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Coupling Virtual Reality Simulator with Instantaneous Emission Model: A New Method for Estimating Road Traffic Emissions

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Abstract: The article presents a new methodology for traffic emissions modeling by coupled the use of dynamic emissions models with a virtual reality driving simulator. The former allows the drivers' behavior to be studied through a virtual reality driving test, focusing the attention on how traffic flow conditions combined with road geometrical characteristics influence the driving behavior. The latter is used to model the instantaneous vehicle emissions, starting from the driving data provided by the driving simulator. The article analyzes the relationship among three factors: the driving behavior, the pollutant emissions, and the traffic flow condition. The results highlight the influence of the drivers' behavior on fuel consumption and emissions factors. Under high traffic flow, despite the reduction of the average vehicle speed, the average emissions level increases due to the increased vehicle accelerations and decelerations, which influence the behavior of the engine and the aftertreatment system. The proposed approach points out the relationship between vehicle emissions and drivers' behavior. Since the coupling among instantaneous emissions modeling and geometry-functionality conditions of the road reveals important elements that traditional approaches miss, the proposed method provides a new way to increase the efficiency of road design and management, from the environmental point of view.

Keywords: emissions factors; emissions models; driving simulator; driver behavior

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1. Introduction

Many studies have been performed with the aim of understanding the relationship between vehicular emissions–climate change and human health [1].

Thanks to mathematical formulations of the relationship between emissions and the variables on which these emissions depend, it is possible to define models to simulate vehicular emissions. According to [2], there are two types of emissions models: static and dynamic models, which are distinguished depending on the parameters considered by the model. The static model refers to average values; it examines emissions phenomena by means of average speed value and returns the average value of pollutants in a timeslot. Despite its wide applicability, the static model has some limits. Indeed, in many cases the average value of speed is not representative of the real operation of the infrastructure. A more significant parameter is the instantaneous speed profile, which depends on acceleration and deceleration of the vehicle along a single stretch of road.

The models that consider instantaneous values are called dynamic models. Dynamic models allow emissions values to be estimated more accurately, as shown by the application of the CORINAIR [3] methodology to urban areas. Several very accurate dynamic models have been developed that are able to provide detailed results about emissions estimation, as shown by [4]. Furthermore, as demonstrated by [5,6], this accurate type of model needs many data as inputs. According to [7,8], this means that these models must be coupled to transport models, which provide the necessary inputs.

When dynamic models are used, according to [9], the influence of drivers' behavior plays a key role. Typically, in the different traffic flow conditions, drivers adapt their driving style by changing speed through acceleration and deceleration; therefore, each speed profile is reflected by the emissions level. As shown by [10], besides the influence on emissions, the different driving styles affect fuel consumption. Ref. [11] also describes the influence on emissions and fuel consumption of different vehicle parameters, driving styles, and traffic measures adopted to increase the safety of transport or to reduce traffic jams. The issue of increasing levels of emissions caused by drivers' behavior is a very sensitive topic for many institutional organizations that have felt the need to promote driving education programs to reduce traffic emissions [12]. In the frame of the Intelligent Energy Europe Programme of the European Commission carried out from 2010 to 2013, the ECOWILL project has been proposed [13] (ECOdriving—Widespread Implementation for Learner Drivers and Licensed Drivers). As already mentioned, due to the high number of input data, dynamic models for estimating emissions cannot be used alone and must be coupled with transport models.

Several contributions can be found in the field-related literature concerning the application of microsimulation transport models to the specific purpose [14,15]. However, these models do not take drivers' behavior (e.g., trajectories) into account, instead dealing with issues related to transportation logistics, as shown by [16]. Moreover, microsimulation was found to require additional model construction time and input data for calibration, which is not always available information [17]. Among the transportation studies/infrastructures, a good contribution to microsimulation modeling and control is provided by smart roads and smart networks [18–20]. These infrastructures can contribute to controlling and monitoring traffic volume and the operating speed profile that affect pollutant emissions.

Thus, a promising step forward can be represented by the coupling between a virtual reality driving simulator and a complete model of a vehicle, having the capability to predict the transients of emissions and fuel consumption depending on drivers' behavior while driving. A virtual reality driving simulator is an advanced tool capable of investigating how traffic flow conditions combined with geometrical characteristics of roads can influence drivers' behavior [21]. Among the major advantages of this tool, it is worthwhile to mention the possibility of repeating an identical set of simulations while varying a single parameter, which allows its actual influence on traffic emissions to be assessed. At the same time, an adequate numerosity of the tested sample ensures a statistical validation of the results of the model, based on real driving behaviors rather than on theoretical assumptions.

The main contribution of the current paper is to propose a new method, representing a valuable tool to study the relationship between driving behavior in different driving situations and emissions. The proposed method for estimating road traffic emissions is based on the coupled use of dynamic models for estimating emissions with a virtual reality driving simulator. The instantaneous parameters obtained by the driving simulator are used as transient inputs for the emissions and consumption dynamic models. In this way, it is possible to obtain an accurate prediction of emissions according to the different drivers' behavior. The method is presented and used in a practical case study, pointing out the influence of different levels of traffic on driving behavior and emissions.

