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Original Article

REDUCING CO_2 EMISSIONS BY IMPROVING ROAD DESIGN: A DRIVING SIMULATOR STUDY

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Highlights:

- the study demonstrates that horizontal road geometry significantly influences CO_2 emissions;
- curves often induce higher emissions compared to tangents;
- curves with radii below a certain value (in the range of 120…180 m) enforce cautious driving behaviour, resulting in lower emissions;
- the research validates the use of simulated environments;
- the study identifies gaps in current road standards.

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Abstract. In the last decade, the causes of Greenhouse Gas (GHG) emissions were widely studied, to delete or, at least, mitigate them. In the road context, as reasonable, greater importance was assigned to the vehicles, since huge traffic flows, including high percentages of trucks, determine negative impacts on the environment. On the contrary, the role of the road infrastructure has always been considered marginal. It was thought as a functional element on which the traffic flows move, without evaluating the role of its geometrical characteristics on exhaust gas emissions. The proposed research aims to verify whether some road features, related to its horizontal geometry, influence the carbon dioxide production of vehicles or, on the contrary, if it is not sensitive to the different geometrical compositions. A driving simulator gives the opportunity to calculate the emissions from fuel consumption data, in turn, calculated through the engine mapping of an ordinary vehicle. The proposed procedure may be easily applied to any road context and may represent a further checking element for the infrastructure efficiency, in terms of environmental impacts. The results, derived from a test phase in a simulated environment and obtained using 3 different one-way ANOVAs, allowed the authors to define some interesting conclusions. The trend of the carbon dioxide function depends on curve radius and lengths and on tangent length; therefore, an opportune alignment design can effectively contribute to control emission values. The experiments confirmed that designing a consistent road is fundamental, but this cannot be deduced by traditional literature models.

Keywords: environmental impact, fuel consumption, simulation, sustainable transport, road, emissions, CO_2.

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Notations

ADAS – advanced driver assistance system;
ANOVA – analysis of variance;
CCR – curvature change rate;
COPERT – computer model to calculate emissions from road traffic;
GHG – greenhouse gas;
GPS – global positioning system;
GWP – global warming potential;
HD – high definition;
HSD – honestly significant difference;
MOVES – motor vehicle emission simulator;
SUV – sport utility vehicle.

1. Introduction

Among the dangerous substances released in the environment while driving, in the last decades research has mainly focused on GHG emissions (CO_2, CH_4, N_2O, O_3, etc.), since they contribute to global warming and climatic changes causing critical damages to our planet. Similar analyses interested all the components of the road industry, from material production and road construction (Ma *et al.* 2016; Franzitta *et al.* 2020; Sollazzo *et al.* 2020; Dolge, Blumberga 2021; Huang *et al.* 2023) to vehicle impacts in the use phase (Hulail *et al.* 2016; Agarwal, Mustafi 2021). The carbon dioxide, CO_2, represents the most studied element in similar research. Although it has the lowest GWP in comparison, for instance, with CH_4 and N_2O that determine 28 and 265 times more powerful effects on GWP, CO_2 was often considered as a symbolic index of the damage caused by road transportation. Since it is directly proportional to the fuel consumption, it is easily quantifiable and, thus, is generally chosen for analytical evaluations.

In this regard, the numerical results of studies on the emissions should be acquired with a clear view of the quantification methods, to understand the unavoidable inaccuracies. At this purpose, the calculation methodologies for internal combustion engines may be classified, substantially, in 2 different procedures (Agarwal, Mustafi 2021):

- measures through dynamometer testing in the laboratory. The hypothesized driving conditions could be generally different than real ones, in which there is a random influence of vehicle mechanical features, road characteristics, traffic and environmental conditions. According to recent experience in the scientific community, these measurements underestimate the real emissions;
- on-board emission measurements. These, instead, consider remote sensing, tunnel studies, etc., but are very expensive and, in any case, strictly dependent on the type of vehicle adopted for the experiments.

Consequently, the available literature results should be considered with caution, focusing on the boundary conditions on which they rely and without dangerous generalization to contexts different from the original ones (Abo-Qudais, Qdais 2005; Mateo Pla *et al.* 2021).

