Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 37 (2019) 385–392

Transportation Research Procedia

www.elsevier.com/locate/procedia

21st EURO Working Group on Transportation Meeting, EWGT 2018, 17th – 19th September 2018, Braunschweig, Germany

Environmental effects of road geometric and operational features

Federica Nobili[a]*, Francesco Bella[a], David Llopis-Castelló[b], Francisco Javier Camacho-Torregrosa[b], Alfredo García[b]

[a]Roma TRE University, Via Vito Volterra 62, Rome 00146, Italy
[b]Highway Engineering Research Group (HERG), Universitat Politècnica de València, Camino de Vera S/N, Valencia 46022, Spain

---

Abstract

The aim of this study is to analyze the influence of horizontal geometric design and vehicle operation on fuel consumption and gas emissions produced by passenger cars. Continuous speed data were collected along 15 two-lane rural road sections. Different horizontal alignment indexes and operational variables were obtained. Fuel consumption and gas emissions were estimated by applying the VT-Micro model. The results showed that Curvature Change Rate and average speed have a significant impact on average fuel consumption and gas emissions. Finally, different regression models were calibrated based on these variables to estimate fuel consumption [l/100 km] and emissions [gr/km]. These results could be the basis to incorporate environmental sustainability principles into road design guidelines, since currently they do not take into account the environmental impact related to highway geometric design.

Selection and peer-review under responsibility of the scientific committee of the 21st EURO Working Group on Transportation Meeting, EWGT 2018, 17th – 19th September 2018, Braunschweig, Germany.

Keywords: highway geometric design; environmental impact; sustainable transport; traffic operation; naturalistic data

---

1. Introduction

In 2016, Greenhouse Gases (GHG) emissions from transport accounted for 25% of total emissions in Europe (European Environment Agency, 2016). Furthermore, highway vehicles represented more than 70% of all GHG transportation emissions (European Commission, 2016). Over the years, many changes have been made to vehicle components to reduce fuel consumption and emissions. However, no policies include emission reduction strategies through road geometric design.

With the aim of analyzing fuel consumption and GHG emissions, machine learning techniques have been used

---

* Corresponding author. Tel.: (+39) 0657333633.
E-mail address: federica.nobili@uniroma3.it

Selection and peer-review under responsibility of the scientific committee of the 21st EURO Working Group on Transportation Meeting, EWGT 2018, 17th – 19th September 2018, Braunschweig, Germany.
10.1016/j.trpro.2018.12.207

(Wu and Liu, 2012; Li et al., 2017) and several emission models have been developed, based on operational variables. One of these instantaneous emission models is VT-Micro model developed by Ahn et al. (2002). This is based on a non-linear regression model that uses a multi-dimensional polynomial model structure to predict vehicle fuel consumption and emissions, using the operational variables instantaneous speed (km/h) and acceleration (km/h/s) as explanatory variables for different types of vehicle. El-Shawarby et al. (2005) validated this model from real-world conditions. The analysis showed that vehicle fuel consumption and emission rates per unit distance were optimum in the range between 60 and 90 km/h.

While most studies only investigate the impact of operational variables on fuel consumption and emission rates, few studies have also analyzed the influence of design geometric features.

The most studied geometric feature is the longitudinal grade; less often the horizontal alignment is investigated. Boriboonsomsin and Barth (2009) estimated fuel consumption and emission attributes based on the measured average speed. They observed that the relationship between fuel consumption and longitudinal grade is parabolic ($R^2 = 0.93$), meaning that the longitudinal grade has a significant effect on the fuel economy of light-duty vehicles.

Park and Rakha (2006) used the INTEGRATION traffic simulation software to estimate speeds and accelerations and concluded that vehicle fuel consumption and emission rates increase more than 9% for a 1% increase in longitudinal grade.

Ko et al. (2013) estimated fuel consumption and emissions by using Motor Vehicle Emission Simulator (MOVES) model considering a truck dynamic model and non-uniform acceleration/deceleration models. They found out that fuel consumption produced by a speed reduction, due to longitudinal grade, greater than 20 km/h was five times larger than fuel consumption produced by a speed reduction lower than 10 km/h.

