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Traffic Emissions Estimation Along a Road Infrastructure
Using a Driving Simulator
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Abstract

It is well known that traffic has increased in the last years. This phenomenon has significantly changed traffic flow conditions and has produced a significant increase of interferences. Because of this, it is more effective using emission data calculated point by point instead of average values. In order to generalize the phenomenon of emissions, the analysis took advantage of the experiments carried out in the virtual reality laboratory. This research takes into account two different geometries and for each geometry, three different flow conditions. Data recorded using the driving simulator will be compared with data obtained from real scale tests.

1. Introduction

As discussed in the publication of the White Paper’s "Roadmap to the Single European Transport Area - Towards a competitive and resource efficient transport system", the target of reducing emissions of carbon dioxide - from 1990 to 2050 – represents a decrease of 60\%, set by the European Commission, \cite{1}. This objective provides a clear indication of the role of transport within the framework of air quality improvement. It is therefore necessary to provide tools that can give to planners real opportunities to look at different strategies to be put in place. In other words, there is a need to refer to models that are more reliable and precise, due to the higher demand for the reduction of pollutants dictated by the European Union, and more generally by the environmental requirements of pursuing sustainable development. Henceforth this study aims to define the state of the art of tools currently available to assess the limits and opportunities, in order to evaluate the design parameters influencing emissions.

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2. Literature Review

Emission models are based on mathematical formulations of the existing relationships between emissions and variables on which these emissions depend. They can be categorized into three categories: average speed models, traffic situation models - used at macro-scale or meso-scale level (national, regional, city level) -, and instantaneous (modal) models - useful at micro-scale level (street, vehicle level) - [2]. The first category is also known as static models, whereas, the other two categories are known as the dynamic models. The main difference between static and dynamic models is based on the parameters taken into account: static model refers to average values, while dynamic models make reference to instantaneous values.

Static models are used for evaluating emission phenomenon according to average speed. In other words, they evaluate the average value of pollutant emissions within a defined time. This model is easy to use in the simulation of emission and therefore is what is most generally used. However, there are many cases where the average speed is not representative of the real functioning of the infrastructure investigated. In urban areas, for example, where the sequence of intersections can be high, the average speed cannot be taken into account as a significant parameter of the emissions that occur along the stretch of road studied. In order to consider models which measure the instantaneous speed profile, acceleration or deceleration and vehicle emission along a single stretch of road, it is necessary to move from average parameters to instantaneous values. These models are called dynamic models.

Dynamic models are based on a set of parameters designed to evaluate instantaneous emissions as a function of specific significant variables. The functions themselves vary depending on the different kinematic motions taken by the drivers in the different traffic flow and geometrical conditions. As demonstrated by a Chinese study, [3], there was an immediate need to look at the emission phenomenon in terms of instantaneous values. To better understand how the traffic control could affect vehicle emissions, a novel TRaffic And Vehicle Emission Linkage (TRAVEL) approach was developed based on local traffic activity and emission data. This approach consisted of two-stage mapping from general traffic information to traffic flow patterns, and then to the aggregated emission rates. The results were validated by traffic and air quality monitoring data during the Olympics, as well as other emission inventory studies.

It is well known that different traffic flow conditions leads to different driving styles; average speed, acceleration and deceleration values. It is also known that frequent speed-change induces high emission levels. [4] presented a study on sensitivity finalizing the analysis of the influence of speed on emissions. The study discusses the aspects linked to the speed in the application of the CORINAIR methodology to urban areas, in particular the introduction of a speed frequency distribution by vehicle category (Thirteen classes with range 10 km/h). The results show that a deeper knowledge of driving characteristics and speed is essential to understanding the means of the estimates and pollutants that are emission dependant on speed are strongly non-linear.

Moreover, [5] showed the effects on fuel consumption and tail pipe emissions of applying different driving styles in modern passenger cars. The final goal of the investigation was to come up with practical tips for energy conscious driving, also addressing the effects of driving styles on tail pipe emissions. Furthermore, it is also shown that the rise of emission levels due to drivers’ behavior is a very sensitive issue for many governments, because the close connection between the two directly results in the release of air pollutants. Recently this issue has increased so much so that governments are feeling the need to offer driving education programs to help reduce traffic emissions.