Some synthetic data will help in understanding the GHG emission issue. Their overall quantity produced by all the transport means still raises, with critical rates constant in the 2000–2018 range and +0.5% in 2019. The transportation sector determines 24% of the CO_2 emissions due to fuel burning; ¾ of these emissions are directly produced by the road vehicles, while air and maritime transports cause the remaining quarter. This increase in exhaust gas emissions will surely produce a delay in achieving international goals on sustainable development and, for this reason, their mitigation cost will certainly increase. The last years have been characterized by the introduction in the market of numerous electrical vehicles that should have rebalanced the overall equilibrium. Despite this, the emissions have still risen. This is probably due to the increasing use of the so-called SUVs, bigger and heavier than ordinary cars, and to the spread of online trades causing a constant increase in truck flows, especially in urban areas (Kazancoglu *et al.* 2021).

In some investigations at territorial or network scale, reference is made to specific emission mapping, generally updated very rarely (usually once a year). These GHG levels are only useful for qualitatively describing the phenomenon or for year-by-year comparisons. In terms of the single transport infrastructure, this data is not useful, with risks of under or overestimating the phenomenon. Only the location or the environmental context features cannot characterize alone the emission level. There are other conditions to evaluate, such as the traffic flows, and, consequently, the speed trend. Whether the latter is too low, and the vehicle often accelerates and decelerates, more emissions are produced. For deepening this issue, Seo & Kim (2013) derived some detailed quantifications in Korea and evidenced that highways are the most polluting roads, owing to the high incidence of trucks and the overall traffic flows. In another research, Li *et al.* (2020) related the main traffic emissions released by the 7 most used vehicles in Beijing (China) to speed and the main traffic flows, obtaining some simplified correlations.

The driving style represents another relevant component, mainly for young users with high-risk inclination. In this regard, Muslim *et al.* (2018) estimated the emissions through specific physical, psychological, and psychosocial features of the drivers. They obtained remarkable results, but hardly verifiable in different contexts. Further, in recent years, some studies concerning emission derivation from vehicle GPS data have gained increasing attention. This methodology is extremely interesting because of some relevant advantages: it is possible to acquire huge quantities of data, even from users' smartphones (in this case, referring to low-frequency surveys); further, position and time data can be used for evaluating movement, speed, and acceleration measurements, obviously with the typical inaccuracies of similar devices (Chen *et al.* 2014; Kan *et al.* 2018). Other authors installed GPS sensors on public vehicles (such as taxi) that, especially in the biggest cities, are numerous, allowing the analysts to reduce the device error and to analyse in real-time the emission trend during the entire day with accurate approximations (EPA 2010; Nyhan *et al.* 2016; Luo *et al.* 2017).

These analyses indirectly provide even other details on the vehicle motion, otherwise difficult to determine, such as the cold start emissions, representing 20% of the overall vehicle emissions. These findings, together with data available in modern estimation models as COPERT (Ntziachristos, Samaras 2000) or MOVES (Vallamsundar, Lin 2011), guarantee a more reliable quantification of emissions and not only an approximate space–time estimation.

Another recent topic has regarded the influence of the road geometry, to quantify its incidence on the total emissions. For example, Park & Rakha (2006) conceived a large-scale simulation model from which they derived consumptions and emissions as a function of vehicle speed, that depends, in turn, on the road geometry. However, this has always been considered as a marginal cause that, eventually, assumes relevance only when large truck flows move along high-grade segments. They concluded that when territory/traffic characteristics determine similar conditions, the evaluation of mixed transport modalities (i.e., including railways, ships, etc.) would be convenient. A recent study by Heinold & Meisel (2018) indicated some thresholds beyond which other transport means – such as railways – become more convenient. Some studies on the road profile suggested some correlations between a certain fixed grade (4%) and the emissions (Ko *et al.* 2012, 2013). Unfortunately, also in this case, the practical utility is limited, since numerous relevant variables are not involved (Boriboonsomsin, Barth 2009).