The same research group analyzed the design of vertical crest curves (Ko et al., 2012). The results showed that the fuel consumption decreased along the vertical curves as the rate of vertical curvature (*K)* increased. The design vehicle—a passenger car in the simulation—consumed about 10% less fuel (and thus produced 10% less CO_2) on a curve designed with a 50% higher *K* than the minimum standard according to the Green Book (AASTHO, 2011). In addition, 10% more fuel was consumed (CO_2 was produced) for a 50% smaller *K*. For other emissions—CO, NO_x, and HC—there were also reductions by up to 31% on the curve.

Ko (2015) also explored the impact of horizontal geometric design on fuel consumption and GHG emissions through the simulation. In the case of 70 km/h tangent speed, the passenger car consumed 34% more fuel for horizontal curves with a 50% lower radius than the minimum standard according to the Green Book (AASTHO, 2011). When the horizontal curves were designed with radii greater than minimum standards, there was no change in fuel consumption and emissions. On the other hand, horizontal curves with speeds between 90 and 110 km/h and radii greater than or equal to minimum standards showed larger fuel consumption and emissions. Likewise, high tangent speeds, such as 90 or 110 km/h, produced greater CO and HC emissions as the radius of the horizontal curve was lower. Related to this, maximum values of CO emission rate are produced while drivers accelerate, or the engine is idling (Christopher Frey et al., 2001).

It is important to highlight that in some studies (Ko et al., 2012, 2013; Ko, 2015), authors assessed fuel consumption and emission rates per trip instead of per unit distance. The advantage of estimating emissions per unit of length is to be able to compare emissions between different homogeneous road segments (portion of a road with uniform horizontal alignment).

To increase the knowledge about the impact of the horizontal geometric design on fuel consumption and emission rates, this research analyzes the relationship between horizontal alignment indexes and operational variables on fuel consumption and GHG emissions produced in several sections of two-lane rural roads by applying the VT-Micro model to naturalistic data.

2. Objectives and Hypotheses

The main objective of this study is to analyze how highway geometric design influence fuel consumption and CO_2, NO_x, HC, and CO emissions. As a result, several regression models will be calibrated to estimate fuel consumption and emissions on an entire homogeneous road segment. Additionally, different speed percentiles will be studied to identify which of them is able to better estimate fuel consumption and emissions.

The underlying hypotheses of this research are:

- Road design influences fuel consumption and emissions, since this strongly influences drivers' operation
- Fuel consumption and emissions increase as the homogeneous road segment is more winding
- Fuel consumption and emissions increase as drivers' speed variations are higher.

3. Methodology

Fig. 1 shows the methodology of this research. First, road geometry was recreated following the procedure proposed by Camacho-Torregrosa et al. (2015). Then, each road section was divided into homogeneous road segments. A naturalistic data collection was performed to obtain the speed profile of each homogeneous road segment using GPS devices. Fuel consumption and GHG emissions were estimated by applying the VT-Micro model considering the actual individual second-by-second speed profiles gathered during the field study. Finally, the relationship between geometric and operational variables and fuel consumption and GHG emissions was analyzed and several prediction models were proposed.

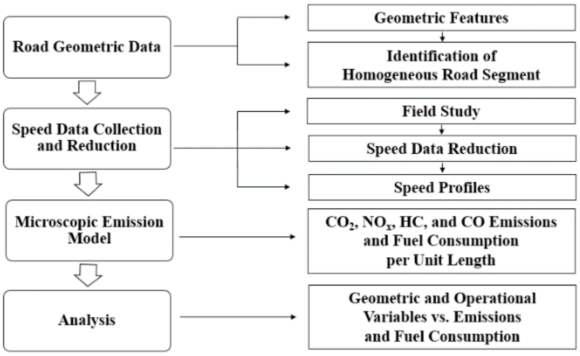

Fig. 1. Methodology

3.1. Road Geometric Data

A total of 15 two-lane rural road sections located in the Valencian Region (Spain) were selected for the study. The length of these road sections ranged from 5 to 20 km, with an estimated Annual Average Daily Traffic volume between 850 and 7,000 vehicles per day. The geometry of each road section was recreated by means of the methodology proposed by Camacho-Torregrosa et al. (2015), which uses an algorithm based on the heading direction. As a result, 48 homogeneous road segments were identified according to their traffic volume, cross-section, and geometric behavior through the German methodology (Richtlinien für die Anlage von Strassen: Linienführung RAS-L, 1995), which is based on the analysis of the Curvature Change Rate (CCR). This parameter is defined as the rate between the sum of the absolute deflection angles per unit length. Diagrams constructed with cumulative sum of the absolute deflection angles on x-axis and progressive length on y-axis for each of the rural road sections were analyzed; same gradients in the graph identify road segments characterized by the same CCR, i.e. homogeneous road segments.

