Llopis-Castelló, D.; Camacho-Torregrosa, FJ.; García García, A. (2019). Analysis of the Influence of Geometric Design Consistency on Vehicle CO2 Emissions. Transportation Research Part D Transport and Environment. 69:40-50. https://doi.org/10.1016/j.trd.2019.01.029

ANALYSIS OF THE INFLUENCE OF GEOMETRIC DESIGN CONSISTENCY ON VEHICLE CO_2 EMISSIONS

Corresponding Author:
David Llopis-Castelló
Postdoctoral Research Assistant
Highway Engineering Research Group (HERG), Universitat Politècnica de València
Camino de Vera, s/n. 46022 – Valencia. Spain
Tel: (34) 96 3877374
Fax: (34) 96 3877379
E-mail: dallocas@doctor.upv.es

Other Authors:
Francisco Javier Camacho-Torregrosa
Assistant Professor
HERG, Universitat Politècnica de València
E-mail: fracator@tra.upv.es

Alfredo García
Professor
HERG, Universitat Politècnica de València
E-mail: agarciag@tra.upv.es

Submission Date: September 3, 2018
Revision Date: December 20, 2018
Revision Date: January 28, 2019

ABSTRACT

Highway vehicles driving on rural roads account for more than 50% of all CO_2 emissions produced by the transportation sector in Europe. Although the policy measures to mitigate Greenhouse Gas emissions are increasing, these do not include policies aimed at reducing emissions by means of highway geometric design, which significantly influences drivers' speeds and accelerations and, consequently, plays a major role on fuel consumption and emissions.

Therefore, the main objective of this research is to study the influence of the geometric design consistency on vehicle CO_2 emissions. To do this, continuous speed data were collected on 47 homogeneous road segments by means of Global Positioning System devices. Vehicle CO_2 emissions were estimated by applying the VT-micro model, whereas geometric design consistency was assessed considering different global consistency models.

As a conclusion, vehicle CO_2 emissions decreases as the consistency level of a homogeneous road segment increases. Specifically, a good consistency road segment has been found to present an emission rate 20-30% lower than a poor-consistent one. Therefore, the design of consistent roads allows, in addition to maximize road safety, to help to achieve more environmentally sustainable highways, reducing CO_2 emission production.

Keywords: geometric design consistency, CO_2 emission, two-lane rural road, traffic operation, environmentally-friendly transport, naturalistic data

1. INTRODUCTION

1.1. Transportation and Greenhouse Gas emissions

In 2015, the transportation sector contributed 25.8% of total EU-28 Greenhouse Gas (GHG) emissions (European Environment Agency, 2017). These emissions were 23% above 1990 levels, presenting a general increasing trend despite a decline between 2008 and 2013. Specifically, highway vehicles driving on rural roads accounted for more than 50% of all CO_2 emissions produced by the transportation sector (European Environment Agency, 2017).

According to the United States Environmental Protection Agency (2016), emissions from transportation also rose significantly (17%) in this country between 1990 and 2014. Additionally, the combustion of fossil fuels associated to transport accounts for about 30% of total US CO_2, being the second largest source of CO_2 emissions in 2014. The largest sources were associated to passenger cars (42.4%), medium- and heavy-duty trucks (23.1%), and light-duty trucks (17.8%) (US EPA, 2016).

Faced with this situation, both the United States and Europe have recently proposed some strategies to deal with issues regarding air pollution from transport. These policies mainly focus on intelligent transport systems, eco-driving courses, urban mobility/smart cities, road pricing and internalization, and fuel switching and efficiency (European Commission, 2016; IPCC, 2015). However, these policies do not include measures related to highway geometric design despite the fact that the geometric alignment can meaningfully influence vehicle fuel consumption and emissions.

Some researchers have studied the influence of geometric design on fuel consumption and emissions, being the longitudinal grade the most examined geometric variable. Boriboonsomsin and Barth (2009) analyzed the fuel consumption from a single vehicle (2007 Nisan Altima) travelling at 90 km/h along three routes: (i) level, (ii) upgrade, and (iii) downgrade. Both upgrade and downgrade routes had an average grade about 4% and each route was covered three times. The findings showed a 2nd-degree relationship between fuel consumption and longitudinal grade ($R^2 = 0.93$). Specifically, a great influence of this geometric variable on fuel economy of light-duty vehicles was identified. In addition, the vehicle fuel economy on level routes was 15-20% larger than for upgrade and downgrade routes.

Other studies have used microscopic and dynamic models to obtain speeds and accelerations, which are easier and less expensive than field data collection (Park and Rakha, 2006; Ko et al., 2012; Ko et al., 2013).

Regarding the influence of horizontal alignment on GHG emissions, Llopis-Castelló et al. (2018a) concluded that CO_2 emission rates on an entire road segment increase with the Curvature Change Rate (*CCR*). Low *CCR* values mean that the homogeneous road segment is mainly composed of flat curves and long tangents, allowing drivers to reach greater speeds without large speed variations. By contrast, homogeneous road segments with high *CCR* values impose important geometric controls on drivers, leading to lower speeds and greater speed variations. In this way, CO_2 emission rate was lower for higher average speeds and lower speed variations. For LDV5 vehicles, up to 13% of emissions can be attributed to the horizontal alignment. This is a congruent conclusion to the findings by Boriboonsomsin and Barth (2009).

This example is only related to operational emissions, i.e. emissions due to road lifecycle and vehicle manufacturing have not been considered. In addition, this does not mean that 13% of the emissions could be reduced by optimizing the horizontal alignment: there are many constraints that prevent designers from creating a minimum-impact horizontal alignment. However, some sort of emission reduction could be addressed having this into account in the alignment optimization process.

1.2. Geometric design consistency

Geometric design consistency is closely related to road safety and can be defined as how drivers' expectations and road behavior relate. Thus, a consistent road aims to provide a harmonious driving experience free of surprises, whereas an inconsistent road segment tends to show up numerous unexpected events to drivers, which usually results in wrong driver decisions increasing the likelihood of crash occurrence.

The most commonly method to assess geometric design consistency relies on the examination of the operating speed profile (Gibreel et al., 1999). Operating speed is usually defined as the 85th percentile of the speed distribution for passenger cars under free-flow conditions and favorable weather conditions (V_{85}).

There are two types of consistency models: local and global. Local models aim at identifying localized issues, such as great differences between design and operating speeds or sudden speed reductions; whereas global models analyze the overall speed variation through an entire homogeneous road segment, allowing the estimation of the number of road crashes by means of Safety Performance Functions.

Polus and Mattar-Habib (2004) proposed the first global consistency model, which was based on the hypothesis that the larger the speed variations along a road segment, the greater the likelihood of crash occurrence. In this regard, the model was defined through the following variables: relative area (R_a) and operating speed deviation (σ).

$$R_a = \frac{\sum_i^n a_i}{L} \ (m/s) \tag{1}$$

$$\sigma = \sqrt{\frac{\sum_i^n (V_{85i} - \overline{V_{85}})^2}{n}}\ (km/h) \tag{2}$$

where a_i is the area bounded by the operating speed profile and the average operating speed (m^2/s); L is the length of the homogeneous road segment (m); $\overline{V_{85}}$ is the average operating speed (km/h); V_{85i} is the operating speed at station i (km/h); and n is the number of distance intervals (n is equal to L when i is considered meter by meter).

In this way, Polus and Mattar-Habib (2004) defined a new consistency parameter (C_P), which qualifies the consistency level of a homogenous road segment as good, fair, or poor (Table 1).

The same variables were also studied by Garach et al. (2014) on Spanish two-lane rural roads. As a conclusion, Garach et al. (2014) found that the consistency parameter proposed by Polus and Mattar-Habib (2004) was too conservative, so a new global consistency model was suggested (C_G) with the same consistency thresholds (Table 1).

Camacho-Torregrosa (2015) also calibrated a global consistency model in Spain relying on two operational parameters: average operating speed ($\overline{V_{85}}$) and average deceleration rate ($\overline{d_{85}}$). According to the proposed consistency parameter (C_C), an increase in consistency level usually leads to a greater $\overline{V_{85}}$ and/or a lower $\overline{d_{85}}$ (Table 1).