In [6] the influence on vehicle emissions and energy consumption of different vehicle parameters and driving styles, as well as traffic measures taken in order to increase transport safety or to reduce traffic jams is described. This allowed the Flemish Regional Government to perform more realistic modeling of the impact of transport on air pollution. Different driving styles (sportive, EcoDriving, etc.) were measured on-road and evaluated on a roll-bench. Typical speed profiles corresponding to different traffic measures such as roundabouts, phased traffic lights, etc., were also recorded at different locations in the Flemish Region. All data was distilled into small
driving cycles, representative of a certain traffic situation or driving style, and repeated on a roll-bench to measure the emissions in controlled circumstances. It was evident that average speed values were not very representative of particular traffic conditions. For example, urban areas characterized by several intersections - the sequence of acceleration and deceleration sections - meant that the speed profile was very distant from the average value. In environmental terms, this translates into an underestimation or overestimation of emissions and therefore the simulated value did not match with the real one, as [7] also showed.

[7] researched the quality of an emission calculation model. This was based on emission factors measured on roller test stands and statistical traffic data source strength, as well as the emission factors calculated from real-world exhaust gas concentration differences measured upwind and downwind of a motorway in southwest Germany. In this research, both Gaseous and particulate emissions were taken into account and detailed traffic census data was taken during the measurements. The main conclusion by the model was the underestimation of CO and NOx source strengths. On average, 23% of CO and 17% for NOx was found.

[8] on the other hand studied the lack of accuracy related to models that are based on the analysis of standard driving cycles and standard emissions. The study presents a meta-analysis of 50 other studies dealing with the validation of various types of traffic emission models, including ‘average speed’, ‘traffic situation’, ‘traffic variable’, ‘cycle variable’, and ‘modal’ models. The mean prediction errors of CO emission values occur within a factor of 3, although differences as high as 5 have been reported, therefore in order to avoid this kind of prediction-error, models with an accuracy level as high as possible must be used. With the same aim, [9] have shown the results of a research carried out using ‘instantaneous’ high-resolution (1 Hz) emission data for the estimation of passenger car emissions during real-world driving. Extensive measurements of 20 EURO-I gasoline passenger cars have been used to predict emission factors for standard (i.e. legislative) as well as non-standard (i.e. real-world) driving patterns. Emission level predictions based upon chassis dynamometer tests over standard driving cycles significantly underestimate emission levels during real-world driving were shown.

[10] developed a microscopic instantaneous emission model to address the needs of researchers and policy makers on local levels. This model aims to predict vehicle fuel consumption and emissions for a given speed profile, for various scenarios. The need to study more in depth the speed profile and its variation to calculate emission is very evident, since the accurate study of the real driving cycle depends on the accuracy and the reliability of the prediction of emission levels. For this reason, dynamic models that are able to calculate emissions based on instantaneous speed values deduced from the study of a real driving cycle were combined with the traffic simulation models.

[11] studied effects of active speed management on traffic-induced emissions. In particular, the traffic emissions caused by acceleration and deceleration of vehicles were modeled based on an instantaneous emission model integrated with a microscopic traffic simulation model. The emission model was based on empirical measurements which related vehicle emission to: the type, the instantaneous speed, and acceleration of the vehicle. The traffic model captured the second-by-second speed and acceleration of individual vehicles travelling in a road network based on: their individual driving style, the vehicle mechanics and their interaction with other traffic and with traffic control in the network. The study suggests that the analysis of the environmental impacts of any traffic management and control policies is a complex issue and requires detailed analysis of not only their impact on average speed, but also on other aspects of vehicle operation; such as acceleration and deceleration.