Even the horizontal geometry might cause variations, despite slighter, in vehicle fuel consumption and, in turn, in their emissions, since they depend on the use of engine torque or load. However, while the grade deeply stresses the engine only for a short segment, eventual horizontal inhomogeneities may have effects for longer sections and, thus, determine particularly remarkable total emissions. Then, whether the horizontal alignment induces numerous speed variations, also fuel consumptions and emissions consequently rise. In this regard, measurements and considerations regarding road homogeneity are strategical. For measuring road consistency, Lamm *et al.* (1988) proposed a very simple index that gained huge success, named CCR, i.e., the rate of curvature variation of the single curve. For long straights and flat curves, CCR values are low. Consequently, the related speed will be high and almost constant, with contained consumptions and emissions. On the contrary, high CCR values, measured on more tortuous alignments, determine a more active driving and higher consumptions and emissions (Llopis-Castelló *et al.* 2018a, 2018b, 2019). Subsequent studies confirmed the significance of CCR respect to consumptions and emissions, but Nobili *et al.* (2019) involved also the average speed, although, at least theoretically, speed and geometry are not independent variables (MIT 2001; AASHTO 2018). However, in some cases, this dependence is not so clear and, further, the authors identified the speed percentiles causing the main issues.

The summary of the literature evidences some limitations that make complicate and uncertain the study of the relationship between emissions and infrastructure features:

- the emissions calculation, measured using control units in fixed locations, is generally referred to a territorial-based scale. Consequently, extracting details regarding the single road or, more hardly, the different geometric elements, such as curves or tangents, is not feasible;
- the empirical models related to pollutant emissions by a specific vehicle are only sensitive to its mechanical characteristics. Owing to this limitation, further investigations are required to evaluate even the influence of the road geometry on the vehicle performance;
- the geometric characteristics of the road have been considered, in the past, only in terms of the road profile. The study of the emissions due to horizontal geometry was poorly investigated and, in those few cases, the related driving behaviour models – generally based on operative speed – are mostly obsolete.

In order to overpass the above limitations, this research aimed to:

- quantify in detail the CO_2 emissions, both in time and space, through an experimental test session by means of a driving simulator, for correlating this data with the main telemetry variables; this choice also allows the analysts to minimize the influence of the other environmental variables, not relevant in research phase (traffic, weather, etc.);
- correlate the CO_2 emissions to the geometry of curves and tangents, to identify, if existing, the most sustainable design solutions;
- provide considerations concerning the reliability of traditional procedures for determining road alignment consistency (such as Lamm's index – CCR).

2. Methods

Currently, the effort of the scientific community is referred to the identification and mitigation of all pollution causes, even those related to the road infrastructure. The limited quantity of references concerning the relationship between road geometry and CO_2 emission indicates that evidencing this correlation is not simple. For this purpose, in the past, only the road profile was investigated, to evaluate the possible performance of trucks, their interaction with other vehicles and their fuel consumption. Studies concerning the horizontal geometry, which represents the focus of this research, are almost absent or poorly reliable.

In particular, the authors aim to verify whether different design configurations induce incorrect driving behaviours, in terms of speed and acceleration and, thus, of increasing emissions.

This goal requires an optimized experimental phase, to prevent the influence of other variables (such as vertical profiles, traffic flows, sight conditions, etc.) on the driving behaviour. Further, the environmental context must be identical for the entire drivers' sample, to avoid eventual differences due to random variables. To satisfy these conditions, the experimental tests were performed in a simulated environment, considering an alignment characterized by a proper succession of curves and tangents. The specific selection of curve radii and tangent lengths induced the users to choose driving behaviours that were, then, analysed in the following sections.

Therefore, the basic hypotheses of this research are:

- there are no grade variations in the road profile; consequently, only the horizontal geometry influences the driving behaviour;
- the horizontal alignment is made up of 3 types of transition curves, in compliance with Italian Standards (MIT 2001), with radii of the residual circular curve equal to 120, 180, and 240 m;
- the tangent segments between 2 curves values are respectively 146.58, 80.60, and 20.71 m long;
- the deviation angle between the straight segments is constant and equal to 50°;
- there is no traffic, to correlate variations of the driving behaviour and, thus, emissions, to the horizontal geometry only;
- the experiments were performed in a simulated environment, on a selected sample of 25 users; however, the results of 4 users were discarded, since they were affected by nausea while driving.

- the output variable is the quantity of CO_2 instantly released, measured in [g/s]. To evaluate homogeneous geometric elements (curve or straight), the average CO_2 emission on the single element is considered.