Recently, Llopis-Castelló et al. (2018b) proposed a new global consistency model based on the difference between the inertial operating speed profile (V_i) and the operating speed profile (V_{85}). The inertial operating speed represents drivers' expectancies and was defined at every station k of the road segment as the weighted average operating speed of the preceding 15 seconds, considering a linear weighting distribution. This weighting factor (w_j) ranges between 0 and 1, increasing linearly as station j gets closer to the critical section k. This speed calculation is carried out considering intervals of 0.1 seconds through the following equation:

$$V_{i,k} = \frac{\sum w_j \cdot V_{85,j}}{\sum w_j} \tag{3}$$

where $V_{i,k}$ is the inertial operating speed (km/h) at station k; $V_{85,j}$ is the operating speed at station j; and w_j is the weighting factor at point j.

Table 1 shows the consistency parameter defined by Llopis-Castelló et al. (2018b), which is calculated from the positive differences between V_i and V_{85} considering the following variables (Figure 1):

- A_+: Area bounded by the positive differences between V_i and V_{85}.
- L_+: Road segment length where the difference between V_i and V_{85} is positive.
- σ_+: Standard deviation of the positive difference between V_i and V_{85}.

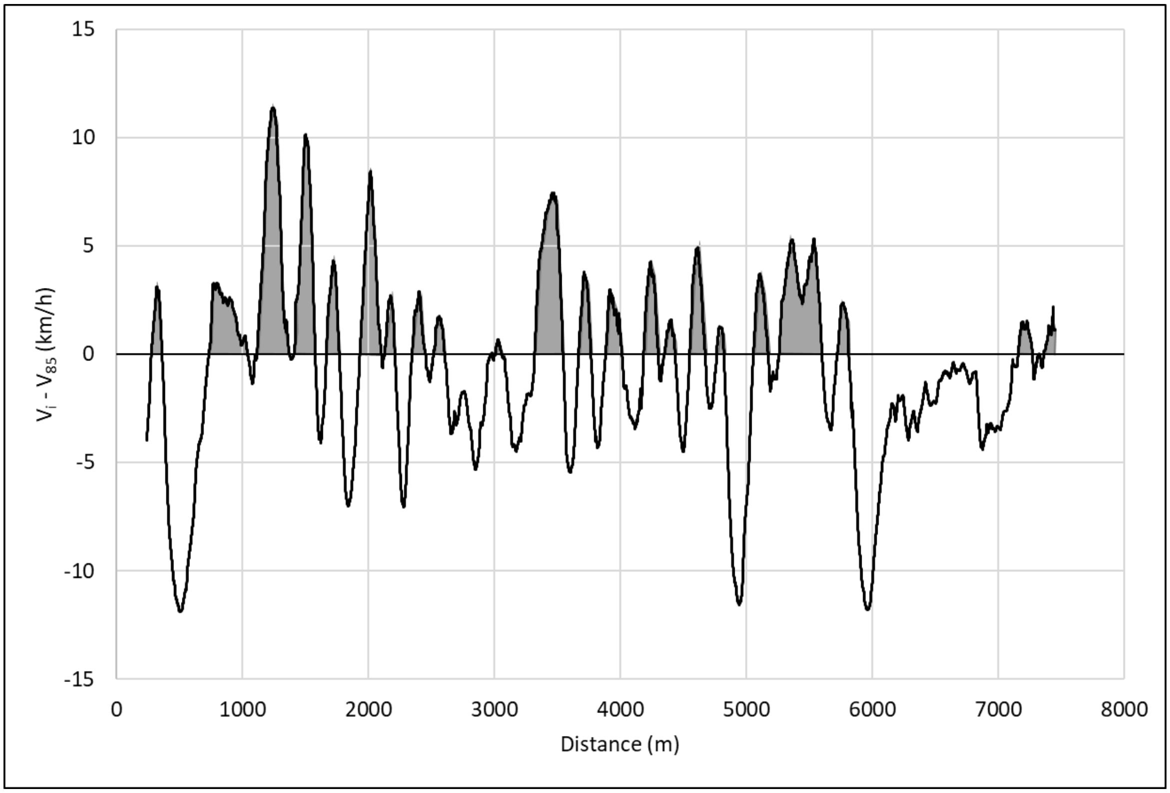

FIGURE 1 Difference between V_i and V_{85}.

A low value of this consistency parameter is associated to lower differences between drivers' expectancies and road behavior, leading to a higher consistency level.

TABLE 1 Global consistency models

Model	Consistency parameter (C)	Consistency level		
		Good	Fair	Poor
Polus and Mattar-Habib (2004)	$C_P = 2.808 \cdot e^{-0.278 \cdot Ra \cdot \frac{\sigma}{3.6}}$	$C_P > 2$	$1 < C_P \leq 2$	$C_P \leq 1$
Garach et al. (2014)	$C_G = \frac{195.073}{\left(\frac{\sigma}{3.6} - 5.7933\right) \cdot (4.1712 - R_a) - 26.6047} + 6.7826$	$C_G > 2$	$1 < C_G \leq 2$	$C_G \leq 1$
Camacho-Torregrosa (2015)	$C_C = \sqrt[3]{\frac{V_{85}}{d_{85}}}$ (s$^{1/3}$)	$C_C \geq 3.25$	$2.55 \leq C_C < 3.25$	$C_C < 2.55$
Llopis-Castelló et al. (2018b)	$C_L = \sqrt{\frac{A(+) \cdot \sigma(+)}{L(+)}}\ (km/h)$	$C_L \leq 2.75$	$2.75 < C_L \leq 4.5$	$C_L > 4.5$

The current way of selecting a road design among a set of alternatives considers several items to maximize, such as cost, environment, road safety, functionality, etc. A concomitant maximization of all criteria is impossible in most occasions, so some techniques to balance between all factors are needed. Maximizing the benefit for one criterion normally impacts negatively in other criteria, so weighting factors have to be considered in order to provide the globally best solution.

1.3. Objective and hypothesis

All previous consistency models reveal that a higher speed variation along a road segment results in a lower consistency level. Likewise, winding road segments are prone to have a higher speed variation and, consequently, produce larger vehicle CO_2 emissions (Llopis-Castelló et al., 2018a). Merging up both statements, we can presume that lower CO_2 emissions might be expected on consistent roads under similar conditions of driver behavior, vehicle, and traffic, which are other important factors affecting this phenomenon.

Since minimizing CCR (and hence, enhancing the road design) and minimizing emissions have proven to be concomitant effects, the exploration of the relationship between consistency and road emissions due to horizontal design are suggested. A good level of correlation would ease the maximization of the alternative selection in the predesign process, since two important goals would be achieved in the same direction.

Therefore, the main objective of this research is to examine the influence of geometric design consistency on vehicle CO_2 emissions through actual continuous speed profiles collected on 15 two-lane rural road sections. The study focuses on CO_2 emissions because this Greenhouse Gas is the main responsible for global warming and, in addition, this is directly proportional to vehicle fuel consumption.

2. METHODOLOGY

This study was developed by analyzing the relationship between geometric design consistency and CO_2 vehicle emissions on 15 two-lane rural road sections localized in the Valencian Region (Spain). Speed data and estimated vehicle CO_2 emissions used in this research are part of a previous study developed by the same research group (Llopis-Castelló et al., 2018a).

These speed profiles correspond to actual drivers and were gathered during a naturalistic data collection following the methodology proposed by Pérez-Zuriaga et al. (2010). Two checkpoints were localized at the beginning and at the end of each road section. Then, every vehicle travelling along the road was stopped, and drivers were asked to participate in the speed data collection. If the driver accepted, a 1 Hz pocket-sized GPS was placed on the vehicle. As a result of the data collection, the individual continuous speed profile for each driver was obtained.

Then, free-flow conditions were checked by means of the procedure proposed by Pérez-Zuriaga et al. (2013), which relies on the hypothesis that every single driver behaves according to a specific speed percentile. Thus, non-free flow road sections are associated to sudden variations in its usual operating percentile. After removing individual non-free-flow sections, the operating speed profile of each road section was estimated for both forward and backward direction (Figure 2).