In order to approach this complex issue, an advanced tool is required to be able to reproduce the same driving conditions - in terms of traffic conditions, geometrical characteristics and surroundings - for different drivers. The driving simulator is an instrument able to guarantee these test conditions. It is also capable to record every 0,3 seconds of all data regarding drivers’ behavior during driving, providing the real driving cycle for each driver. This study has been developed, providing a comparison between the static and dynamic models using driving simulator data.

3. Methodology
In order to characterize drivers’ behavior during driving, STI driving simulator has been used at the Virtual Reality laboratory of Inter Universities Research Centre for Road Safety (CRISS). The reliability of full instrumentation has been fully validated, [12], [13].

The simulator is installed inside a real vehicle to have the best feeling of reality during the experiments. The images are projected in front of the car and sideways just to cover the visual angle of 135° and the sound speakers are inserted inside the engine to emulate the acoustic environment at the best.

3.1 Statistical validation

Through a statistical method based on the verification of the stability of average parameters – the convergence of the average values of speed kept by each driver – it has been assessed that the number of participants is significant from a statistical point of view, and it assures a correct statistic data interpretation [14]. Moreover, to exclude outliers, Chauvenet criterion has been used. This criterion is a statistical method useful to evaluate the reliability of the output of simulation data, [14]. Consistent with this and for each scenario some drivers were excluded because they showed anomalous behaviour during driving, in particular in terms of average speed registered. Exclusion reasons were considered as the speed values strongly higher/lower than average value. According to the Chauvenet criterion 7 drivers were excluded and the authors considered a sample of 28 drivers.

3.2 Procedure

At the beginning of simulations, participants were informed about the procedure of the test in terms of: duration, use of the steering wheel, pedals and gear. According to the strict procedure of simulation experiments,
participants were required to complete a training simulation scenario for at least 10 minutes driving. The drivers were requested to drive along the two simulated stretches of road, in three different runs for each stretch, where no speed limit has been imposed. Subjects could see their speed on the speedometer visualized on the screen and they were free to choose the velocity, according to what the road scenario suggested to them. Scenario (A) represented highway geometry, while Scenario (B) represented a suburban one, with a more complex geometry. Each scenario was performed with three different flow conditions as qualitatively indicated as: Low Interfering Flow (LIF), Medium Interfering Flow (MIF), High Interfering Flow (HIF). Two geometries combined with three different traffic flows provided 6 simulation scenarios. Between each scenario participants were allowed a short break. This break was intended to avoid as much as possible the fatigue effect of each driving period.

3.3 The Static Model

In recent years, through many European projects, many static emission models have been developed. In 2003, project [15], the emission inventory guidebook 3rd edition was developed. The correlation between emissions and average speed was provided by Equation 1

\[
EF=9.846-0.2876 \times V + 0.0022 \times V^2
\]

Equation (1) Correlation Between Emissions and Average Speed by emission inventory guidebook 3rd.

Where:
- EF: Emission Factor for CO
- V: Speed value expressed in km/h

This correlation should be applied to Euro 1 vehicle. In the present paper, Euro 3 vehicle has been considered, and for this class, the guidebook provided for a reduction of the emission rate by 44%. A more recent version of the guidebook is [16] air pollutant emission inventory guidebook – 2009. In this case the correlation between emissions and average speed has been provided by Equation 2:

\[
EF=((a+c \times V + e \times V^2))/(1+b \times V+d \times V^2)
\]

Equation (2) Correlation Between Emissions and Average Speed by air pollutant emission inventory guidebook.

Where:
- a: Constant, for calculation of CO Euro 3 is equal to +7.17E+01
- b: Constant, for calculation of CO Euro 3 is equal to +3.54E+01
- c: Constant, for calculation of CO Euro 3 is equal to +1.14E+01
- d: Constant, for calculation of CO Euro 3 is equal to -2.48E-01
- e: Constant, for calculation of CO Euro 3 is equal to 0
- V: Speed value expressed in km/h

Also the [17] model version 9.0 developed by EMISIA has been used. This model estimates emissions of all major air pollutants (CO, NOx, VOC, PM, NH3, SO2, heavy metals) produced by different vehicle categories (passenger cars, light commercial vehicles, heavy duty trucks, buses, motorcycles, and mopeds) as well as greenhouse gas emissions (CO2, N2O, CH4). It also provides specification for NO/NO2, elemental carbon and organic matter of PM and non-methane VOCs, including PAHs and POPs. In this paper, COPERT 4 is been used to calculate CO emissions.