2. Materials and Methods

According to the specific literature, in some applications the models used in the estimation of road traffic emissions may need further improvement. Indeed, a desirable feature is the capability to predict road emissions in specific traffic conditions; such a modeling approach would support the analysis of the road environmental impact in the attempt to define efficient strategies to reduce vehicular emissions. Another important factor determining the level of traffic emissions is represented by the drivers' behavior. In fact, it has been shown that traffic emissions strictly depend on drivers' maneuvers. Therefore, it is important to model the link among drivers' behavior, road variables (geometry and traffic flows), and vehicular emissions.

In the current article, an integrated modeling approach (Figure 1) is proposed and used. Two simulation tools are coupled and used; these are the STI virtual reality driver simulator and the Simcenter Amesim environment.

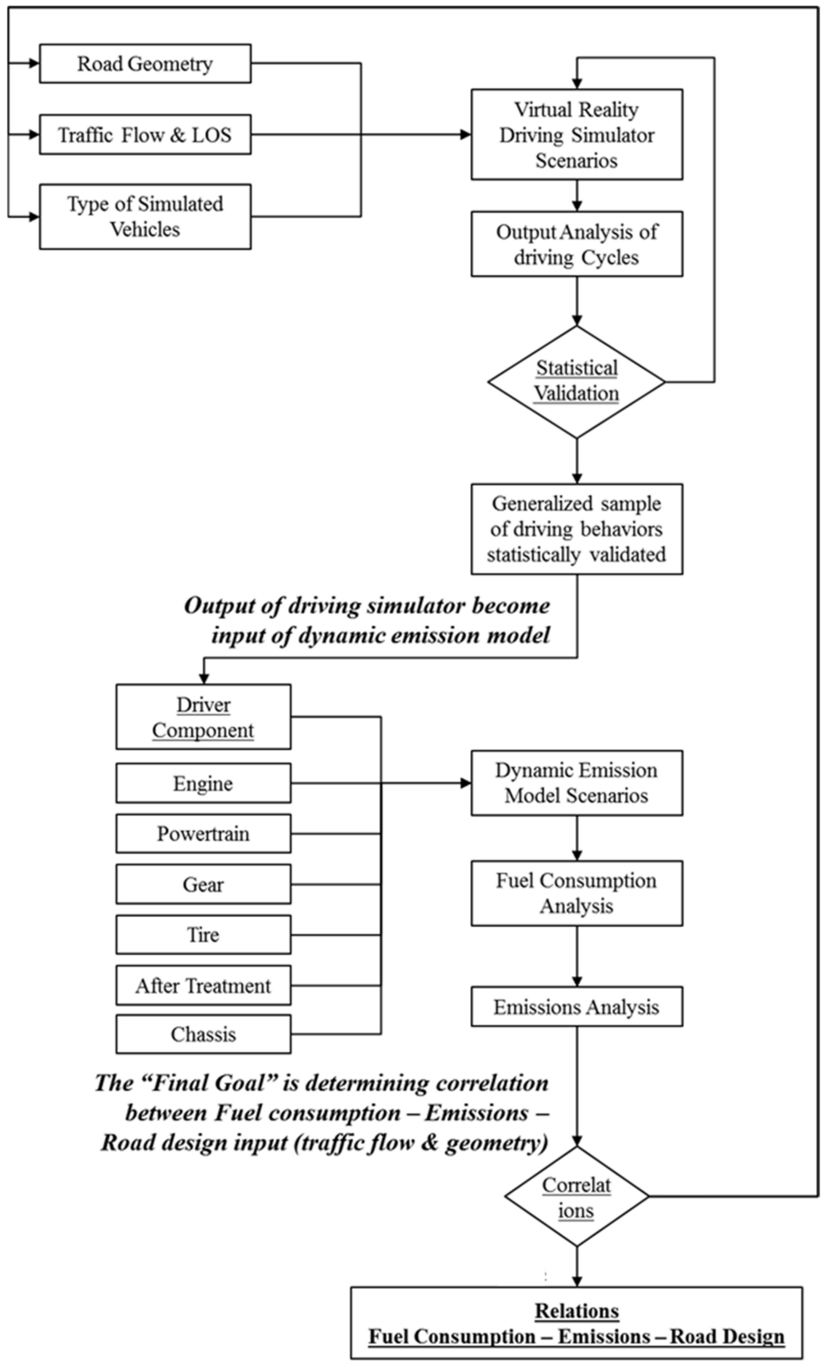

Figure 1. Methodology flow chart.

2.1. STI Driving Simulator

Drivers' behavior was characterized by means of the STI driving simulator, available at the Virtual Reality Laboratory of University Research Centre for Road Safety (LASS3, Figure 2). The reliability of the complete facility was fully validated [22,23]. The simulator was installed within a real vehicle in an effort to ensure a high feeling of reality during the experiments. The virtual scenario was projected in front of the car and sideways, covering a 135 degree visual angle; sound speakers in the motor hood emulated the acoustic environment.

Figure 2. STI driving simulator in Virtual Reality Laboratory LASS3.

The simulator allows for the modeling of roadway characteristics, driving situation events, and roadway environment. Moreover, to achieve an adequate level of realism in the simulation, the road scenario was implemented by defining many elements of the road environment, such as buildings, service stations, trees, and background sceneries.