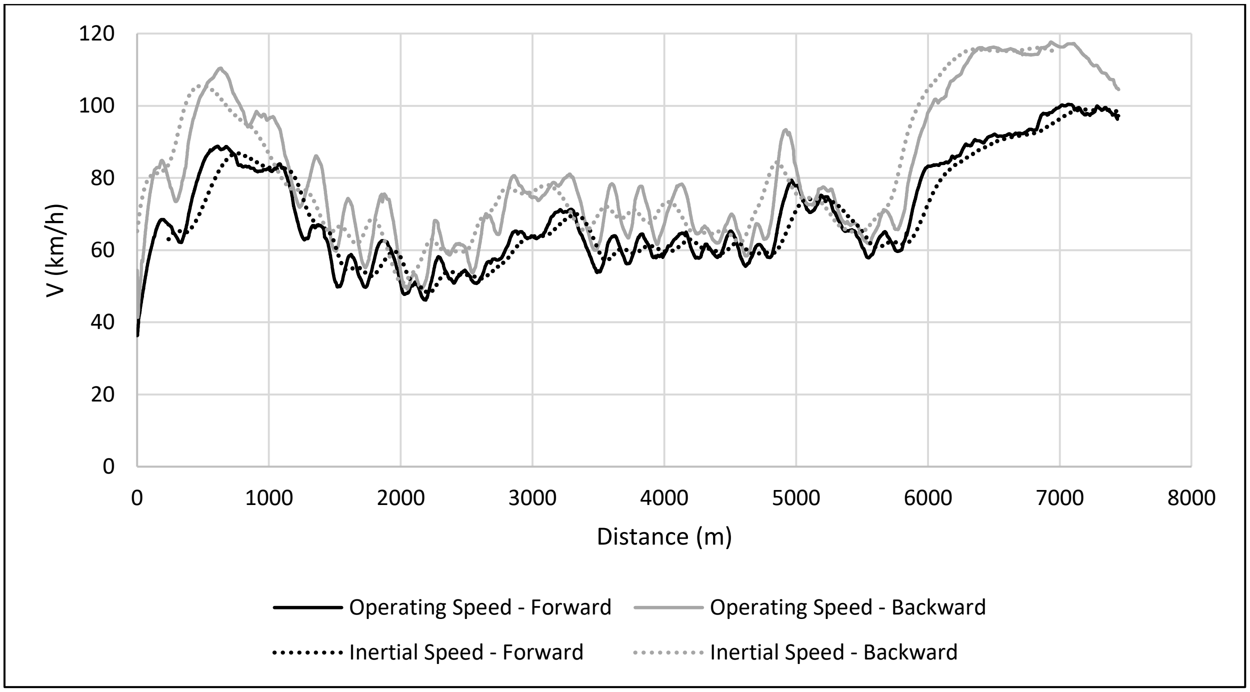

FIGURE 2 Speed profiles for both forward and backward direction.

Additionally, the studied road sections were divided into homogeneous road segments in order to assess geometric design consistency and estimate CO_2 emissions. In this regard, a homogeneous road segment is one which has a constant traffic volume, does not contain major intersections and interchanges that might significantly influence drivers' behavior, and presents a similar geometric behavior regarding the German method, which is based on the parameter Curvature Change Rate (*CCR*).

The German method aims at identifying homogeneous road segments by depicting the cumulative absolute deflection angle versus the road station, so that the parameter *CCR* is represented by the slope (Figure 3). In this way, a homogenous road segment is one which has an approximately constant value for *CCR*, i.e., a similar slope.

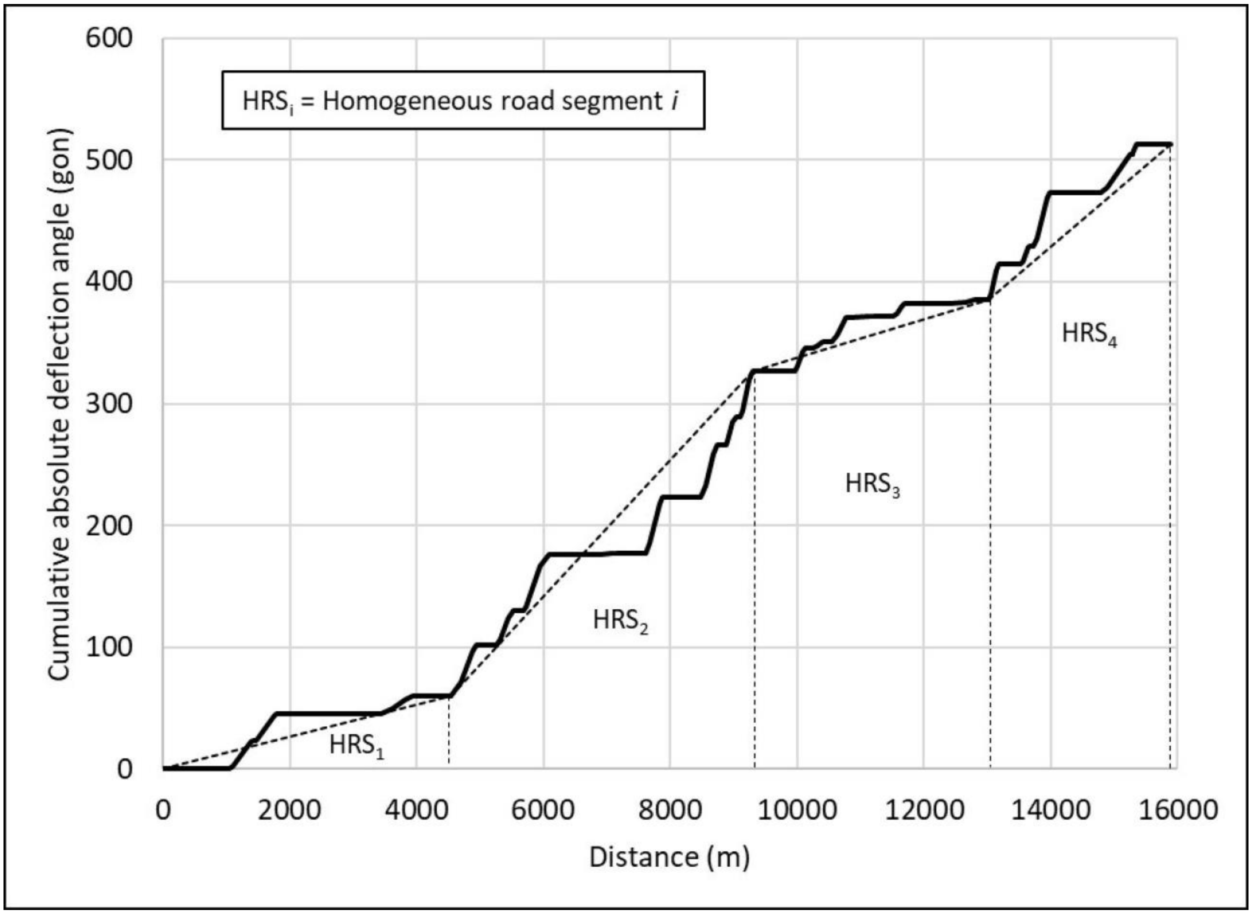

FIGURE 3 Homogeneous road segment identification based on the German method.

As a result, 47 homogeneous road segments were identified. These have a length ranging from 955 m to 7,864 m, with an average length of 2,183 m. Their Curvature Change Rates (*CCR*) range from 0 gon/km to 645 gon/km with an average value of 156 gon/km. Regarding cross-section, lane width ranges between 3.00 and 3.50 m, whereas shoulder width varies between 0.5 and 1.50 m. Their longitudinal grade is not greater than 5%.

Finally, vehicle CO_2 emissions and geometric design consistency were estimated and the influence of the geometric design consistency on vehicle emissions was studied by comparing the level of consistency of each homogeneous road segment with its CO_2 emission rate (g/km).

3. ESTIMATION OF VEHICLE CO_2 EMISSIONS AND CONSISTENCY LEVEL

Vehicle CO_2 emissions were estimated previously by Llopis-Castelló et al. (2018a) using the microscopic model VT-Micro (Ahn et al., 2002), which estimates GHG emission rates for different categories of vehicle considering second-by-second vehicle speed (km/h) and acceleration (km/h/s) as input variables (Figure 4). This model was preferred over other softwares such as MOBILE5a, MOBILE6, and CMEM because VT-Micro is able to provide more reliable estimations and is frequently updated (Rakha et al., 2003).