Every homogeneous road segment was then characterized by the following geometric features: L – Length of the homogeneous road segment (m), AR – Average radius (m), R_{max} – Maximum radius (m), R_{min} – Minimum radius (m), CCR_{HRS} – Sum of absolute deflection angle divided by the length of the homogeneous road segment (gon/km), CCR_C – Sum of absolute deflection angle divided by the sum of the length of the horizontal curves (gon/km), RR – R_{max}/R_{min}, $\overline{\gamma}$ – Average of deflection angles (gon), $\overline{L_t}$ – Average of tangent length (m), L_c/L_t – Ratio between horizontal curve length and total length.

3.2. Speed Data Collection and Reduction

A naturalistic data collection was carried out. Individual speed profiles were obtained through 1Hz GPS devices on work days between 8:30 a.m. and 2:00 p.m. and under dry weather conditions (Pérez-Zuriaga et al., 2010). Drivers' speeds under non-free-flow condition were removed based on the procedure proposed by Pérez-Zuriaga et al. (2013). For each homogeneous road segment, the following operational variables were obtained: $\overline{V_{ms}}$ - mean value of the average speeds profile (average speed versus distance), obtained from the average speed of all drivers at each meter of the homogeneous road segment (km/h), $\overline{V_{mt}}$ - mean value of the average speeds profile (average speed versus time), obtained from the average speed of all drivers at each second of travel on the homogeneous road segment (km/h), $\overline{V_{min}}$ - mean value of the minimum speeds profile (minimum speed versus distance) (km/h), $\overline{V_{85}}$ - mean value of the 85th percentile speeds profile (85th percentile speed versus distance) (km/h), $\overline{V_{max}}$ - mean value of the maximum speeds profile (maximum speed versus distance) (km/h).

3.3. Microscopic Emission Model

Fuel consumption and CO_2, NO_x, HC, and CO emissions was obtained by using VT-Micro model. The inputs for the calculation of these emissions and consumption are second-by-second individual vehicle speed (km/h) and acceleration (km/h/s) and vehicle characteristics. The observed vehicles during the field data collection were classified in the following classes provided by VT-Micro model:

- LDV3: year model ≥ 1995, engine size < 3.2 L, mileage < 83653
- LDV4: year model ≥ 1990, engine size < 3.2 L, mileage ≥ 83653
- LDV5: year model ≥ 1990, engine size ≥ 3.2 L.

Therefore, the simulation was only implemented for these three categories of vehicles, considering a number of 140 vehicles per class. As a result of the microsimulation, fuel consumption (l) and total emissions (g) were obtained for every vehicle of each homogeneous road segment. Fuel consumption and emissions on each homogeneous road segment were estimated as the average of all drivers' fuel consumption and emissions divided by the length of the homogeneous road segment, considering both forward and backward direction (l/100 km for fuel consumption and g/km for emissions). The results for LDV3 category are shown in Tab. 1.

Table 1. Average of all driver's consumption and emissions at each homogeneous road segment for unit length for LDV3 category.