After the scenario definition, it was necessary to select a homogeneous sample of subjects to drive in the scenario simulation. The output of the simulator allows data to be recorded every 0.3 s. Each data record is composed of a set of parameters, which are then used to study and analyze the driving behavior of each driver. The output variables recorded by the simulator are listed in Table 1.

Table 1. Output variables.

Distance traveled	[m]
Distance from the center of the roadway	[m]
Longitudinal speed	[m/s]
Transverse speed	[m/s]
Longitudinal acceleration	[m/s^2]
Transverse acceleration	[m/s^2]
Curvature of vehicle and roadway	[1/m]
Vehicle angle	[rad]
Steering wheel angle	[rad]
Throttle valve position (from 0 (closed) to 1 (fully open))	-
Force on brake pedal	Pounds
Gear engaged	#
Rate of deviation of vehicle along three directions (x, y, z)	%

2.2. *Vehicle Engine and Powertrain Model*

The vehicle engine and powertrain model was built in a multi-domain simulation environment. The model was conceived to be coupled to the output of the driving simulator (in terms of the time–speed profile), enhancing the output of the driving simulator with vehicle fuel consumption and transient exhaust emissions (and the emissions factors) with a high degree of accuracy. Thanks to such an approach, the fuel consumption and the pollutant emissions are simulated depending on the operation point of the engine. In the research two different types of vehicles were modeled, as described in the following.

2.2.1. Gasoline Vehicle

The gasoline engine features were expressed in terms of characteristic maps, as regards mechanical torque, fuel consumption, and gaseous raw emissions (CO, HC, NOx).

During the simulations, depending on the road-traffic conditions and on the driver behavior, the resulting engine operation point determines fuel consumption and raw emissions. Figure 3 reports the used engine maps; these maps are well suited to the considered vehicle, which was chosen to represent the class of gasoline vehicles under investigation.

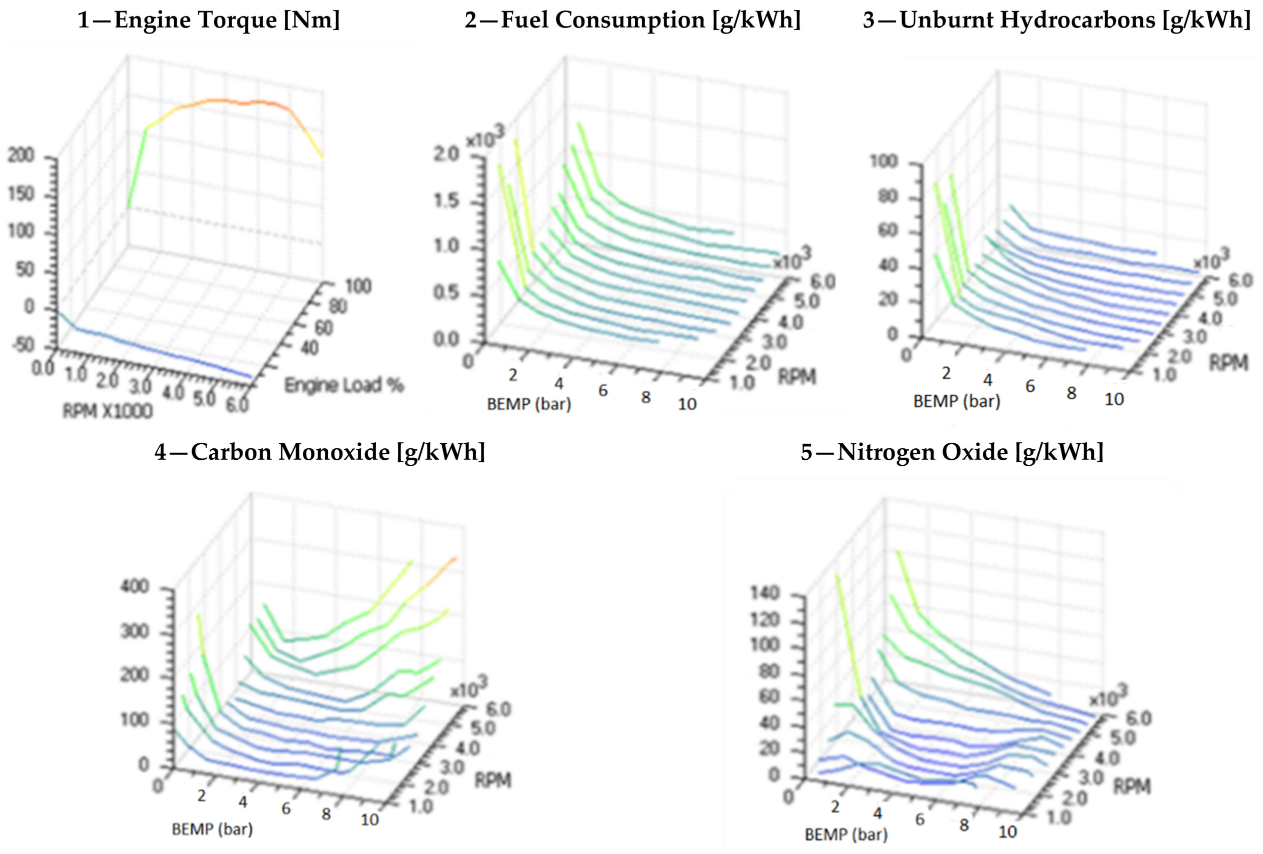

Figure 3. Engine and emissions maps—gasoline vehicle.