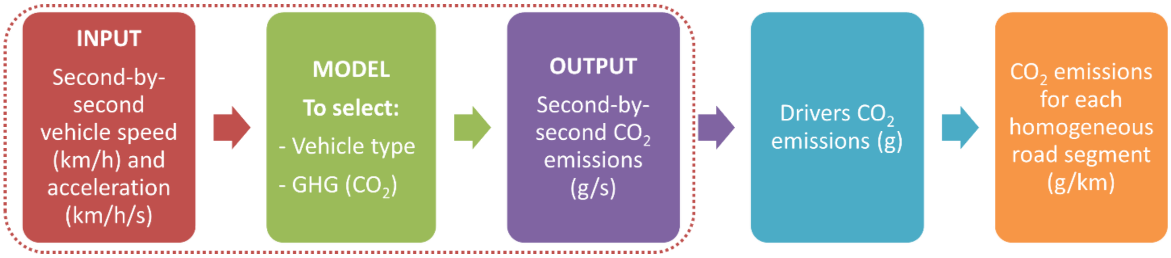

FIGURE 4 VT-Micro model procedure.

The vehicles which took part in the field data collection were largely sedan-type vehicles and van-type vehicles which correspond to the following categories of vehicles according to Rakha et al. (2004): LDV3, LDV4, and LDV5. Therefore, CO_2 emissions were only calculated for these vehicle categories.

Finally, the CO_2 emission rate (g/km) for each homogeneous road segment was estimated as the average of all drivers CO_2 emissions divided by the length of the homogeneous road segment, taking into account both forward and backward directions (Table 2).

On the other hand, the consistency level for each homogeneous road segment was obtained considering the global consistency models developed by Polus and Mattar-Habib (2004), Garach et al. (2014), Camacho-Torregrosa (2015), and Llopis-Castelló et al. (2018b). All their consistency parameters are based on different consistency variables extracted from the operating speed profile (Table 1).

However, the model developed by Camacho-Torregrosa (2015) was developed only for operating speed profiles calculated with speed models (estimated speed profile). Field-extracted operating speed profiles (actual speed profile) present much more noise than estimated ones, so results might be biased. Thus, a smoothing algorithm was applied to field operating speed profiles prior to this consistency model to ensure a feasible average deceleration rate (Figure 5). This algorithm estimated the speed at each station as a function of a moving average speed.

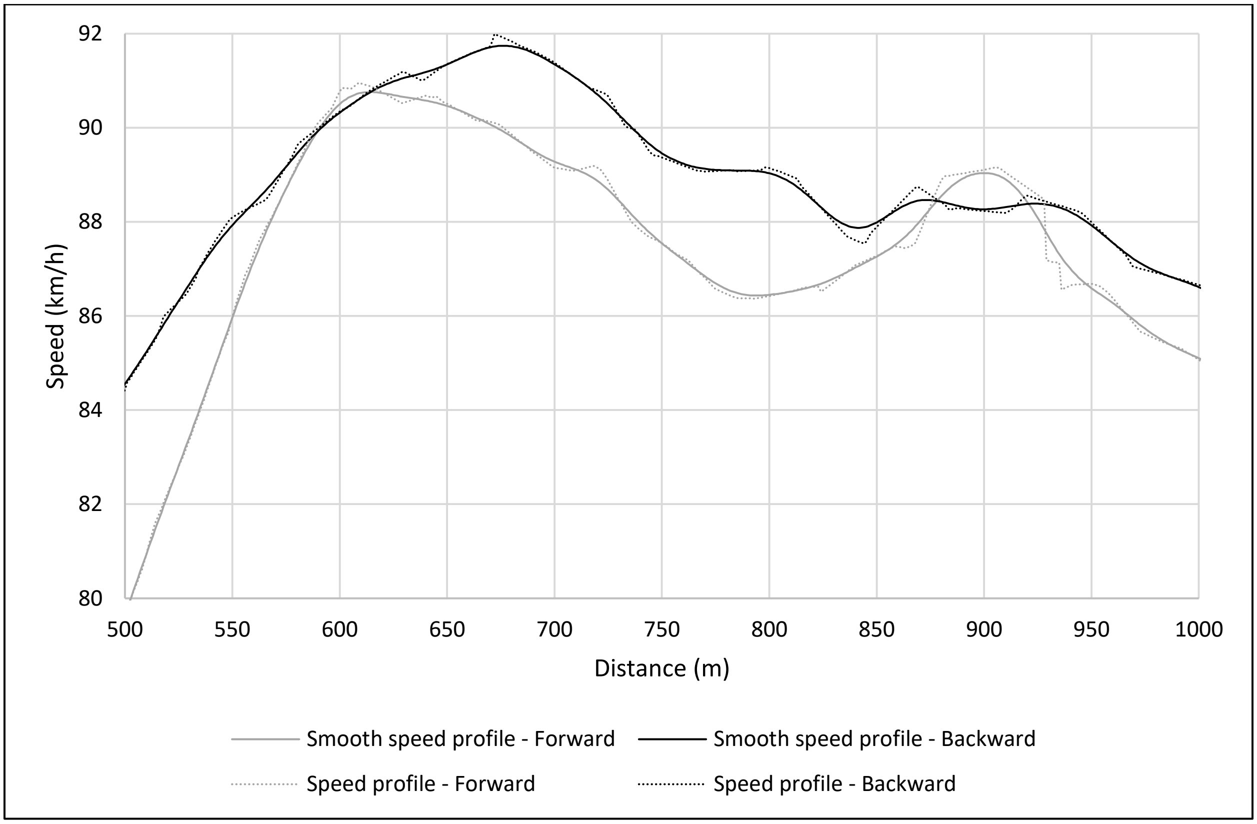

FIGURE 5 Smooth speed profiles.

Additionally, the consistency thresholds proposed by Camacho-Torregrosa (2015) were redefined for the same reason. To do this, the consistency parameters obtained through the actual speed profiles collected in field (C_F) were compared with those obtained considering estimated speed profiles (C_E), which were calculated by means of the speed models proposed by Pérez-Zuriaga (2012).

Figure 6 shows the close relationship between C_F and C_E. As a result, an expression than relates C_F to C_E were calibrated and new consistency thresholds were defined taking into account the previous ones shown in Table 1. To this regard, a homogeneous road segment has a good consistency level when C_F is greater than 4.8 $s^{1/3}$, a poor consistency level when C_F is lower than 4 $s^{1/3}$, and a fair consistency level otherwise.

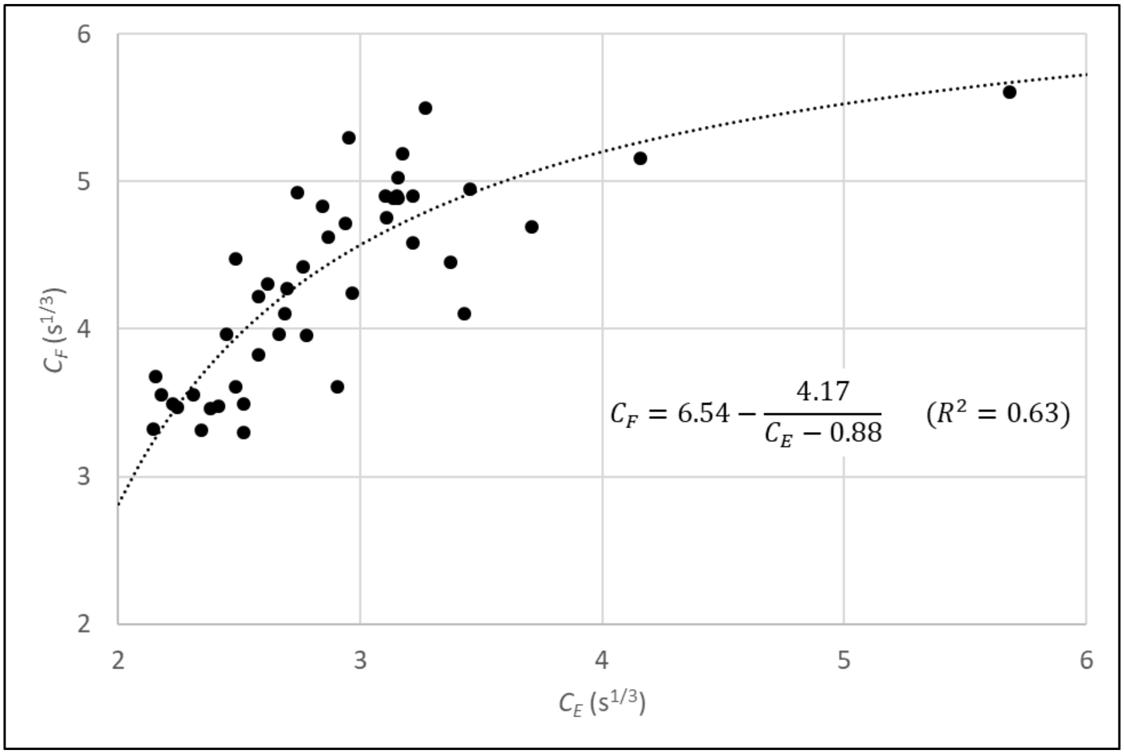

FIGURE 6 Analysis of the consistency thresholds proposed by Camacho-Torregrosa (2015).