Hom. Seg.	Fuel	CO_2	HC	CO	NO_X	Hom. Seg.	Fuel	CO_2	HC	CO	NO_X
1.1	7,13	165,40	0,02	0,46	0,08	6.3	6,59	153,30	0,02	0,46	0,09
1.2	8,08	187,96	0,02	0,45	0,06	7.1	5,99	139,64	0,02	0,89	0,08
1.3	7,21	167,65	0,02	0,40	0,07	7.2	6,17	143,83	0,02	0,58	0,08
1.4	7,43	172,83	0,02	0,42	0,06	8.1	6,05	141,07	0,02	0,42	0,08
1.5	7,32	170,07	0,02	0,44	0,07	8.2	5,96	138,70	0,02	0,60	0,07
1.6	6,33	147,50	0,02	0,52	0,08	8.3	6,11	142,35	0,02	0,56	0,08
2.1	7,22	167,68	0,03	0,88	0,10	9.1	7,06	164,34	0,02	0,39	0,07
2.2	7,72	179,36	0,02	0,47	0,07	9.2	7,79	181,41	0,02	0,41	0,06
2.3	8,29	188,16	0,02	0,53	0,08	9.3	7,87	183,08	0,02	0,44	0,07
2.4	9,21	214,29	0,02	0,50	0,06	9.4	7,80	180,82	0,02	0,49	0,08
2.5	7,79	180,80	0,02	0,50	0,08	10.1	6,70	155,87	0,02	0,94	0,08
2.6	7,31	169,82	0,02	0,50	0,09	10.2	6,28	146,27	0,02	0,67	0,08
3.1	5,93	137,99	0,02	0,92	0,07	11.1	6,20	144,49	0,02	0,38	0,07
3.2	6,35	147,85	0,02	0,52	0,08	11.2	6,21	144,79	0,02	0,34	0,08
3.3	7,52	174,33	0,02	0,49	0,07	12.1	5,96	138,77	0,02	0,64	0,07
3.4	6,62	153,90	0,02	0,46	0,08	12.2	6,07	141,58	0,02	0,34	0,07
3.5	5,91	137,55	0,02	0,61	0,07	13.1	6,54	152,34	0,02	0,40	0,08
4.1	6,45	150,16	0,02	0,35	0,07	13.2	6,37	148,32	0,02	0,40	0,07
4.2	6,37	148,42	0,02	0,35	0,08	13.3	6,18	144,15	0,02	0,39	0,07
5.1	5,91	137,75	0,02	0,74	0,08	13.4	6,33	147,53	0,02	0,34	0,07
5.2	5,49	127,84	0,02	0,81	0,05	14.1	6,20	144,38	0,02	0,61	0,08
5.3	5,73	133,48	0,02	0,51	0,06	14.2	6,69	155,70	0,02	0,40	0,08
6.1	6,63	154,14	0,02	0,43	0,08	14.3	6,34	147,73	0,02	0,35	0,08
6.2	6,16	143,15	0,02	0,48	0,08	15.1	6,04	140,76	0,02	0,33	0,07

4. Analysis

This section shows the effects of geometric and operational variables on fuel consumption and GHG emissions.

4.1. Analysis of Geometric Variables

The relationship between each horizontal geometric feature with fuel consumption and CO_2, NO_x, HC, and CO emissions was analyzed for all vehicle types (LDV3, LDV4, and LDV5). The geometric variables that showed a better correlation with GHG emissions were CCR_C and AR. Fig. 2 shows how CO_2, NO_x, HC, and CO emissions increase as CCR_C increases.

Road designs with high CCR_C produce a geometric control over drivers and, consequently, lower speeds but greater accelerations, increasing CO_2, NO_x, and HC emissions. In addition, these conditions lead to increase driving times and, consequently, CO_2, NO_x, and HC emissions. These conclusions can also be applied to fuel consumption. With reference to AR, these pollutants decrease with increasing AR, when the road becomes less sinuous.

On the other hand, CO emissions depend on the number of revolutions per minute of the engine (RPM). When CCR_C is low the engine operates at a low number of revolutions and CO emissions are high. On the contrary, drivers tend to achieve greater engine RPM as CCR_C increases, which results in lower CO emissions. Likewise, accelerations and decelerations increase for high CCR_C. This explains the initial decreasing trend, the steady and then lightly rising trend in CO emissions as CCR_C increases. Referring to the AR for CO emissions, the trend is exactly mirrored to that for the CCR_C.

Non-significant results for the LDV3 vehicle type regarding NO_x, HC, and CO emissions and for LDV4 regarding CO emissions were identified. For this reason, these relationships are not shown in Fig. 2.