In principle, the uncertainty that accompanies the data contained in the maps is linked to two factors. On the one hand, there is the uncertainty associated with the experimental torque and emissions measurements for each engine, and on the other, there is the uncertainty, or the approximation, deriving from the fact that the chosen map is assumed to be representative of the engines belonging to the same category. The influence of such uncertainties would obviously affect the final forecast of vehicle emissions, but considering the objectives of the present work, here it was not taken into consideration because these uncertainties were assumed to be independent of the driver's driving style.

Based on these maps, the engine model was coupled to the model of an after-treatment device (namely, the Three-Way Catalyst), and the exhaust gases (carrying raw emissions) were treated. In this configuration, NO reduction and CO and HC oxidation are carried out in the same catalytic structure. The kinetic models are associated with reaction mechanisms. The reaction rates are of the Langmuir–Hinshelwood type. All the kinetic constants are parameters of the TWC model, and the used values are available in the literature and implemented in the libraries provided with an Amesim code [24]. The assumption that the kinetic constants follow an Arrhenius law was adopted. As the simulation referred to highway-driving conditions, and as the engine did not experience cold-to-hot transition, a zero-dimensional approach was adopted.

2.2.2. Diesel Vehicle

Like the gasoline engine, the diesel engine features were expressed in terms of characteristic maps, as regards mechanical torque, fuel consumption, and gaseous raw emissions

(PM, NOx). herein addition, depending on the road-traffic conditions and on the driver behavior, the resulting engine operation point determined fuel consumption and raw emissions. As in the previous case, Figure 4 reports the engine maps used.

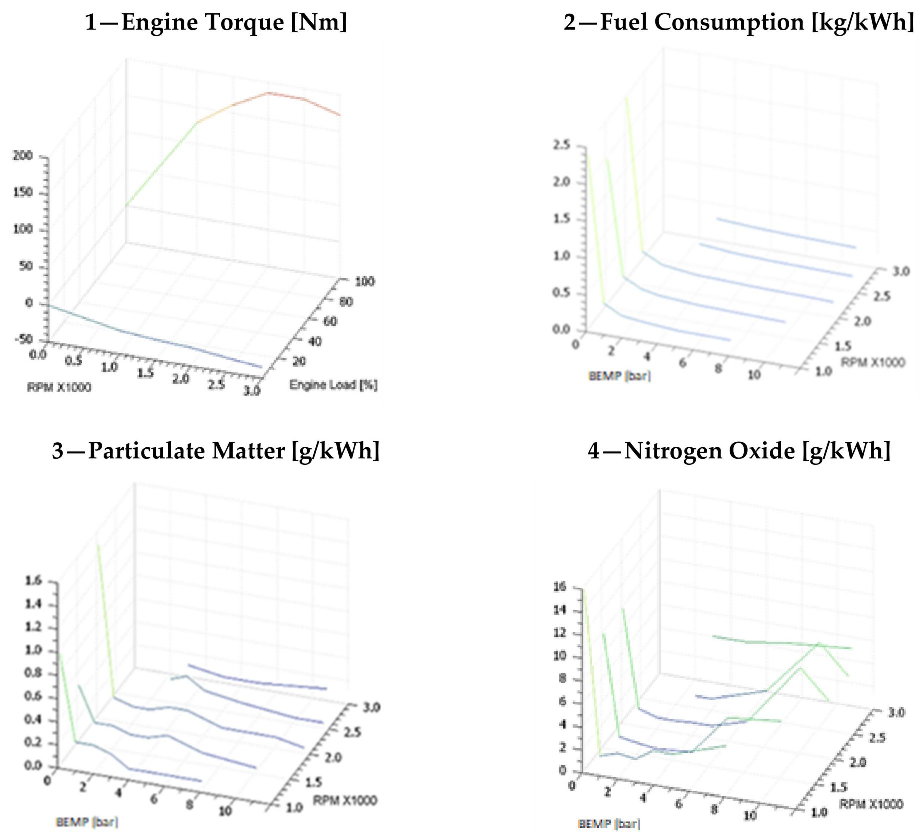

Figure 4. Engine torque and emission maps—diesel vehicle.

The diesel engine model was coupled to the Diesel Oxidation Catalyst (DOC) model and the raw exhaust gases were treated. In this configuration, excess oxygen converts all CO and HC. The kinetic models are associated with reaction mechanisms. The reaction rates are of the Langmuir–Hinshelwood type. As the simulations referred to highway-driving conditions, and as the engine did not experience cold-to-hot transition, a zero-dimensional approach was adopted.

2.2.3. Virtual Vehicle Behavior under Real-like Conditions

From a strictly scientific point of view, it is extremely onerous and challenging to build models that can accurately and quantitatively predict the level of exhaust emissions of a real vehicle. On the other hand, for the purpose pursued here, it would be sufficient to employ models capable of providing results simply in the form of a trend.

Although the lumped-parameter approach adopted here is tied to the necessary simplifications in modeling, it undoubtedly allows the variability of the operating conditions of the engine and of the exhaust aftertreatment to be considered. As will be highlighted in the Results section, the virtual vehicle model was validated on the basis of the emission limits that apply to the considered vehicle class.