Table 2 contains the consistency parameter and the qualitative consistency level for each homogeneous road segment according to all consistency models.

TABLE 2 CO_2 emission rates and consistency

Homogeneous Road Segment	Length (m)	*CCR* (gon/km)	CO_2 (g/km)			Polus and Mattar-Habib (2004)		Garach et al. (2014)		Camacho-Torregrosa (2015)		Llopis-Castelló et al. (2018b)	
			LDV3	LDV4	LDV5								
1.1	1477	68	165.40	150.50	202.45	0.1532	Poor	0.0857	Poor	3.4598	Poor	5.8718	Poor
1.2	1292	645	187.96	169.52	237.19	1.6040	Fair	1.7425	Fair	3.3241	Poor	3.1513	Fair
1.3	1093	292	167.65	152.34	208.39	1.7595	Fair	1.8661	Fair	3.5533	Poor	3.1243	Fair
1.4	955	628	172.83	156.52	216.54	2.1948	Good	2.1966	Good	3.5551	Poor	2.4016	Good
1.5	1059	245	170.07	154.16	211.04	1.1558	Fair	1.4059	Fair	3.4784	Poor	2.5865	Good

1.6	1519	36	147.50	137.65	175.00	1.1828	Fair	1.4396	Fair	4.4567	Fair	2.3016	Good
2.1	1592	4	167.68	156.32	194.86	0.9955	Poor	1.1508	Fair	4.1015	Fair	4.6799	Poor
2.2	2392	534	179.36	162.35	222.14	0.6535	Poor	0.7714	Poor	3.3163	Poor	4.0450	Fair
2.3	2583	347	188.16	168.08	234.72	0.4366	Poor	0.3500	Poor	3.4902	Poor	5.2579	Poor
2.5	2069	254	180.80	164.20	222.34	0.4819	Poor	0.6829	Poor	3.6112	Poor	4.1897	Fair
2.6	5937	103	169.82	155.50	205.70	0.7882	Poor	0.9860	Poor	3.7709	Poor	4.3571	Fair
3.1	2691	20	137.99	129.05	161.86	1.0650	Fair	1.3324	Fair	4.6921	Fair	1.9407	Good
3.2	2689	136	147.85	136.90	177.07	1.2119	Fair	1.4529	Fair	4.1064	Fair	3.4578	Fair
3.3	1721	549	174.33	157.62	216.03	0.4219	Poor	0.6272	Poor	3.4891	Poor	4.1733	Fair
3.4	2867	151	153.90	141.91	184.97	0.9171	Poor	1.1839	Fair	3.9672	Poor	3.5499	Fair
3.5	2396	0	137.55	129.08	160.53	0.7563	Poor	1.0435	Fair	4.8871	Good	2.6363	Good
4.1	2321	317	150.16	137.97	183.56	0.7745	Poor	1.0736	Fair	4.4804	Fair	2.5619	Good
4.2	1625	139	148.42	137.84	178.32	1.9006	Fair	1.9717	Fair	4.8313	Good	1.8456	Good
5.1	1374	0	137.75	129.86	159.28	1.8687	Fair	1.9607	Fair	4.6121	Fair	1.0766	Good
5.2	1879	50	127.84	119.40	147.28	2.4101	Good	2.3754	Good	5.1607	Good	1.1073	Good
5.3	7864	5	133.48	125.66	154.50	1.9705	Fair	2.0171	Good	5.1407	Good	1.3883	Good
6.1	1082	220	154.14	141.77	186.56	0.1002	Poor	-0.1070	Poor	3.9641	Poor	3.8874	Fair
6.2	2968	60	143.15	132.76	169.56	0.8513	Poor	1.1296	Fair	4.2431	Fair	3.6301	Fair
6.3	3627	173	153.30	141.39	184.36	0.6627	Poor	0.9558	Poor	3.9577	Poor	4.0517	Fair
7.1	1604	0	139.64	131.38	162.94	2.2773	Good	2.2572	Good	5.6071	Good	1.1216	Good
7.2	2833	44	143.83	134.44	169.43	1.1086	Fair	1.3277	Fair	4.9530	Good	2.2575	Good
8.1	1739	81	141.07	132.54	165.84	2.3698	Good	2.3168	Good	5.0305	Good	1.1747	Good
8.2	1138	14	138.70	131.84	159.87	2.6772	Good	2.6197	Good	5.5033	Good	0.7770	Good
8.3	2349	73	142.35	133.59	167.64	1.2973	Fair	1.5264	Fair	4.5874	Fair	3.2706	Fair
9.1	1264	156	164.34	149.68	203.86	0.9814	Poor	1.2663	Fair	3.8255	Poor	3.2273	Fair
9.2	1663	596	181.41	164.12	228.85	1.7757	Fair	1.8727	Fair	3.6786	Poor	2.9986	Fair
9.3	2226	406	183.08	165.45	229.52	0.8282	Poor	1.1302	Fair	3.4679	Poor	4.4371	Fair
9.4	1006	125	181.87	164.25	225.94	0.0933	Poor	-1.1499	Poor	3.2991	Poor	5.8896	Poor
10.1	1775	83	155.87	143.33	189.09	1.2207	Fair	1.4608	Fair	4.2230	Fair	3.9538	Fair
10.2	2141	31	146.27	135.53	175.02	1.0671	Fair	1.3420	Fair	4.6234	Fair	2.5445	Good
11.1	2529	157	144.49	134.11	174.02	2.0222	Good	2.0518	Good	5.2943	Good	1.5044	Good
11.2	1239	9	144.79	134.78	173.79	1.8841	Fair	1.9538	Fair	4.8881	Good	3.0104	Fair
12.1	4638	21	138.77	129.15	164.17	1.1818	Fair	1.4376	Fair	4.9045	Good	2.4739	Good
12.2	2843	59	141.58	131.99	168.79	2.3036	Good	2.2660	Good	4.9041	Good	1.8530	Good
13.1	1054	42	152.34	140.92	183.74	0.4255	Poor	0.6614	Poor	4.9226	Good	2.6877	Good
13.2	1529	80	148.32	137.17	179.21	0.9904	Poor	1.2713	Fair	4.4242	Fair	2.1560	Good
13.3	1915	9	144.14	134.27	171.99	2.1650	Good	2.1594	Good	4.9001	Good	2.2186	Good
13.4	1128	62	147.53	135.95	179.93	2.3307	Good	2.2856	Good	4.2750	Fair	2.3563	Good
14.1	1832	15	144.38	135.64	169.76	1.9500	Fair	2.0031	Good	5.1923	Good	1.7371	Good
14.2	1702	172	155.70	143.37	188.79	1.2732	Fair	1.5076	Fair	4.3042	Fair	2.4194	Good
14.3	2457	92	147.73	137.05	177.72	1.9296	Fair	1.9885	Fair	4.7141	Fair	2.2999	Good
15.1	2930	36	140.76	130.82	169.08	1.4683	Fair	1.6529	Fair	4.7541	Fair	2.4592	Good

4. ANALYSIS AND RESULTS

The analysis of this study was developed through the comparison between geometric design consistency and vehicle CO_2 emissions considering the above defined global consistency models.

The relationship between each consistency parameter and CO_2 emissions for each homogeneous road segment and vehicle type (LDV3, LDV4, and LDV5) was studied with a descriptive analysis. Figure 7 shows this relationship for LDV3 vehicle type. Although the global consistency models proposed by Polus and Mattar-Habib (2004) and Garach et al. (2014) showed a greater variability than those models defined by Camacho-Torregrosa (2015) and Llopis-Castelló et al. (2018b), all of them result in higher vehicle CO_2 emissions as the consistency level gets lower. The same conclusion was observed for all vehicle types (LDV4 and LDV5).