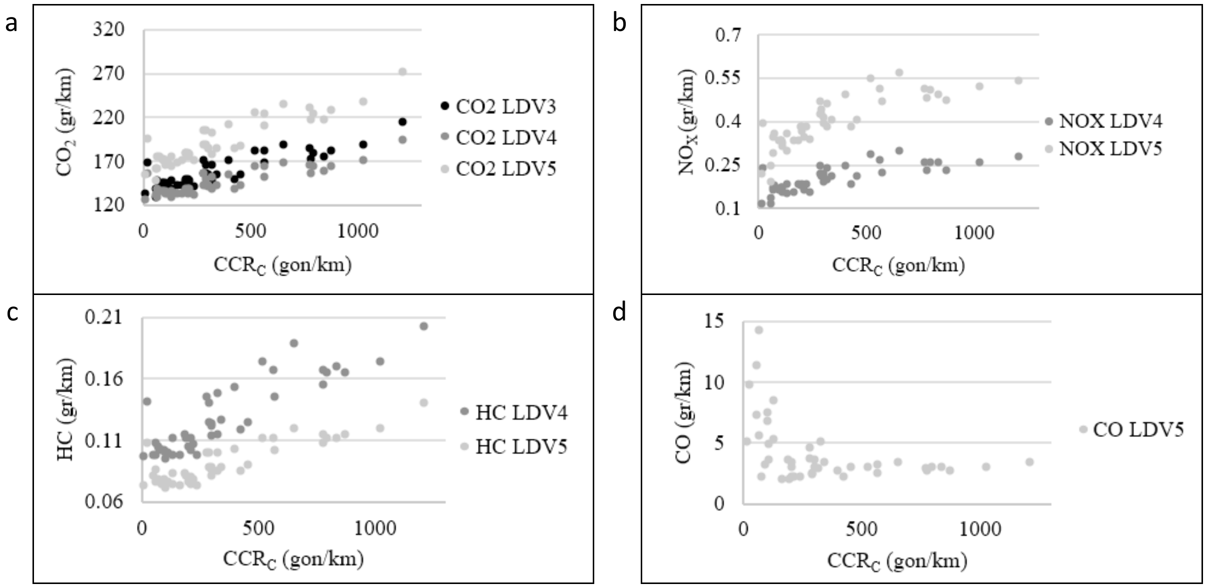

Fig. 2. (a) CO_2, (b) NO_x, (c) HC and (d) CO emissions rate vs. CCR_C

4.2. Analysis of Operational Variables

Regarding the influence of the operational variables, the mean value of the average speeds profile, built from the speed of each individual user at each second of travel ($\overline{V_{mt}}$) showed the closest relationship to fuel consumption and CO_2, NO_x, HC, and CO emissions. Fig. 3 shows how CO_2, NO_x, HC, and CO emissions increase as $\overline{V_{mt}}$ increases.

Specifically, fuel consumption and CO_2, NO_x, and HC emissions decrease as $\overline{V_{mt}}$ increases. CO_2 and HC show a strongly decreasing trend up to 70 km/h, and then slightly decreasing; for HC there is even a sign of an increase in emissions exceeded 100 km/h. On the contrary, for NO_x the trend is always decreasing.

CO emissions remained constant up to 70 km/h average speed, then these emissions increased as the $\overline{V_{mt}}$ increased, when the engine speed is kept low.

Additionally, CO_2, NO_x, and HC emissions decreases as the average acceleration and deceleration decreases. Related to this, the higher the average speed, the lower the average acceleration and deceleration.

Non-significant results for the LDV3 vehicle type regarding NO_x, HC, and CO and for LDV4 regarding CO were identified. For this reason, these relationships are not shown in Fig. 3.