The complete model is intended as a useful tool in the forecasting of traffic behavior (towards the environment) during the road-design phase. Thus, its fundamental significance is represented by this chance it offers to road and infrastructure designers.

3. Case Study

A case study was set up to analyze the relationship among three factors: driving behavior, pollutant emissions, and vehicular interference. Consistent with the methodology, the following paragraphs illustrate the general protocol for virtual reality simulation, the road scenario implemented, and the modeled vehicles for emissions and consumption analysis.

The case study analyzed the relationship among traffic emissions and driving behavior by increasing the level of traffic on a simulated two-lane rural highway. It is well known that an increase in traffic level is reflected by the change in driving style, often resulting in intense accelerations and decelerations. Therefore, the case study allowed the way in which the change in driving behavior is reflected by emissions levels and fuel consumption to be investigated.

3.1. General Protocol for Virtual Reality Simulation

A homogeneous sample of subjects was selected and the same driving conditions were determined for each driver to avoid biasing the results through driver attitude, driving experience, age, stress level, emotional state, neuro-cognitive status, or other factors. Twenty-two subjects (10 women and 12 men, mean age of 40 years and range 20–60) composed the sample. The driving results of the whole sample were fully validated through a statistical method based on the verification of the stability of average parameters. Moreover, to exclude outliers, the Chauvenet criterion [25] was adopted. According to the strict procedure of simulation experiments, participants were required to complete a training driving simulation scenario for at least 10 min; after each virtual drive, a short break was given to the drivers.

3.2. Road Scenario

The drivers were requested to drive along the simulated road stretches in five different runs. Subjects could see their speed on the speedometer visualized on the screen and they were free to choose the speed according to what the road scenario suggested to them. The scenario represented a two-lane rural highway geometry (section length: 10 km, lane width: 3.5 m, n° of lanes: 1, shoulder width: 1.25 m) and it was performed in five different traffic flow conditions, as shown in Table 2.

Table 2. Traffic flow conditions.

Scenario	Average Speed (km/h)	Density (veh/km/ln)	LOS
1	91	6	A
2	88	9	B
3	72	14	C
4	64	18	D
5	61	20	D

The different scenarios were built to investigate different levels of traffic according to the HCM classification of Capacity and Level of Services (LOS) [26].

To reduce the variables of analysis it was decided to simulate a real Italian road, representative of a typical Italian two-lane rural highway, with a grade that did not exceed 2.5%. In accordance with the aim of the case study, only the relationship between traffic flow and emissions/fuel consumption was investigated; indeed, through the proposed method, it was also possible to investigate the relationship between road geometry and emissions/fuel consumption.

3.3. Powertrain, Wheel Base, and General Features

Regarding the choice of the vehicles, two "medium-class" vehicles (EURO 3 compliant) were considered for the present work, whose features are representative of a wide share of vehicle fleets. The relevant features are summarized in Table 3.

Table 3. Main features of simulated vehicles.

Engine type, displacement	Gasoline, 1.6 L	Diesel, 1.6 L
Mass	1350 kg	1300 kg
Active area in aero drag	1.91 m^2	1.92 m^2
Aerodynamic coefficient	0.3	0.3
Tire width	175 mm	175 mm
Gear ratios	I = 3.1; II = 1.6; III = 1, IV = 0.7	I = 3.1; II = 1.6; III = 1, IV = 0.7
Axle gear ratio	3.85	3.85
Powertrain	Automatic gearbox, integrated torque converter	

3.4. European Emissions Standard Validation

To assess the virtual vehicle compliance with the emissions regulation (EURO 3), both vehicles were tested on the New European Driving Cycle (NEDC). Figure 5 show the NEDC duty cycle and the simulation output in comparison to the European emission standards. All the species considered by the regulation (CO, HC, HC + NOx etc.) were compared to the emissions limits, pointing out that the simulated vehicles were fully compliant with EURO 3 regulation. Such a class of vehicles was considered for the current investigation due to its relevance in the Italian context; indeed, referring to Italian passenger car fleet vehicles, over 60% of vehicles are included between EURO 1 and EURO OK 3. Furthermore, EURO 3 vehicles represent about 20% of the fleet.