2.1. Opportunities of the simulated environment

The advantages of the experiments on a driving simulator respect to a real road are several and may be synthetized as follows (Labi 2014; Bassani *et al.* 2019):

- drivers' safety during tests;
- repeatability and homogeneity of the investigated scenarios in terms of weather condition, light, and traffic, impractical to obtain in real contexts;
- complete control of the vehicle telemetry, the pavement condition, and the main driver's psychophysiological factors;
- accurate design of the road geometry;
- proper choice of the variable that may influence the road environment; at this regard, the external disturbance was limited (absence of elements that may distract the driver or represent an obstacle to visibility, absence of traffic, fully plan alignment, etc.) to refer eventual irregularities in the driver behaviour and CO_2 emissions to the horizontal alignment only.

2.2. The driving simulator at the University of Messina (Italy)

The experimentation was performed using the driving simulator named SimEASY® (Figure 1), produced by AVSimulation, available in the Road Infrastructure Laboratory of the University of Messina. This simulator has the following features:

- 3 29-inch full HD screens (1920×1080 pixels each) with a horizontal field of view of 130° and a frequency higher than 50 Hz;
- a steering wheel characterized by a force feedback sensor to simulate the rolling motion of wheels and shocks;
- sound effects reproduced through several speakers and subwoofers;
- the SCANeR® studio software, used to design tracks, generate the environmental context and run trials;
- data collected with a frequency of 10 Hz;
- a family car powered by a 130 hp gas engine, with 6 manual gears and automatic clutch.

Figure 1. The driving simulator of the Road Infrastructure Laboratory in Messina (Italy)

2.3. Characteristics of the experimentation

The testing road, characterized by a succession of transition curves (in and out clothoids and a residual circular arc) and straight segments, is 4862 m long. Some elements of the alignment were considered in the analysis. In detail, there are 3 curves with radius R = 120 m (C_1), followed by 2 with R = 180 m (C_2), and finally 3 curves with R = 240 m (C_3). These 8 curves, with the same deviation angle equal to 50°, are fully in compliance with the Italian Road Standards (MIT 2001). In Table 1, the geometrical features of the 3 types of curves are provided, together with the length of 3 recurrent tangents: in particular, L_1 relates to C_1, L_2 to C_2, and L_3 to C_3. The alignment presents other geometrical elements not involved in the statistical analysis because the motion in these segments could not exhibit stationary features useful to guarantee a good reproducibility of the results.

In Figure 2, the reader can notice some elements (tangents and curves), named L_x and R_x. The 1st elements were not included because along there the driver, starting from rest, strongly accelerated, not in compliance with the effective geometrical characteristics of that segment. Similarly, the tangents between curves with different radii, named L_x too, were excluded from the ANOVA, since their length is different from L_1, L_2, and L_3 and depends on the length of the closest curves. In simple terms, the levels of the independent variable L should be increased from 3 to 5 (as L_x is equal to 113 m between C_1 and C_2 and to 50 m between C_2 and C_3), with a critical reduction in the reliability of the ANOVA results.

The curves and straights with the subscript x are those at the ends, when the vehicle started from rest or had to arrive at a speed equal to zero. For this reason, they were not included in the statistical analysis.

Table 1. Main characteristic of the road section

Geometrical elements	Radius of the curve [m]	Overall length of the transition curve [m]	Length of the tangent [m]
C_1	120	145.72	–
C_2	180	208.08	–
C_3	240	264.44	–
L_1	–	–	146.58
L_2	–	–	80.60
L_3	–	–	20.71

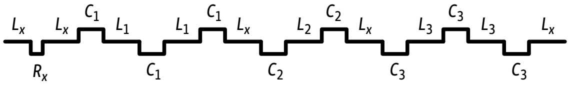

Figure 2. Testing road in an abstract scheme

2.4. The drivers' sample

The driving tests involved 25 users, between 21 and 29 years old. All the drivers have already 3 years of driving experience, without critical road accidents and in absence of pathologies that may negatively influence their driving behaviour. The experimental phase was characterized by the following steps:

- complete a pre-drive questionnaire;
- drive on the 1st pre-selected track (the duration of this step was subjective, since the driver keeps driving until he felt comfortable with the driving commands);
- drive on the main track (for about 10 min);
- complete a post-drive questionnaire.

By the analysis of the post-drive questionnaire, it was evident that 4 users were affected by nausea while driving. Then, their results were discarded and the final processed sample was made up of 21 users.