3.4 The Dynamic Model

This model allows for the simulation of a vehicle (2-liter gasoline engine with automatic transmission) on a stretch of road by imposing the speed during the test. The operating point of a car engine is calculated on the characteristics of the combination car-environment (e.g. type of engine and transmission, running resistances and mass of the car etc.), and then it calculates the gaseous emissions into the atmosphere. Moreover, the correlations
used to calculate pollutant emissions (CO) usually used in the automotive sector have been applied. In particular, these correlations are part of libraries of the commercial calculation code LMS [18], used for the simulations. The chosen approach for the simulation reproduces the test methodology prescribed by international regulations on atmospheric emissions for the approval of vehicle’s engine.

4. Results and Discussion

The simulation's outcomes were accurately collected, validated and analyzed in order to define the emissions level as a function of different kind of models and drivers behavior in different scenarios characterized by different geometry and under different traffic flow conditions. As previously mentioned, four different models have been used to estimate emission of Carbon Monoxide (CO) : Copert 4, EMEP/CORINAIR, EMEP/EEA and AMESim.

4.1. Speed and Emissions

The first analysis regarded the comparison between the average speed performed by the drivers along the stretch and the emission levels calculated by the models. For example, as can be seen in Figure 2, the operating speed profile could be very different compared with the average speed value recorded in the scenarios.

![Operating speed profile vs average speed value](image)

Fig 2. Operating speed profile vs average speed value

Starting from this, the four different models have been applied to calculate emissions rate in order to verify the different results obtained. The different models have provided different results when the operating speed profile changed. Figure 3 shows an example of different emission levels produced by the operating speed profile showed in Figure 2.
The difference between emission rate values obtained using static models and dynamic models are evident. In particular, it is important to highlight that while in the static models there is a direct correlation between emission rate and average speed, the correlation is not clearly defined within the dynamic model. In Figure 4 the correlation between average speeds and their emission rates defined by the two models’ categories have been shown.

According to [8], the dynamic model for similar speed values (differences of 2-3 km/h) provides emission rates that are very different from each other, within a factor between 5 and 10. This happens because emission rate also depends on the operating speed profile along the route and not only on the average speed value.

A comparative analysis of the results in terms of emission trends and the operating speed has shown the average speed is not representative of the emissive phenomenon. As stated in the introduction, the dynamic model showed a strong dependence on speed change.

In order to identify a synthetic indicator able to make a comparison between speed variation and its average value, the standard deviation has been studied. The standard deviation (SD) of the operating speed profile of each driver can give an indicative and synthetic measure of how the sample is scattered from an average value. Figure 5 shows the relationship between SD and the emission factor calculated by dynamic model.
As shown in Figure 5, the higher standard deviation increases the value of emission rate. Despite this, there isn’t a high degree of correlation between the two variables (the value of R² is about 0.6) as the trend clearly identifies above. This correlation can be explained as small fluctuations of speed around its average values, which lead to low standard deviation values but high emission rate values. In accordance, it is necessary to refer to other synthetic indicators that take into account how speed changes over time.

4.2 Drivers Behavior and Emissions

According to the aim expressed in the introduction, the instantaneous speed values have been investigated as representative of drivers’ behavior. This second analysis attempts to correlate drivers’ behavior to vehicular emissions. In particular, the common behavior kept by the sample of drivers, according to different scenarios performed during the simulations, have been analyzed.

Fig 5. Emission Factor – Standard Deviation

Fig 6. Scenario Analysis
As shown in Figure 6 - for non-binding geometry - a swing of 10% has been registered in the average emission factors, calculated by dynamic models with a minimum value in the medium flow. A reduction of the emission factor has been calculated applying static models, similarly as in previous paragraph, with an increase of interference. This reduction is due to the decrease of average speed with the increase of interference flow.