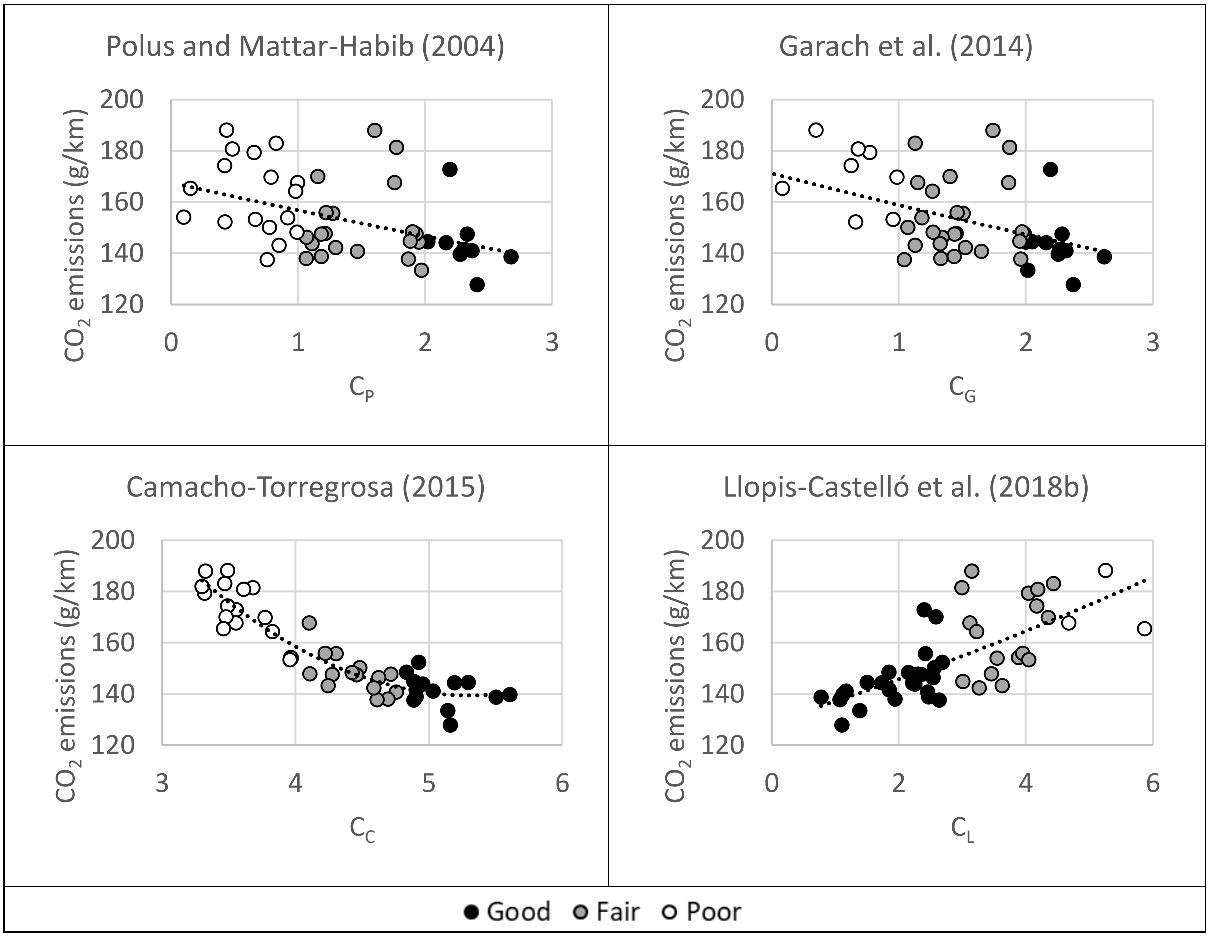

FIGURE 7 Geometric design consistency Vs. Vehicle CO_2 emissions (LDV3 vehicle type).

Additionally, the average CO_2 emissions was calculated for any consistency level considering each global consistency model and vehicle type (Figure 8). Although the level of CO_2 emissions is different for each vehicle type, all of them show a similar trend. A consistent road segment leads to lower vehicle CO_2 emissions, supporting the above-mentioned results.

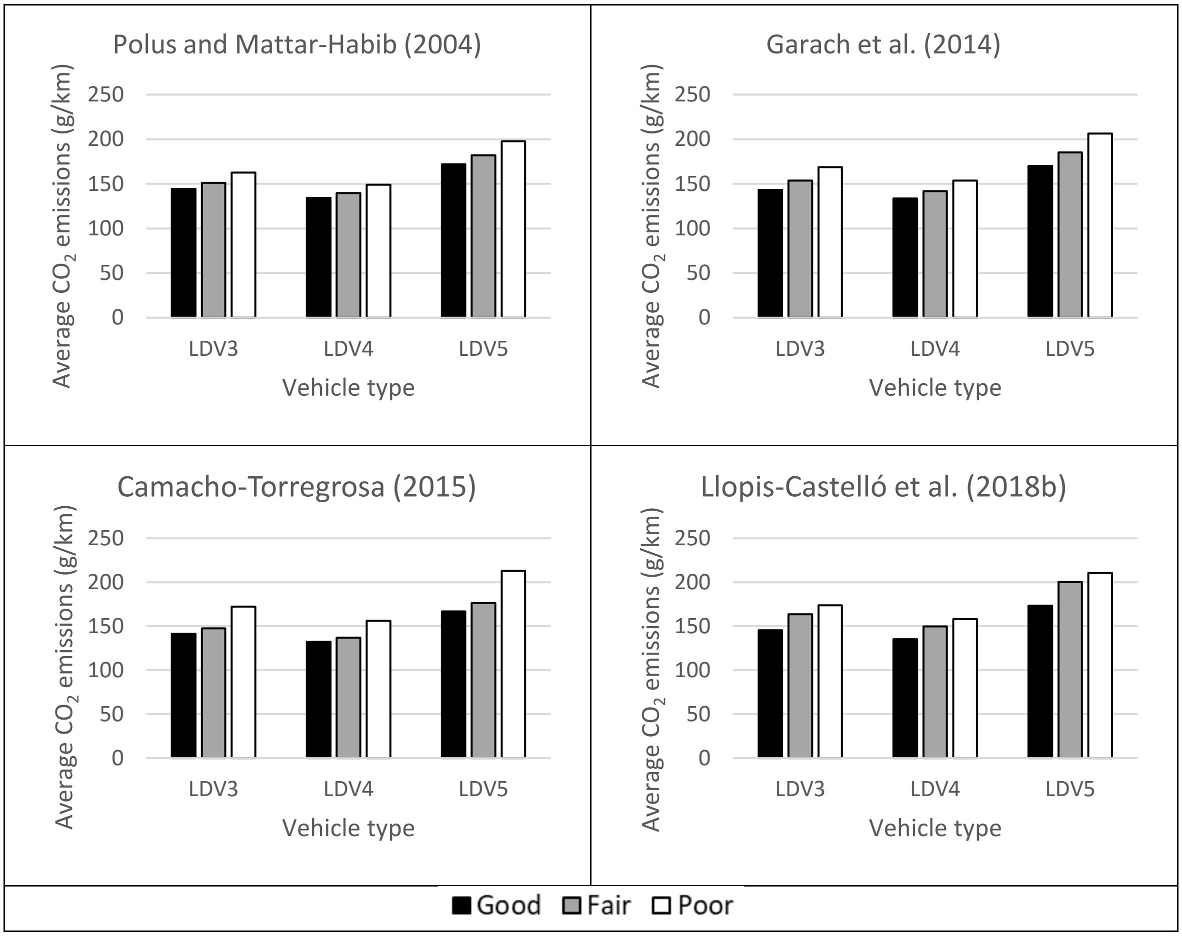

FIGURE 8 Consistency level Vs. Average CO_2 emissions.

Finally, a hypothesis test was performed to identify whether the average CO_2 emissions for the different consistency levels are statistically different or not (Table 3). For this, the following hypotheses were formulated: (a) Null hypothesis (H_0): the average CO_2 emissions for all consistency levels may be equal; (b) Alternative hypothesis (H_1): the average CO_2 emissions for the different consistency levels differ from each other. The confidence level considered was 95%.

The P-value for all global consistency models and vehicle types was lower than 0.05.

Therefore, we can conclude – at a 95% confidence level – that the average CO_2 emissions differ with the consistency level, regardless the consistency criterion. In addition, the Least Significant Difference (LSD) intervals were analyzed. Most of these intervals did not overlap, strengthening the previous statement.