2.5. Statistical design

Since each user is measured more than once under all the levels of the independent variables, the authors performed 3 different one-way ANOVA factorial design within subjects with the following characteristics:

- *A1*: *one-way ANOVA No 1*:
  - independent variable: curve (3 levels: C_1 (R = 120 m), C_2 (R = 180 m), C_3 (R = 240 m), according to Table 1};
  - dependent variable: average of CO_2 measures [g/s] along the geometrical element (the curve);
- *A2*: *one-way ANOVA No 2*:
  - independent variable: tangent (3 levels: L_1 (*length* = 146.58 m), L_2 (*length* = 80.60 m), L_3 (*length* = 20.71 m), according to Table 1);
  - dependent variable: average of CO_2 measures [g/s] along the geometrical element (the tangent);
- *A3*: *one-way ANOVA No 3*:
  - independent variable: curve and the following tangent (3 levels: C_1&L_1 (*length* = 292.30 m), C_2&L_2 (*length* = 288.68 m), C_3&L_3 (*length* = 285.15 m), according to Table 1);
  - dependent variable: average of CO_2 measures [g/s] along the geometrical element (the curve and the following tangent).

The reliability of the results depends on the satisfaction of the assumptions on which the ANOVA analysis relies. In this case, the assumptions regard the following:

- the dependent variable must be measured at the continuous level. In this case, the measures of the indices are expressed in [g/s], i.e. in a continuous way;
- the independent variable should consist of at least 2 related groups, meaning that the same subjects are present in both groups. They have been divided into 3 levels, respectively, in every of the 3 one-way ANOVA;
- the observations are independent;
- absence of significant outliers;
- tests for normality by means of residuals;
- checks for the sphericity, i.e., the variances of the differences between all combinations of related groups were equal.

When these conditions are violated, the Mauchly's sphericity test were performed, adjusting the analysis by a Greenhouse–Geisser correction.

Since the authors must perform 3 one-way ANOVA there is a pair of null or alternative hypotheses, as follows:

- *H0*: the means of the independent variable groups are equal;
- *H1*: the mean of the independent variable groups are different.

However, if an ANOVA test shows significant results, the analysts cannot know where those differences lie. In these cases, the post-hoc Tukey's HSD test is used to find out which specific groups' means (mutually compared) are different.

2.6. Emission calculation using the driving simulator

The forecasting of fuel consumptions and CO_2 emissions is hard to be represented through an explicit equation, since it depends on the engine mapping and on a series of mechanical and electrical features that car industries maintain confidential. The SCANeR® software installed on the driver simulator of the University of Messina uses the "Vehicle" modulus to control the vehicle dynamic. In this modulus, there is an advanced management model of the engine component, named CALLAS (in French: *Couplé A La Limite d'Adhérence au Sol*). This model is used in high-quality simulators for its high level of detail and realistic driving, aiming to develop, evaluate, and validate vehicles in complex environmental contexts.

In this study, it is important to define a vehicle model able to process and export information related to the engine load, fuel consumption, and CO_2 emissions. As mentioned in the Introduction paragraph, it is easier to refer only to CO_2 emissions and not to other elements, which, however, will undergo the same proportional variations.

These models are not based on explicit equations, but on a "fuel consumption mapping", measured in [g/s]. This mapping assigns to each engine regime value [rpm] and effective torque a specific fuel consumption value, by using appropriate interpolations. The user can customize the mapping in terms of the unit for fuel consumption [g/s] and/or by selecting a linear or spline interpolation. An opportune coefficient allows, then, the analysts to transform the fuel consumptions in CO_2 emissions, as a function of the triggered chemical reactions. In this research context, a "Small family car" has been selected as a reference vehicle (in Table 2 the related engine mapping is provided). Then, at each time t_i, the measured values of rpm and torque are used to estimate the fuel consumption.

As anticipated in the Section 1 (Introduction), the GHG emissions include several elements, some of which are more dangerous than CO_2 for their higher GWP.

In this research, only the CO_2 was considered as it was easily calculated by the engine mapping of the simulated vehicle used in the tests. In literature, some direct correlations between CO_2 and other GHGs, in terms of GWP, are available. For example, CH_4 and N_2O present show 28 and 265 times higher effects on GWP than CO_2. However, these relationships cannot be adopted as simple multipliers in the same context, as roughly done in some recent studies, since the emissions of different elements depend on specific conditions. For instance, CH_4 is produced by intensive farms, carbon mines, quarries, but less by transport infrastructures. Then, since calculations of CO_2 in this research are not based on literature correlations, the same decision is taken for the other gases. In future studies, the other emission elements will be accurately calculated in the simulated and real environments, to define a more accurate identification of the GHG as a function of the road geometry. However, as previously stated, the emissions of other gases as a function of the horizontal geometry may be considered proportional to CO_2.

