals
VSP1	110	VSP8	8
VSP2	101	VSP9	7
VSP3	149	VSP10	64
VSP4	288	VSP11	5
VSP5	91	VSP12	4
VSP6	82	VSP13	6
VSP7	13	VSP14	145

The vehicle usually fell in the lower VSP ranges, VSP1 to VSP4 (that corresponds to values below -2 and 4 W/kg). These intervals are the most frequent as they are part of the region of transitional regimes that develop in places with urban traffic and crossings with service level D and above.

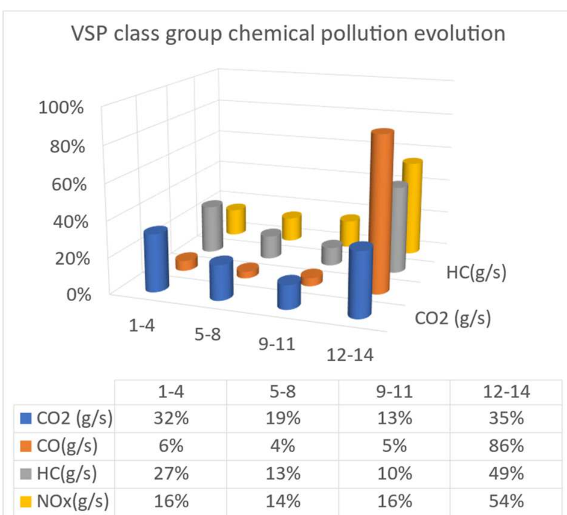
The many slowdowns and brakes characteristic of congested traffic help to explain the VSP falling more than 70% in the first seven ranges out of the total 1073 data.

There were, nonetheless, also areas with a high VSP range (that corresponds to values above 39 W/kg), which indicates traffic speeds that approach the limit of the road.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CO2 (g/s)	5%	4%	5%	19	8%	9%	2%	1%	1%	11	1%	1%	1%	33
CO(g/s)	1%	1%	1%	3%	1%	2%	0%	0%	0%	4%	0%	1%	2%	83
HC(g/s)	4%	4%	6%	13	5%	6%	1%	1%	1%	9%	1%	1%	2%	47
NOx(g/s)	2%	2%	1%	10	5%	7%	1%	1%	1%	13	1%	1%	2%	51

Fig. 4. Chemical pollution evolution based on VSP.



	1-4	5-8	9-11	12-14
CO2 (g/s)	32%	19%	13%	35%
CO(g/s)	6%	4%	5%	86%
HC(g/s)	27%	13%	10%	49%
NOx(g/s)	16%	14%	16%	54%

Fig. 5. Chemical pollution evolution based on VSP classes.

Figure 4 indicates that VSP class emissions are considerably different. VSP14 is the biggest pollutant, contributing 33% of CO2, 83% of CO, 47% of HC, and 51% of NOx.

At the opposite pols VSP4 emits 19% CO2, 13% HC, and 10% NOx as a secondary peak. VSP4 shows that emission reduction solutions must include both severe and moderate-power operation circumstances.

In comparison, VSP classes 7–9 and 11–13 emit just 0-2% of total pollutants.

Different pollutants have different emission patterns. While CO2, HC, and NOx are distributed similarly throughout VSP classes, CO emissions are concentrated in VSP14 with minimal contribution from other classes. Thus, high-power vehicle operations increase CO emissions.

An overview of emission patterns is provided by the figure 5, which groups VSP into classes. The highest VSP class group (VSP 12-14) accounts for 35% of CO2, 86% of CO, 49% of HC, and 54% of NOx emissions. This confirms the previous table's conclusions that high-power demand operations significantly increase emissions.

CO2 and HC emissions are second-largest from VSP 1-4, accounting for 32% and 27%, respectively. CO emissions are 6% and NOx emissions 16% for this group. These numbers imply that automobiles emit significant quantities of some pollutants even at low power demands.

Middle VSP class groupings (VSP 5-8 and VSP 9-11) contribute somewhat to emissions, possibly associated with cruising and modest acceleration.

Considering both charts together, it is clear that certain pollutants, such as CO and HC, show promising trends that may be attributed to advancements in technology or regulatory actions. However, the data also highlights the ongoing environmental issue of increasing CO2 levels as VSP rises. The significance of increased VSP on CO2 emissions highlights the need for stronger measures to address the environmental effects linked to high vehicle-specific power outputs. These trends underscore the importance of ongoing advancements in vehicle design and policy measures to effectively curb greenhouse gas emissions, particularly CO2, in light of increasing demands for vehicle power and performance.