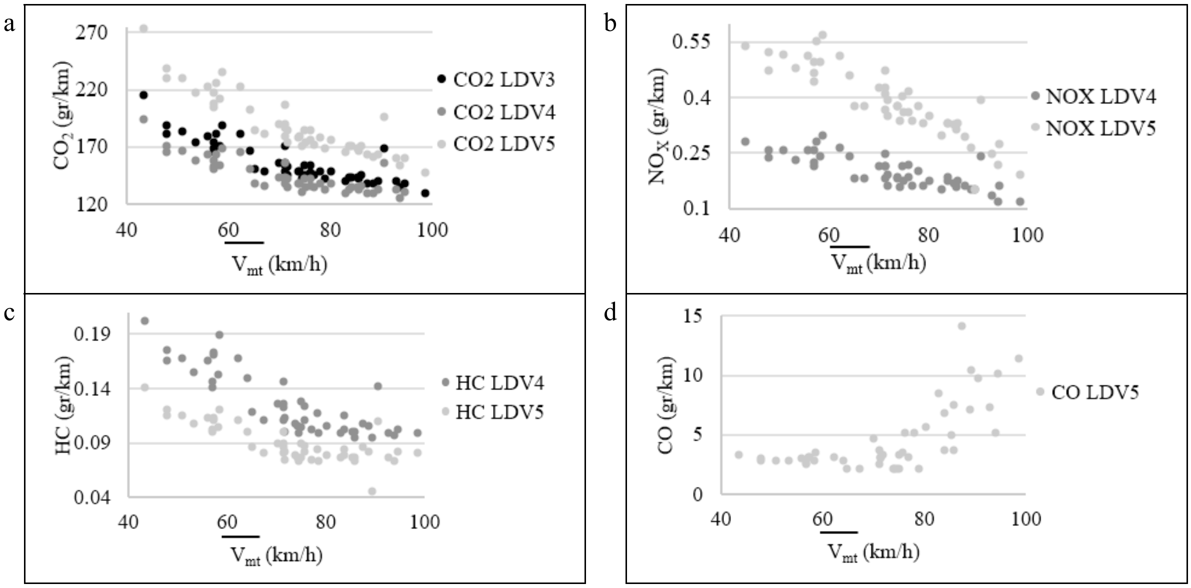

Fig. 3. (a) CO_2, (b) NO_x, (c) HC and (d) CO emissions rate vs. $\overline{V_{mt}}$

5. Proposal of Emission Models

The main objective of the study was to propose different regression models based on geometric and operational variables to predict average fuel consumption and average GHG emissions. Tab. 2 shows the most accurate prediction models for each vehicle category.

Table 2. Average emissions and consumption models based on geometric and operational features.

LDV	Geometric models	R^2	Operational models	R^2
3	$E_{CO_2} = 0.0553 \cdot CCR_C + 137.93$	0.79	$E_{CO_2} = 0.0214 \cdot \overline{V_{mt}}^2 - 4.1979 \cdot \overline{V_{mt}} + 343.7544$	0.81
	$FUEL = 0.0024 \cdot CCR_C + 5.92$	0.78	$FUEL = 0.0009 \cdot \overline{V_{mt}}^2 - 0.1925 \cdot \overline{V_{mt}} + 15.2283$	0.80
4	$E_{CO_2} = 0.0444 \cdot CCR_C + 129.19$	0.77	$E_{CO_2} = 0.0189 \cdot \overline{V_{mt}}^2 - 3.6004 \cdot \overline{V_{mt}} + 301.9004$	0.78
	$FUEL = 0.0021 \cdot CCR_C + 5.64$	0.75	$FUEL = 0.0009 \cdot \overline{V_{mt}}^2 - 0.1778 \cdot \overline{V_{mt}} + 14.0118$	0.75
	$E_{HC} = 8.87E-05 \cdot CCR_C + 0.096$	0.76	$E_{HC} = 3.63\,E-05 \cdot \overline{V_{mt}}^2 - 0.0069 \cdot \overline{V_{mt}} + 0.4317$	0.78
	$E_{NO_x} = 2.99E-07 \cdot AR^2 - 4.06E-04 \cdot AR + 0.2871$	0.71	$E_{NO_x} = 1.93E-06 \cdot \overline{V_{mt}}^2 - 0.0028 \cdot \overline{V_{mt}} + 0.3972$	0.66
5	$E_{CO_2} = 0.0828 \cdot CCR_C + 161.72$	0.83	$E_{CO_2} = 0.0283 \cdot \overline{V_{mt}}^2 - 5.7862 \cdot \overline{V_{mt}} + 454.2076$	0.87
	$FUEL = 0.0036 \cdot CCR_C + 7.06$	0.82	$FUEL = 0.0013 \cdot \overline{V_{mt}}^2 - 0.2663 \cdot \overline{V_{mt}} + 20.3594$	0.85
	$E_{HC} = 2.42E-07 \cdot AR^2 - 2.42E-04 \cdot AR + 0.1333$	0.76	$E_{HC} = 3.04\,E-05 \cdot \overline{V_{mt}}^2 - 0.0053 \cdot \overline{V_{mt}} + 0.3108$	0.73
	$E_{NO_x} = -2.95E-07 \cdot {CCR_C}^2 + 5.52E-04 \cdot CCR_C + 0.2657$	0.77	$E_{NO_x} = -4.47E-05 \cdot \overline{V_{mt}}^2 + 2.05E-04 \cdot \overline{V_{mt}} + 0.6161$	0.81
	$E_{CO} = 1.5825 + 721.9506/(CCR_C + 82.3038)$	0.41	$E_{CO} = 0.0058 \cdot \overline{V_{mt}}^2 - 0.7044 \cdot \overline{V_{mt}} + 23.4548$	0.64