3. Results

As a general example, Figure 3 represents the trend of the CO_2 instantaneous values during driving on a segment of the road. To evaluate the function, the alignment curvature is represented out of scale in the same graph. It should be clarified that the “stepped” trend of the curvature representation is due to the data sampling in the time domain. Moreover, the perfect symmetry between the 2 clothoids can be reached only in the case of absolutely constant speed. This figure represents driving along Curve 2 (C_1, R = 120 m) for User 2 and may evidence some recurrent driving behaviours perceived in the users’ sample.

In detail, this figure was introduced to examine the relationship between the CO_2 emissions and the road horizontal geometry during one driving test, at a single geometric element scale. As already said, the CO_2 emissions are affected by the succession and the characteristics of curves and tangents. Figure 3 evidences that the emissions are the lowest at the end of the tangent and the beginning of the curve, while they become stable towards the highest values at the end of the curve and the beginning of the tangent.

As the quantity of the CO_2 emissions is directly proportional to the longitudinal acceleration, it is possible to infer that the driver in this case accelerates in curves and slowdown in the tangent.

The absolute minimum and maximum values and the extension of the (almost) constant CO_2 zones depend on the radius value and the lengths of curves and tangents. This evidences that an appropriate choice of the related values in the design phase may, thus, contribute to emission control.

The value of CO_2 emissions is calculated with a sampling frequency of 1/10 s and measured in [g/s].

The relationship between the geometry and the emissions is not univocal but depends on the driving behaviour along the road and, in particular, on the speed variations adopted by the driver, according to his perception of the environmental conditioning.

Data related to the CO_2 emissions has been referred to the single elements of the alignment and the average values for curves and tangents are provided respectively in Tables 3 and 4. Then, in Table 5 the values concerning the couples of subsequent curves and tangents are reported.

The data of the 21 drivers were used to perform 3 one-way ANOVAs, indicated in the following as A_1, A_2, and A_3. As anticipated, each ANOVA considered a different independent variable, respectively represented by the curves (Table 3), the tangents (Table 4) or the summation of curves and tangents (Table 5). The independent variable is always represented by the average value of CO_2 along the curves alone, the tangents, or their summations.

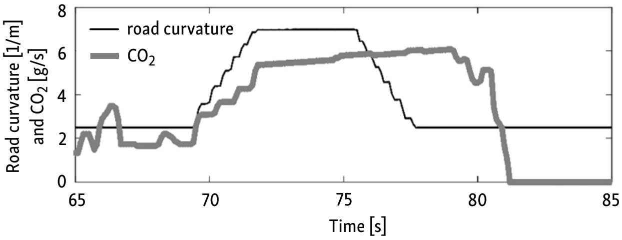

Figure 3. A typical trend of the CO_2 emission along the road

Table 2. Engine mapping [g/s] for the “Small family car”

Engine speed [rpm]	Engine load [%]										
	0	10	20	30	40	50	60	70	80	90	100
200	282.65	270.89	270.89	259.11	259.11	247.33	247.33	235.55	247.33	259.11	270.89
1000	282.65	270.89	270.89	259.11	259.11	247.33	247.33	235.55	247.33	259.11	270.89
1500	270.89	259.6	259.6	248.31	248.31	237.03	237.03	225.74	237.03	248.31	259.6
2000	270.89	259.6	259.6	248.31	248.31	237.03	237.0J	225.74	237.03	248.31	259.6
3000	259.11	248.31	248.31	237.52	237.52	226.72	226.72	215.92	226.72	237.52	248.31
4000	259.11	248.31	248.31	237.52	237.52	226.72	226.72	215.92	226.72	237. 52	248.31
5000	247.33	237.03	237.03	226.72	226.72	216.42	216.42	206.11	216.42	226.72	237.03
6000	247.33	237.03	237.03	226.72	226.72	216.42	216.42	206.11	216.42	226.72	237.03
6350	235.55	225.74	225.74	215.92	215.92	206.11	206.11	196.3	206.11	215.92	225.74

The assumptions of the ANOVA have been all satisfied. Among these, in Figures 4–6 the quantiles of the residuals in the ANOVA (A_1, A_2, and A) are plotted to verify the normal distribution. The normal probability plot of the residuals should approximately follow a straight line and this hypothesis is quite satisficed.