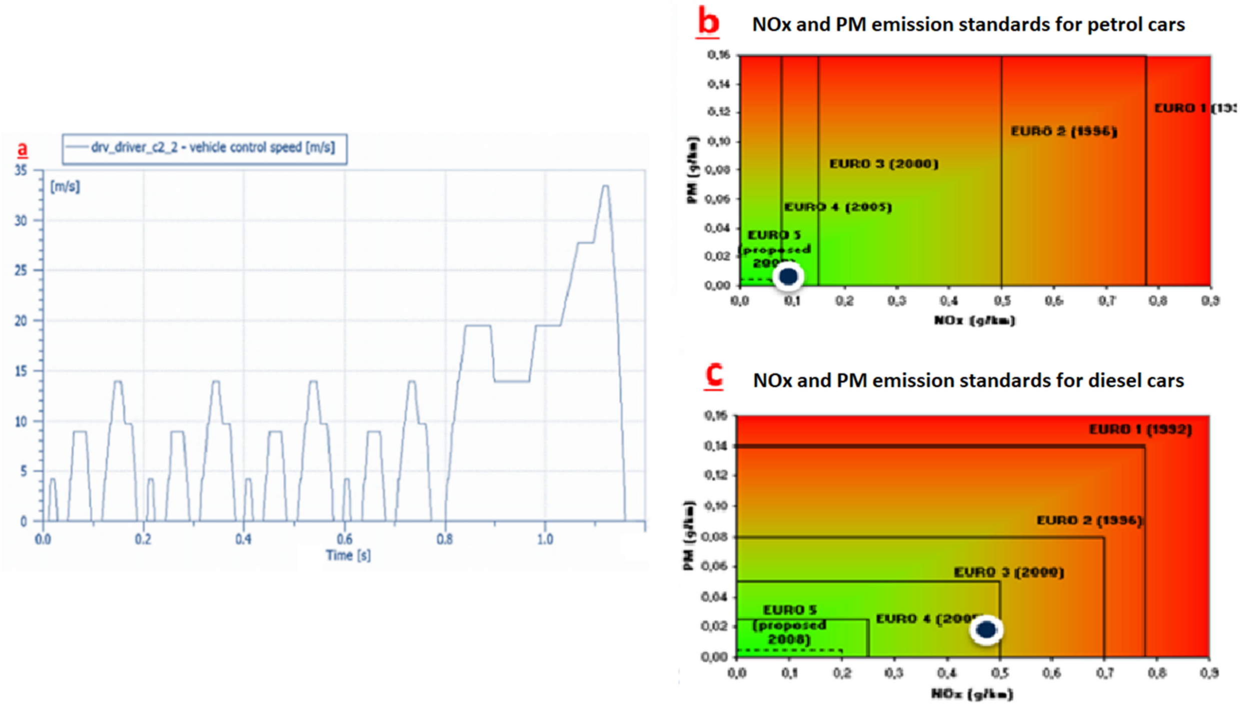

Figure 5. NEDC (**a**) and output of simulation compared to EURO regulation for gasoline (**b**) and diesel (**c**).

3.5. Statistical Analysis: ANOVA Test

In accordance with the literature [27], the analysis of variance test (ANOVA) was used to research the statistically significant differences in the indicator values among the analyzed configurations. For each scenario, the ANOVA test was performed to investigate the effects of different traffic flow conditions on emissions. The null hypothesis was that the average of the dependent variable is the same for the configurations being investigated. Rejecting the null hypothesis would mean that the independent variable, the traffic flow, influences the dependent variable.

4. Results and Discussions

4.1. Results of ANOVA Test

Speed Table 4 shows the results of the ANOVA test for each pollutant performed on traffic volume factor (five scenarios). The null hypothesis was rejected for almost the whole set of data with a statistical significance higher than 80%. Is possible to highlight that:

- For the gasoline vehicle the variation in average emissions on the traffic flow factor had a statistical significance of over 90% (90% for CO and 95% for NOx).
- For the diesel vehicle the variation in average emissions on the traffic flow factor had a statistical significance of over 80% (80% for PM and 90% for NO_2).

Table 4. Results of statistical analysis on traffic volume factor.

Type of Vehicle Pollutant	Gasoline NO_2	Gasoline CO	Diesel NO_2	Diesel CO
ANOVA test	P = 0.05 F = 2.6	P = 0.10 F = 2.2	P = 0.10 F = 2.1	P = 0.20 F = 1.55

4.2. Average Speed and Fuel Consumption Analysis

It is well known that traffic flow has a significant influence on driver speed. Table 5 shows the decrease in average speed values for increased traffic flow, where scenarios with low interference flow are related to scenarios with high interference flow.

Table 5. Average speed and fuel consumption.

Scenario	Average Speed (km/h)	Fuel Consumption Gasoline (g/km)	Fuel Consumption Diesel (g/km)
1	91	66.8	47.7
2	88	66.1	48.1
3	72	70.7	47.3
4	64	75.9	48.9
5	61	74.9	47.3

Furthermore, Table 5 shows the average fuel consumption for the whole sample of drivers performed in each scenario; as expected, the fuel consumption of the diesel vehicle was always lower than the gasoline one. The gasoline fuel consumption trend recorded a rise, and the diesel fuel consumption trend was similar, but the increases were more moderate, at around 3% maximum.

4.3. Emissions Analysis

Bearing in mind what was previously presented about average speed, the results of the emissions analysis show that the decrease in average speed did not involve a general reduction of pollutant emissions, both for diesel and gasoline vehicles.

As shown in Figure 6, regarding the gasoline vehicle, pollutant emissions were calculated in terms of NOx and CO (the different behavior of the trends is due to the TWC operation). Regarding the diesel vehicle, more moderate reductions and increases were recorded, both for NOx and PM.

Since the average speed value along a stretch of road is not indicative of the real conditions of vehicle emissions, it is important to analyze the instantaneous speed values. In fact, it is significant to highlight that vehicle emissions depend on many factors, both in terms of engine operation and in terms of the exhaust gas aftertreatment system. For a gasoline engine it is important to maintain the operation with an almost stoichiometric air/fuel ratio within a convenient catalyzer temperature range. The continuous and sudden opening–closing of the throttle tied to the driver's behavior has the capability to affect the effectiveness of the aftertreatment system; thus, a significant increase in emissions is possible.