5. CONCLUSION

The VSP approach is based on the power-to-weight ratio for each second of vehicle operation throughout a route. It may be used to estimate emissions and fuel consumption by taking into account the intensity and duration in each of the user-selected VSP modes. By considering the power-to-weight ratio and variations in vehicle operation, the VSP approach provides a more detailed and realistic assessment of emissions.
When it comes to all four types of emissions (CO2, CO, HC, and NOx), VSP14 regularly displays the highest levels of emissions by a substantial margin. Based on this information (figure 4 and 5), it appears that the conditions or driving modes linked with VSP14 are particularly inefficient or demanding, which ultimately results in a larger generation of pollutants. In addition, VSP4 and VSP10 exhibit emissions that are somewhat increased; however, these emissions are far less dramatic than those observed at VSP14. The vast majority of other VSP levels keep their emission rates that are quite modest and constant across all three contaminants.

The significant rise in emissions within the VSP11-14 group suggests that vehicles operating in higher power conditions are major contributors to environmental pollution. Monitoring and regulation efforts might need to focus more intensely on this category to mitigate pollution.

This information can be valuable for policymakers and researchers looking to develop strategies for reducing vehicle emissions and improving air quality.

6. REFERENCES

[1] S.Javanmardi, E.Bideaux, R.Trigui, E.Nicouleau Bourles, S.Dehoux, Hervé Mathieu - Effect of trajectory optimization parameters on energy consumption and CO2 emissions for a gasoline powered vehicle, Journal of Earth Sciences and Geotechnical Engineering, Scienpress LTD, 2017, 7 (1), pp.263-276

[2] Poria Fajri, Reza Ahmadi, and Mehdi Ferdowsi, Equivalent Vehicle Rotational Inertia Used for Electric Vehicle Test Bench Dynamic Studies, 2012, IEEE

[3] Duarte, G.N. de O., 2013. A Methodology to Estimate Vehicle Fuel Consumption and Pollutant Emissions in Real-world Driving Based on Certification Data.

[4] Duarte, G.O., Gonçalves, G.A., Baptista, P.C., Farias, T.L., 2015. Establishing bonds between vehicle certification data and real-world vehicle fuel consumption - a vehicle specific power approach. Energy Convers. Manag.

[5] Jisu Park, Jigu Seo, Sungwook Park, Development of vehicle emission rates based on vehicle-specific power and velocity, Science of The Total Environment, Volume 857, Part 3, 2023, 159622, ISSN 0048-9697

[6] Jimenez-Palacios,1998. Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing.

[7] Frey, H., Unal, A., Chen, J., Li, S., Xuan, C., 2002. Methodology for Developing Modal Emission Rates for EPA's Multi-scale Motor Vehicle & Equipment Emission System. State Univ. US EPA, Ann Arbor, MI, pp. 18–20.

[8] Marta V. Faria, Roberto A. Varella, Gonçalo O. Duarte, Tiago L. Farias, Patrícia C. Baptista, Engine cold start analysis using naturalistic driving data: City level impacts on local pollutants emissions and energy consumption, Science of The Total Environment, Volume 630, 2018, Pages 544-559

[9] Roberto A. Varella, Marta V. Faria, Pablo Mendoza-Villafuerte, Patrícia C. Baptista, Luis Sousa, Gonçalo O. Duarte, Assessing the influence of boundary conditions, driving behavior and data analysis methods on real driving CO2 and NOx emissions,

Science of The Total Environment, Volume 658, 2019, Pages 879-894, ISSN 0048-9697

[10] G.O. Duarte, G.A. Gonçalves, T.L. Farias, Analysis of fuel consumption and pollutant emissions of regulated and alternative driving cycles based on real-world measurements, Transportation Research Part D: Transport and Environment, Volume 44, 2016, Pages 43-54, ISSN1361-9209

APLICAREA UNEI METODE DE INDICATOR DE PUTERE SINTETICĂ PENTRU CUANTIFICAREA POLUĂRII CHIMICE LA AUTOVEHICULE

Acest document discută estimarea emisiilor vehiculelor folosind software de simulare a traficului şi calcule de putere specifice. Acesta explică conceptele de modelare directă şi inversă pentru estimarea parametrilor vehiculului şi a funcţionării grupului motopropulsor. Documentul prezintă, de asemenea, ecuaţii pentru calcularea puterii necesare pentru deplasarea unui vehicul şi factorii care afectează rezistenţa la mişcarea înainte. Acesta introduce conceptul de putere specifică vehiculului (VSP) şi modul în care poate fi utilizat pentru a estima emisiile şi consumul de combustibil pe baza diferitelor scenarii de conducere. Documentul oferă rate de emisie pentru diferite intervale VSP şi discută impactul condiţiilor de conducere asupra emisiilor poluante. De asemenea, descrie un studiu de caz de modelare a traiectoriei şi analizarea emisiilor unui singur vehicul folosind software de simulare.

Cuvinte cheie: *Emisiile vehiculului, Puterea specifică vehiculului (VSP), Traseul vehiculului, Simularea vehiculului*

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