All the results are reported:

- A_1: there is an important difference in the average of the levels of the curve variable – $F(2.145) = 11.83$, $p < 0.0001$. As evidenced in Table 6, the Tukey's HSD test revealed remarkable differences in the CO_2 emissions between the curve C_1 (R = 120 m) and the others (C_2, R =180 m and C_3, R = 240 m), with p-values equal respectively to 0.0163 and 0.0073. Between C_2 and C_3, on the contrary, there are no significant statistical differences (p-value= 0.9501). Figure 7, depicting the estimation of the marginal averages of the various levels of the independent variable, graphically evidences this result, in which the CO_2 emissions [g/s] along the curve C_1 are less (4.64 g/s) than the curves C_2 and C_3 (6.44 and 6.62 g/s, respectively);
- A_2: the H0 hypothesis (the means of the independent variable groups are equal) is confirmed by the ANOVA results – $F(2.165) = 0.89$, $p = 0.4133$. Then, the CO_2 emissions along the 3 tangents (L_1, L_2, and L_3) are similar and, thus, the analysis did not continue with the Tukey's HSD test;
- A_3: there is a significant difference in the average of the levels of the curve and tangent variable – $F(2.145) = 6.5$, $p < 0.002$. As evidenced in Table 7, the Tukey's HSD test revealed remarkable differences in the CO_2 emissions between Couple 1 (C_1&L_1) and the others (C_2&L_2 and C_3&L_3), with p-values equal respectively to 0.0026 and 0.0170.

Table 3. Data base regarding only one of the drivers, used for A_1

Observation	Subject	Independent variable: curve	Dependent variable: average CO_2 [g/s]
1	User 1	C_1	7.229
2	User 1	C_1	7.795
3	User 1	C_1	8.763
4	User 1	C_2	6.496
5	User 1	C_2	6.667
6	User 1	C_3	8.780
7	User 1	C_3	7.911
8	User 1	C_3	11.258

Table 4. Data base regarding only one of the drivers, used for A_2

Observation	Subject	Independent variable: tangent	Dependent variable: average CO_2 [g/s]
1	User 1	L_1	6.948
2	User 1	L_1	7.844
3	User 1	L_1	5.291
4	User 1	L_2	5.512
5	User 1	L_2	9.609
6	User 1	L_3	8.952
7	User 1	L_3	10.617
8	User 1	L_3	11.654

Table 5. Data base regarding only one of the drivers, used for A_3

Observation	Subject	Independent variable: curve and tangent	Dependent variable: average CO_2 [g/s]
1	User 1	C_1&L_1	14.177
2	User 1	C_1&L_1	15.639
3	User 1	C_1&L_1	14.055
4	User 1	C_2&L_2	12.008
5	User 1	C_2&L_2	16.276
6	User 1	C_3&L_3	17.732
7	User 1	C_3&L_3	18.527
8	User 1	C_3&L_3	22.912