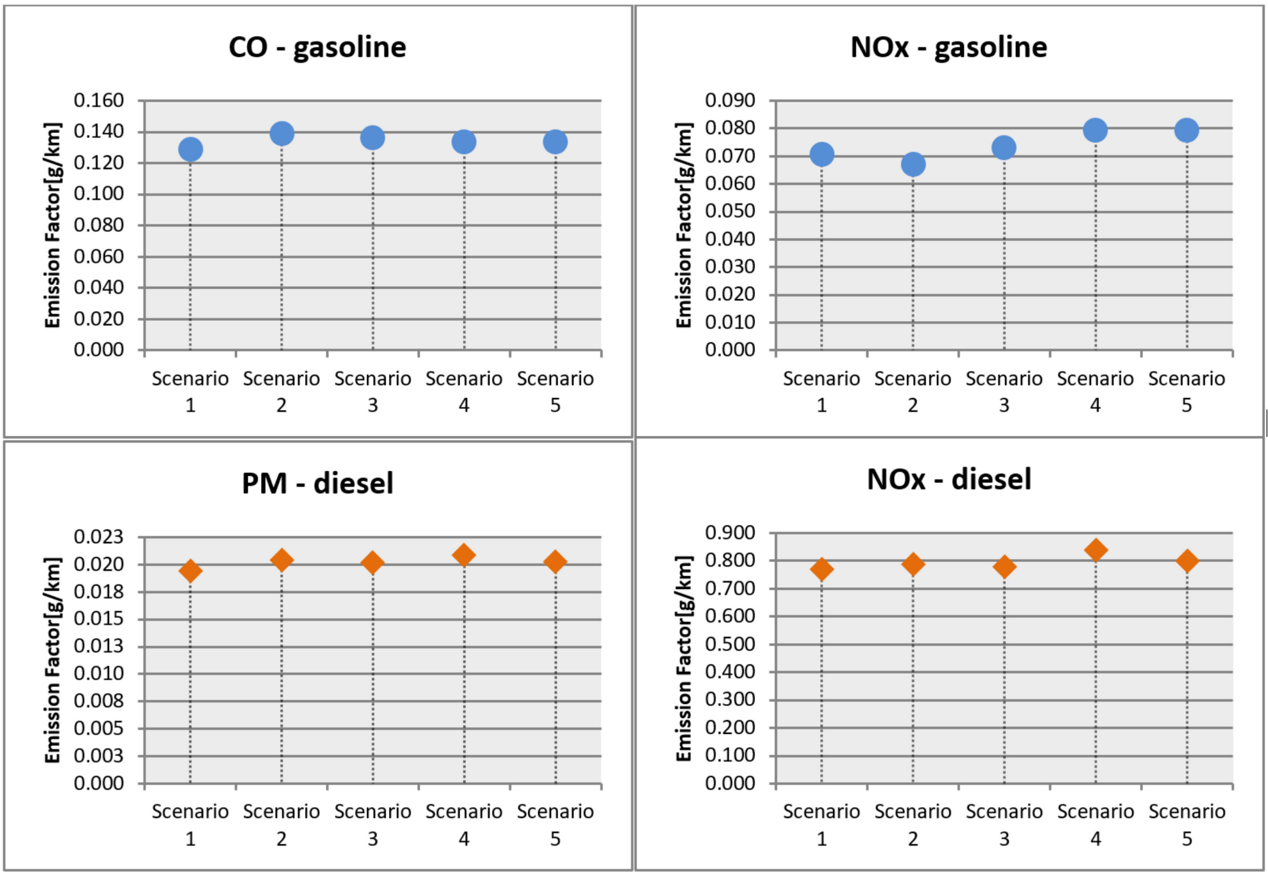

Figure 6. Emissions factor in different scenarios for gasoline (top row) and diesel (bottom row) vehicles.

Therefore, the emissions were related to a synthetic indicator of speed variations. With this aim, the standard deviation of the instantaneous speed values recorded during the simulation was used. The result of this correlation is shown in Table 6 and Figure 7.

Table 6. Values of correlation.

CO—Gasoline	NOx—Gasoline	PM—Diesel	NOx—Diesel
$R^2 = 0.4519$	$R^2 = 0.6024$	$R^2 = 0.2681$	$R^2 = 0.4031$

The results concern a typical two-lane rural highway, whose homogeneity is typically lower when compared to freeway cases. With the increase in traffic flow and then vehicle interference, an expected reduction, in terms of average speed, was recorded. However, the same trend in terms of fuel consumption was not observed. Indeed, for the gasoline vehicle a minimum value of fuel consumption was observed in correspondence to an "optimal" flow, which provides a reference to the driver, allowing them to adopt less polluting behavior. Increasing the vehicular interference, accelerations, and decelerations is more frequent, and then the fuel consumption also increases. This leads to an increase in emissions due to the reduction in the aftertreatment system effectiveness.