Moreover, in Scenario (B) - which represents a complex geometry - a significant increase of emission rates has been recorded with an increase of interfering flow, using the dynamic model. In particular an increase of 40% and 30% respectively between Low Flow - High Flow and Medium Flow – High Flow, has been recorded. On the contrary, in the static model, the same trend analyzed in the A Scenario, has been recorded.

Through Graphical analysis, shown in the previous section, it was possible to analyze the behavior of each user in the different scenarios. This part of analysis has been focused in studying the speed variations with time, for each user. In Table 1, the average values of: emission rate, speed and standard deviation for each scenario are summarized. For scenario (A), an almost constant value of standard deviation has been registered, despite a decrease of speed. On the contrary, Scenario(B) shows an increase of standard deviation, in spite of a decrease of speed.

| Tab 1. Average Emission Factor – Different Scenario Conditions |
|---------------------------------------------------------------|
| Scenario A | Scenario B |
| Low Interfering Flow | Medium Interfering Flow | High Interfering Flow | Low Interfering Flow | Medium Interfering Flow | High Interfering Flow |
| Speed [km/h] | 127 | 89 | 68 | 96 | 78 | 71 |
| Dev. St. | 4.5 | 4.1 | 4.4 | 4.8 | 4.9 | 6.8 |
| LMS AMESim | 10.16 | 9.10 | 10.40 | 18.97 | 19.97 | 26.33 |
| EMEP/CORINAIR Emission Inventory Guidebook - Third edition, October 2003 update | 5.16 | 1.00 | 0.32 | 1.57 | 0.53 | 0.41 |
| EMEP/EEA air pollutant emission inventory guidebook — 2009 | 4.57 | 0.92 | 0.68 | 1.09 | 0.77 | 0.71 |
| COPERT 4 version 9.0 | 2.89 | 0.92 | 0.68 | 1.09 | 0.77 | 0.72 |

Consistent with the findings of the previous analysis, independence between average emission factors and average speed, in different conditions scenario has been registered.

5. Conclusive Remarks and Future Research

In conclusion, this study approaches the topic of emission estimation; analyzing emission factors using static and dynamic models, coming from driving simulator outcomes. It aims to understand the influence of driving behavior on emission factors.

Six different scenarios were implemented to better understand the phenomenon. Results showed that there is a significant difference between the two categories of models, showing lower emission rate values of static models compared to dynamic models. From this, different relationships between average speed and emission factors have been investigated. The results highlight that, for dynamic models, drivers’ behavior strongly influences emission parameters and because of this, the average speed value should be considered as a non-representative parameter of emission phenomenon.

The second analysis focused on driving behavior in different scenarios with regard to emission factors. It was discovered that the emission factors were independent from the average speed, while a good correlation between increase of emission factors and increase of speed changes (assessed by standard deviation of speed) was revealed. These speed variations are functions of design parameters, such as geometries and flow conditions. In the dynamic models, the increasing of the complexity of geometry and interfering flow increases the emission rates exponentially.
On the contrary, static models didn't show this phenomenon and confirm a direct correlation with average speeds. Within the considered speed range (70-130 km/h) the static models show that as speed decreases, emission factors decrease as well.

This study also shows the limits that the standard deviation of speed analysis has, as an emissive phenomenon synthetic indicator. In fact, some cases even presented a significant statistical dependence but were not sufficient enough to provide a correlation; this phenomenon is also due to the limited number of analyzed scenarios.

According to [8] - who showed that the simulated values for CO are 5 times lower than detected values on field - it is necessary to analyze the differences between the two groups of models. In particular, under certain conditions, it is necessary to define a synthetic parameter able to define the right statistical correlation between driving behavior - especially speed variations over time - and emissions.

With this in mind, acceleration analysis is currently underway and several different scenarios, in terms of different flow conditions and geometrical design, will be further implemented. With the aim of assessing the reliability of the models used, real measurements of vehicle emissions will be performed.

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