TABLE 3 Statistical analysis: Average CO_2 emissions Vs. Consistency level.

Consistency model	Vehicle type	Statistical parameter	Consistency		
			Good	Fair	Poor
Polus and Mattar-Habib (2004)	LDV3	Average (g/km)	144.202	151.027	163.761
		Std. dev. (g/km)	12.074	14.787	15.2649
		F	6.49		
		P-value	0.0034		
	LDV4	Average (g/km)	134.222	139.741	149.83
		Std. dev. (g/km)	9.62865	11.752	12.3303
		F	6.42		
		P-value	0.0036		
	LDV5	Average (g/km)	171.911	181.801	199.447
		Std. dev. (g/km)	19.1685	22.6816	21.9267
		F	5.66		
		P-value	0.0065		
Garach et al. (2014)	LDV3	Average (g/km)	143.243	153.495	169.953
		Std. dev. (g/km)	11.2747	14.6771	13.1526
		F	10.2		
		P-value	0.0002		
	LDV4	Average (g/km)	133.572	141.687	154.658
		Std. dev. (g/km)	9.01322	11.8692	10.4346
		F	9.82		
		P-value	0.0003		
	LDV5	Average (g/km)	170.132	185.301	208.398
		Std. dev. (g/km)	17.9229	22.0204	18.7019
		F	9.26		
		P-value	0.0004		
Camacho-Torregrosa (2015)	LDV3	Average (g/km)	141.402	147.774	172.26
		Std. dev. (g/km)	5.92498	7.69506	11.4213
		F	55.61		
		P-value	0.000		
	LDV4	Average (g/km)	132.202	137.157	156.433
		Std. dev. (g/km)	5.11312	6.76259	9.22302
		F	49.43		
		P-value	0.000		
	LDV5	Average (g/km)	166.998	176.512	212.977
		Std. dev. (g/km)	9.29243	10.0512	16.8076
		F	58.88		
		P-value	0.000		
Llopis-Castelló et al (2018b)	LDV3	Average (g/km)	173.393	200.416	214.493
		Std. dev. (g/km)	15.3528	22.9207	18.8907
		F	18.27		
		P-value	0.000		
	LDV4	Average (g/km)	135.13	149.837	159.789
		Std. dev. (g/km)	7.71623	12.4701	7.89258
		F	18.61		
		P-value	0.000		
	LDV5	Average (g/km)	173.393	200.416	214.493
		Std. dev. (g/km)	15.3528	22.9207	18.8907
		F	15.59		
		P-value	0.000		

5. DISCUSSION

This research highlights that geometric design consistency influences vehicle CO_2 emissions. In this regard, lower emissions are expected on consistent road designs.

The consistency models developed by Camacho-Torregrosa (2015) and Llopis-Castelló et al. (2018b) showed a greater correlation with CO_2 emissions than those proposed by Polus and Mattar-Habib (2004) and Garach et al. (2014). This higher correlation could be explained due to the more direct connection to speed and its standard deviation (σ) that these models have. According to Llopis-Castelló et al. (2018a), the average mean speed and σ were operational parameters highly connected to emissions. Figure 9 shows the relationship between CO_2 emissions and the average operating speed. It seems evident that a road segment which presents a higher operating speed would require less time for drivers to perform along it. Therefore, the final emission rate is lower for faster road segments.

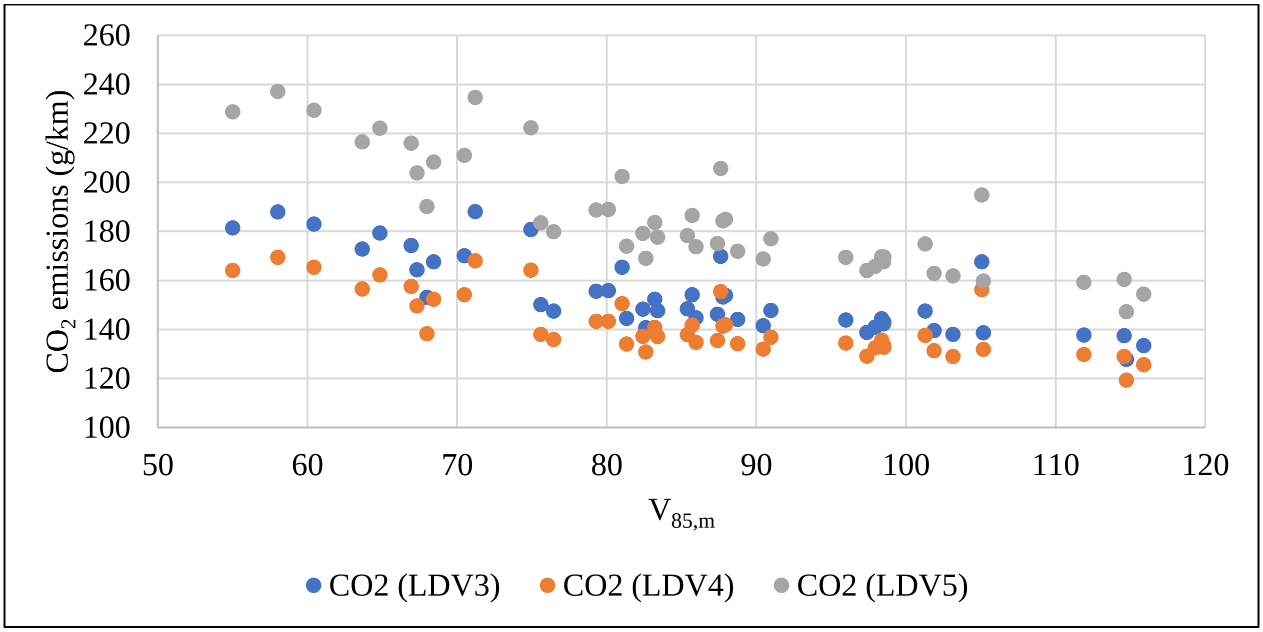

FIGURE 9 CO_2 emissions as a function of the average operating speed.

However, speed is not the only factor causing emissions to rise. Operating speed variability is also a major contributor. Figure 10 shows how speed variation (expressed in terms of average deceleration rate) impacts emissions. As expected, higher decelerations are linked to higher emissions. While decelerations per se are not the main contributor (should be accelerations), this parameter has been examined since it is one of the components of Camacho-Torregrosa's consistency model. Anyway, higher deceleration rates are generally linked to medium to long tangents followed by sharp curves, so high acceleration rates are also expected to be found.

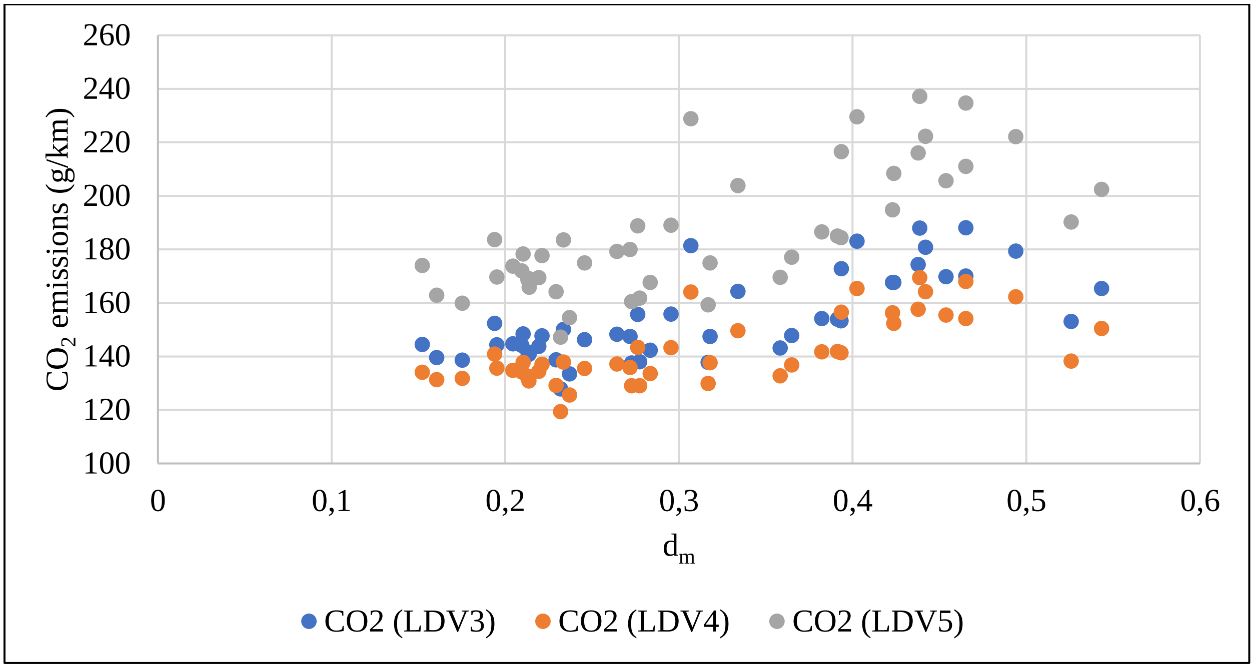

FIGURE 10 CO_2 emissions as a function of the average deceleration rate.