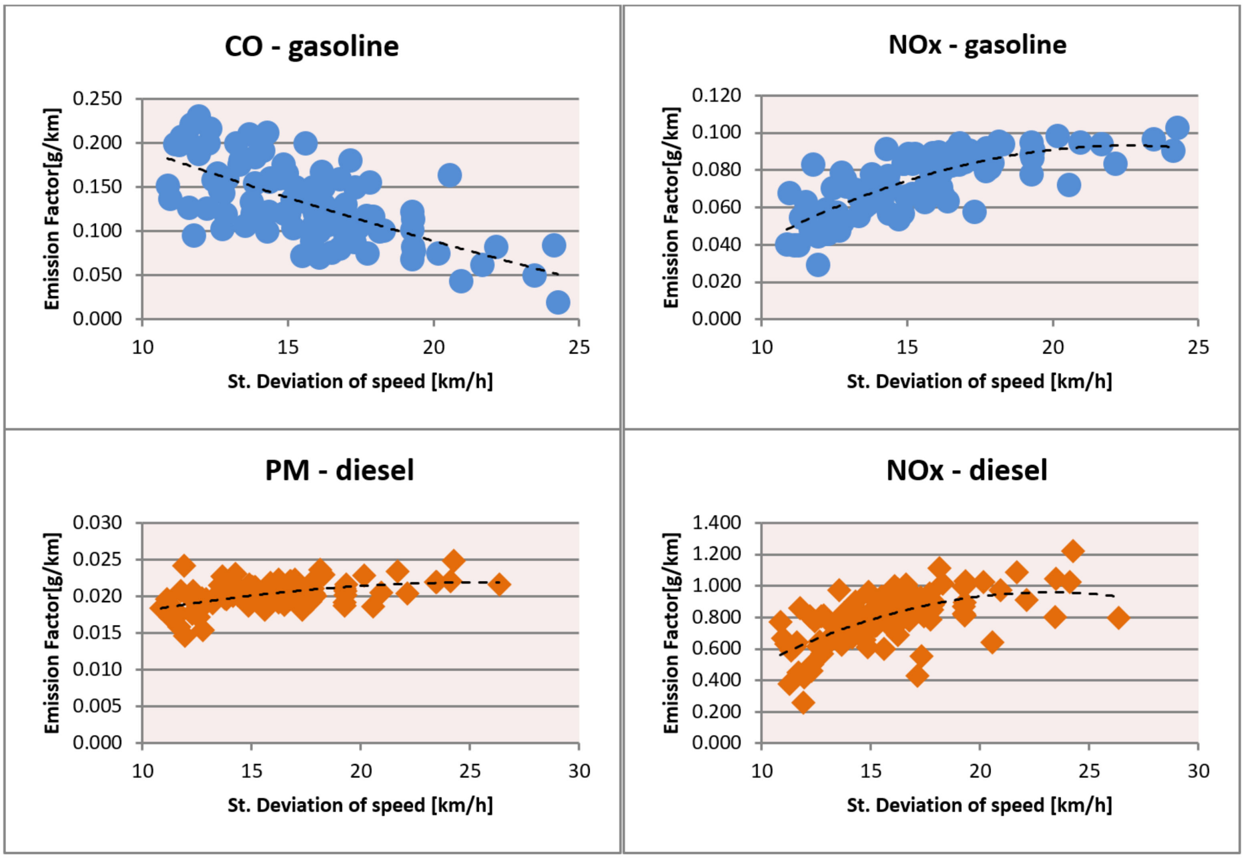

Figure 7. Correlation between standard deviation of speed and emissions factor for gasoline (top row) and diesel (bottom row) vehicle.

Regarding the diesel vehicle, differences in terms of consumption were more contained, showing poor correlation between consumption and vehicular interference. In the same way, emissions were less influenced by the phenomena of acceleration and deceleration. The same conclusions were also attained considering the speed variations through the analysis of the standard deviation, or rather, analyzing how much the instantaneous speed values were dispersed from the mean. As shown in Figure 7, the correlation between the standard deviation and emissions could be approximated by a parabola.

Regarding the gasoline vehicle, NOx and CO showed opposite trends for the phenomena of catalysis mentioned above. The gasoline vehicle showed more significant values of correlation (greater R^2) than the diesel vehicle.

5. Conclusions

The presented research deals with a new method of vehicle emissions estimation by means of the coupled use of a complete lumped-parameter dynamic vehicle model and a comprehensive simulation tool, as is the virtual reality driving simulator. The results highlight the influence of driving behavior on fuel consumption and emissions factors in five different driving conditions, moving from a low level (LOS A) to a high level (LOS D) of vehicular interference. The results show that despite the average speed reduction due to the increase in traffic flow, the average value of emissions increased. This result is due to the increase in acceleration and deceleration phenomena in driving behavior. When such a condition is encountered it penalizes the efficiency of the catalytic converter, producing a significant increase in emissions. What is possible to conclude from the case study is that the relationship between vehicle emissions and drivers' behavior, depending on driving style and the functionality conditions of the road and its geometry, suggests new insights to deepen the field of research.

Future developments of this research will concern the analysis of the effects on emissions due to different geometric conditions. The analysis will aim to assess, independently by the influence of traffic flow, in which way specific geometric elements or different road configurations can influence the driver behavior and consequently emissions. Another interesting topic to explore is uncertainty, as uncertainties are inevitable in transport systems [28]. The authors demonstrate by mathematical models that uncertainty is not always negative and that it can also have positive impacts in some conditions. In fact, if a deterministic model is adopted to study phenomena traditionally carried out through stochastic models, the uncertainty of the problem exists both in the objective function and in the constraints. That is, the uncertainty is observed after the decision-making process; therefore, it appears as an objective function not affecting the performance of the system and therefore presents an advantage for the system.

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