6. Discussion

In recent years, many authors have analyzed the problem of air pollution from road transport. However, no tools have still been developed to be included in road geometric design guidelines and get environmentally-friendly road designs. Several studies have been focused on it, even microsimulation models have been calibrated to estimate vehicle fuel consumption and emission rates during planning, design, and operation road stage (Rakha et al., 2004).

The strength of this study is the use of naturalistic speed data for the calculation of fuel consumption and GHG emissions. Regarding this, continuous speed profiles were gathered from a field data collection. However, most previous studies got these data from a microsimulation model with different scenarios or from models to estimate operating speed and vehicle dynamic (Ko et al., 2012 and 2013; Ko, 2015). In addition, these studies refer to fuel consumption and GHG emissions per trip instead of per unit length, like the current study. Even though, their results showed the same trend of this research, i.e., a sharper horizontal alignment produces larger levels of fuel consumption and GHG emissions. On the contrary, smoother road designs allow drivers to reach higher speeds and reduce accelerations and decelerations and, consequently, reduce fuel consumption and CO_2, NO_x, and HC emissions. Only CO emissions were greater as the average speed or/and accelerations and decelerations increase, which was produced for road designs with high CCR_C.

The analysis performed by El-Shawarby et al. (2005) showed that vehicle fuel-consumption and emission rates per-unit distance are optimum in the range of 60 to 90 km/h, with considerable increases outside this optimum range. Speeds exceeding 90 km/h, or speeds below 60 km/h due to severe congestion, can cause an adverse effect on fuel consumption and emissions. In this case of study, in a range from 70 to 100 km/h, fuel consumption and CO_2, NO_x, and HC emissions are lower (except for CO emissions).

The proposed prediction models might be incorporated into road design guidelines to get environmentally-friendly highway designs. Additionally, in the preliminary design stage, the quantitative assessment of fuel consumption and GHG emissions among several design alternatives might become very useful for the determination of environmental impacts.

7. Conclusion

Pollutant emissions are one of the main negative externalities caused by road transport. In order to calibrate several prediction models to estimate fuel consumption and CO_2, NO_x, HC, and CO emissions, actual individual second-by-second speed and acceleration profiles were collected from a naturalistic field study on 48 homogeneous two-lane rural road segments. These data were the input for the VT-Micro model, which was used for estimating fuel consumption and GHG emissions. After that, the influence of the road geometric design on fuel consumption and emission rates was analyzed considering some alignment indexes and operational variables.

The results showed that fuel consumption and CO_2, NO_x, HC, and CO emission rates are strongly influenced by CCR_C and AR. In particular, fuel consumption and CO_2, NO_x, and HC emission rates increase as CCR_C increases and AR decreases.

A road design with high CCR_C produces a geometric control over road users and, consequently, lower speeds but greater accelerations are expected. This results in an increase of fuel consumption and CO_2, NO_x, and HC emissions. At the same way, a decrease of AR leads to an increase of CO_2, NO_x, and HC emissions.

On the contrary, CO emission rate decreases as CCR_C increases and AR decreases. This phenomenon is closely related to the number of revolutions per minute (*RPM*) of the engine. When CCR_C is low, the engine works at a low *RPM* (< 1900) – for speed below 100 km/h, like the current study – and CO emissions are high. As the CCR_C increases, drivers travel at greater speeds with lower gears, which results in an increase of *RPM*. In addition, accelerations and decelerations increase. This explains, as the CCR_C increases, the steady ($500 < CCR_C < 1000$) and then lightly rising trend ($CCR_C > 1000$) in CO emissions.