Both Camacho-Torregrosa (2015) and Llopis-Castelló et al. (2018b) consistency models are very well connected to these operational parameters, so increasing the consistency level on a road segment would presumably result in higher average operating speeds and/or lower speed variability. Since maximizing consistency increases the safety level of the road segment, its maximization would also work towards minimizing emissions.

Although both consistency models can be used for that purpose, Camacho-Torregrosa's model seems to depict a little bit better the relationship for poor-consistent road segments (lower noise), while Llopis-Castelló et al.'s one works better for medium-to-good consistent road segments (see Figure 7, bottom).

An analytic quantification of the amount of emissions that can be attributed to the horizontal alignment cannot be performed, since there are no boundaries for good and poor consistency levels. However, we can compare the emission rates among consistency levels. According to Camacho-Torregrosa's consistency model, a poor consistency road segment presents an emission rate 27% higher than for a good consistency level (LDV5). For Llopis-Castelló's model, this difference is 21%.

It is also necessary to highlight that all these conclusions have been obtained using operating speed profiles, i.e., free-flow speed distributions. Since a 5-second interval is needed to ensure free-flow conditions, the validity of these conclusions extends up to 720 pc/h/direction. In fact, the maximum volume is even lower, since it has been determined following an ideal, completely uniform distribution of vehicles. However, this hourly volume demand is considered to be high enough to cover most cases in Spain – especially the poor-consistent ones.

The authors are working on the expansion of these conclusions to road segments showing a higher demand. This will be done by means of combining free-flow distributions for other percentiles (García-Jiménez et al., 2016) with normal-distributed time intervals, car-following, and passing models in a microsimulation environment.

6. CONCLUSIONS

There are different factors involved in GHG emissions production derived from the transportation sector, such as driver behavior, vehicle, traffic operation, and road design. Although the policy measures to mitigate emissions are increasing, none of them consider the road geometric design as a potential measure to reduce air pollution.

Thus, the objective of this research was to analyze the relationship between geometric design consistency and vehicle CO_2 emissions using actual continuous speed data collected on 47 homogeneous road segments.

Although the CO_2 emission level was different for each vehicle type (LDV3, LDV4, and LDV5), all of them showed an increase in vehicle CO_2 emissions as the consistency level of a homogeneous road segment decreases. To this regard, statistically significant differences were identified among the CO_2 emission levels associated to the different consistency levels for all vehicle types. Despite absolute values are different as a function of the vehicle type, these differences are homothetical, according to the model provided by Ahn et al. (2002). Thus, a consistent road leads to lower vehicle CO_2 emissions, regardless the vehicle type.

Although the research has been carried out for free-flow conditions, it is worth to say that these are the prevailing conditions for Spanish two-lane rural roads. Higher traffic volumes can be found at urban or suburban environments, which are out of scope of this study.

As vehicle CO_2 emissions are directly proportional to vehicle fuel consumption, the outcomes obtained are also applicable to vehicle fuel consumption. Therefore, the design of consistent roads allows, in addition to maximize road safety, to help to achieve more environmentally sustainable highways, reducing CO_2 emission production.

Since these models only consider the horizontal alignment, further research is suggested to analyze the influence of the vertical alignment and the interaction between vehicles on GHG emissions. In addition, a wider perspective of the road lifecycle assessment could be further explored by including the construction stage in the analysis. While a consistent road segment derives into lower emissions at an operational level; the construction stage would normally involve an increase in earthworks – especially for mountainous highways – so the total emissions for the whole lifecycle might be even higher, compared to a low-consistent alternative.

AKNOWLEDGMENTS

The study presented is part of the research project titled "CASEFU - Estudio experimental de la funcionalidad y seguridad de las carreteras convencionales" (TRA2013-42578-P), subsidized by the Spanish Ministry of Economy, Industry, and Competitiveness and the European Social Fund. In addition, authors would like to thank Professor Hesham A. Rakha, Virginia Tech (USA), for providing the VT-Micro model and assessing the authors in its use to obtain outcomes.

REFERENCES

1. 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.
2. 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.
3. CAMACHO TORREGROSA, F. J. (2015). *Development and calibration of a global geometric design consistency model for two-lane rural highways, based on the use of continuous operating speed profiles*. Universitat Politècnica de València, Valencia (Spain).
4. EUROPEAN COMMISSION (2016). A European strategy for low-emission mobility. *European Commission*, Brussels, 2016.
5. EUROPEAN ENVIRONMENT AGENCY (2017). Greenhouse gas emissions from transport. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-10
6. GARACH, L., CALVO, F., PASADAS, M., & DE OÑA, J. (2014). Proposal of a New Global Model of Consistency: Application in Two-Lane Rural Highways in Spain. *Journal of Transportation Engineering*, 140(8), 04014030.
7. GARCÍA-JIMÉNEZ, M.E., PÉREZ-ZURIAGA, A.M., LLOPIS-CASTELLÓ, D., CAMACHO-TORREGROSA, F.J. & GARCÍA, A. (2016). Examination of the Free-Flow Speed Distribution on Two-Lane Rural Roads. *Transportation Research Record: Journal of the Transportation Research Board*, (2556), 86-97.
8. GIBREEL, G. M., EASA, S. M., HASSAN, Y., & EL-DIMEERY, I. A. (1999). State of the art of highway geometric design consistency. *Journal of transportation engineering*, 125(4), 305-313.
9. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (2015). *Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth*

Assessment Report. Cambridge: Cambridge University Press. doi:10.1017/CBO9781107415416

10. 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.
11. 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.
12. LLOPIS-CASTELLÓ, D., PÉREZ-ZURIAGA, A. M., CAMACHO-TORREGROSA, F. J., & GARCÍA, A. (2018a). Impact of horizontal geometric design of two-lane rural roads on vehicle CO_2 emissions. *Transportation Research Part D: Transport and Environment*, 59, 46-57.
13. LLOPIS-CASTELLÓ, D., CAMACHO-TORREGROSA, F. J., & GARCÍA, A. (2018b). Development of a global inertial consistency model to assess road safety on Spanish two-lane rural roads. *Accident Analysis & Prevention*, 119, 138-148.
14. PARK, S., & RAKHA, H. (2006). Energy and environmental impacts of roadway grades. Transportation Research Record: Journal of the Transportation Research Board, (1987), 148-160.
15. PÉREZ-ZURIAGA, A.M. (2012). *Caracterización y modelización de la velocidad de operación en carreteras convencionales a partir de la observación naturalística de la evolución de vehículos ligeros*. Universitat Politècnica de València, Valencia (Spain).
16. PÉREZ-ZURIAGA, A. M., CAMACHO-TORREGROSA, F. J., CAMPOY-UNGRÍA, J. M., & GARCIA, A. (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(2), 182-189.
17. 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.
18. POLUS, A., & MATTAR-HABIB, C. (2004). New consistency model for rural highways and its relationship to safety. *Journal of transportation engineering*, 130(3), p. 286-293.
19. RAKHA, H., AHN, K., & TRANI, A. (2003). Comparison of MOBILE5a, MOBILE6, VT-MICRO, and CMEM models for estimating hot-stabilized light-duty gasoline vehicle emissions. *Canadian Journal of Civil Engineering*, 30(6), 1010-1021.
20. RAKHA, H., AHN, K., & TRANI, A. (2004). Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. *Transportation Res. Part D: Transport Environment*, 9 (1), 49–74.

21. U.S. ENVIRONMENTAL PROTECTION AGENCY (2016). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014.