A relationship between mean value of the average speeds profile on the time with CO_2, NO_x, HC, and CO emissions was also found. Fuel consumption and CO_2, NO_x, and HC emission rates are larger for lower average speeds, which is also related to greater average accelerations and decelerations. However, CO emission rate increases as average speed increases, i.e., when accelerations and decelerations are lower and the engine is idling.

These conclusions may be the first step on the way to develop some guidelines that facilitate engineers to develop environmentally sustainable highways, reducing fuel consumption and emissions production. Furthermore, those conclusions might be implemented on new advanced navigation systems in order to provide road users the ability to select routes that minimize fuel consumption and pollutant emissions. They could estimate them as a function of road geometric design instead of or complementing other variables, such as traffic volume, density and average speed.

References

A Policy on Geometric Design of Highways and Streets, 6th ed. AASHTO. Washington D.C., 2011.

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating Vehicle Fuel Consumption and Emissions based on Instantaneous Speed and Acceleration Levels. Journal of Transportation Engineering 128(2), 182-190.

Boriboonsomsin, K., Barth, M., 2009. Impacts of Road Grade on Fuel Consumption and Carbon Dioxide Emissions Evidenced by Use of Advanced Navigation Systems. Transportation Research Record: Journal of the Transportation Research Board 2139, 21-30.

Camacho-Torregrosa, F.J., Pérez-Zuriaga, A.M., Campoy-Ungría, J.M., García, A., Tarko, A.P., 2015. Use of Heading Direction for Recreating the Horizontal Alignment of an Existing Road. Computer-Aided Civil and Infrastructure Engineering 19 30(4), 282-299.

El-Shawarby, I., Ahn, K., Rakha, H., 2005. Comparative field evaluation of vehicle cruise speed and acceleration level impacts on hot stabilized emissions. Transportation Research Part D: Transport and Environment 10, 13-30.

European Commission, 2016. A European strategy for low-emission mobility.

European Environment Agency, 2016. Annual European Union greenhouse gas inventory 1990-2015.

Forschungsgesellschaft für Strassen-und Verkehrswesen, 1995. Richtlinien für die Anlage von Strassen: Linienführung RAS-L.

Frey, C., Rouphail, N.M., Unal, A., Colyar, J.D. Annual Meeting of the Air & Waste Management Association, 2001. Measurement of On-Road Tailpipe CO, NO, and Hydrocarbon Emissions Using a Portable Instrument.

Ko, M., 2015. Incorporating Vehicle Emissions Models into the Geometric Highway Design Process. Application on Horizontal Curves. Transportation Research Record: Journal of the Transportation Research Board 2503.

Ko, M., Lord, D., Zietsman, J., 2012. Environmentally Conscious Highway Design for Crest Vertical Curves. Transportation Research Record: Journal of the Transportation Research Board 2270, 96-106.

Ko, M., Lord, D., Zietsman, J., 2013. Environmentally Conscious Highway Design for Vertical Grades. Transportation Research Record: Journal of the Transportation Research Board 2341, 53-65.

Li, Q., Qiao, F., Yu, L., 2017. A Machine Learning Approach for Light-Duty Vehicle Idling Emission Estimation Based on Real Driving and Environmental Information. Journal of Environmental Pollution and Climate Change, vol. 1.

Park, S., Rakha, H., 2006. Energy and Environmental Impacts of Roadway Grades. Transportation Research Record: Journal of the Transportation Research Board 1987, 148-160.

Pérez-Zuriaga, A. M., Camacho-Torregrosa, F. J., García, A., Campoy-Ungría, J. M., 2013. Application of global positioning system and questionnaires data for the study of driver behaviour on two-lane rural roads. IET Intelligent Transport Systems 7, 182-189.

Pérez-Zuriaga, A.M., García, A., Camacho-Torregrosa, F.J., D'Attoma, P., 2010. Modeling Operating Speed and Deceleration on Two-Lane Rural Roads with Global Positioning System Data. Transportation Research Record: Journal of the Transportation Research Board 2171, 11-20.

Rakha, H., Ahn, K., Trani, A., 2004. Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. Transportation Research Part D: Transport and Environment 9, 49-74.

Wu, J.D., Liu, J.C., 2012. A forecasting system for car fuel consumption using a radial basis function neural network. Expert Systems with Applications 39, 1883-1888.