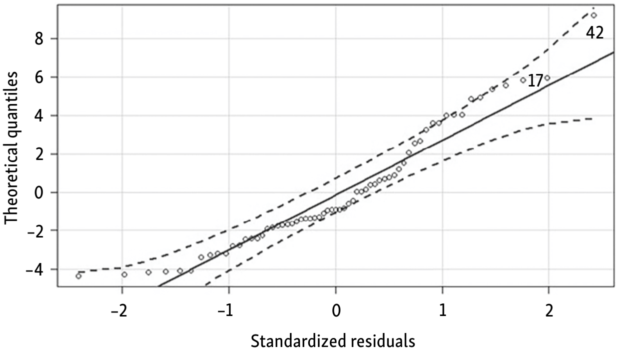

Figure 4. Normality plot of the residuals referred to A_1

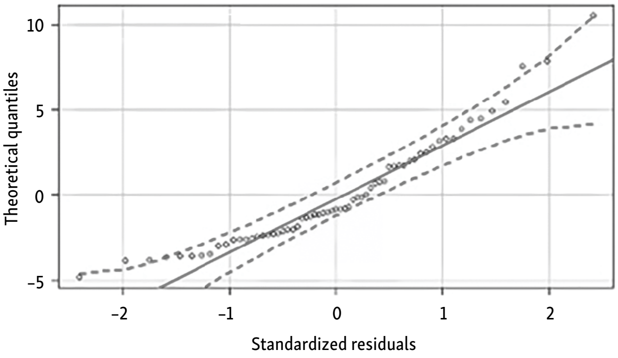

Figure 5. Normality plot of the residuals referred to A_2

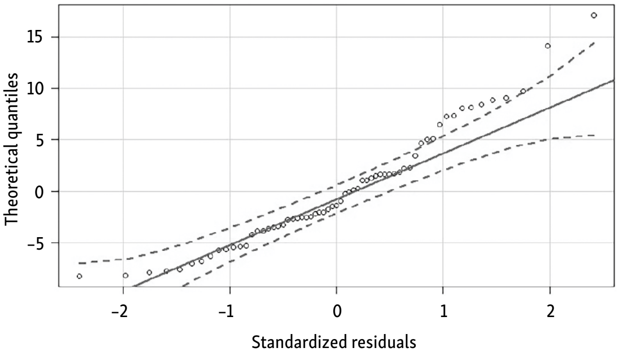

Figure 6. Normality plot of the residuals referred to A_3

Between couples $C_2\&L_2$ and $C_3\&L_3$, instead, there are no significant statistical differences (p-value= 0,6563). Figure 8, depicting the estimation of the marginal averages of the various levels of the independent variable, graphically evidences that the CO_2 emissions [g/s] along $C_1\&L_1$ (9.55 g/s) are less than other sections (>11.55 g/s).

Table 6. Contrasts between all the levels of the independent variable curve (this table is referred to the dependent variable CO_2 averaged on the length of the considered curve)

Element 1	Element 2	p-value
C_1	C_2	0.0163
C_1	C_3	0.0073
C_2	C_3	0.9501

Table 7. Contrasts between all the levels of the independent variable curve and tangent (this table is referred to the dependent variable CO_2 averaged on the length of the considered curve and the following tangent)

Element 1	Element 2	p-value
$C_1\&L_1$	$C_2\&L_2$	0.0026
$C_1\&L_1$	$C_3\&L_3$	0.0170
C_2&L2	$C_3\&L_3$	0.6563

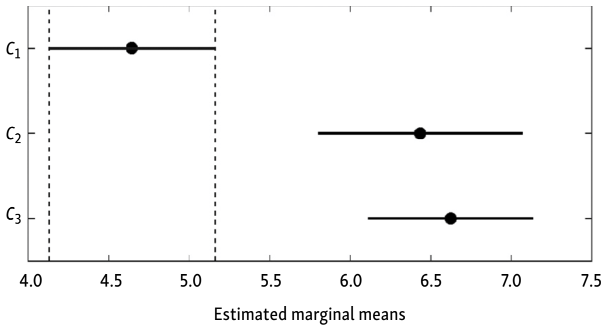

Figure 7. Estimated marginal means for the dependent variable CO_2 (the circular black marker indicates the mean value, while the interval represents the used confidence level (0.95))

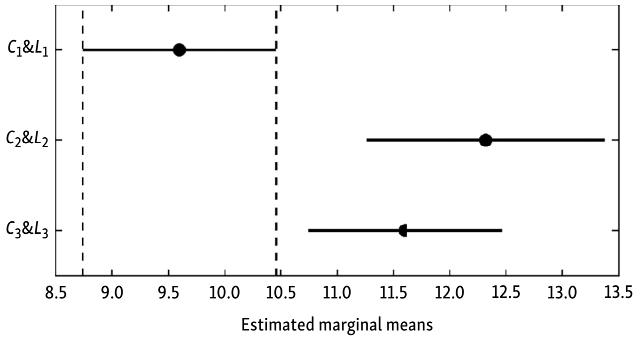

Figure 8. Estimated marginal means for the dependent variable CO_2 (the circular black marker indicates the mean value, while the interval represents the used confidence level (0.95))

4. Discussions

The problem of controlling fuel consumption and CO_2 emissions can be analysed from different points of view. Although the highest responsibilities interest the automotive sector, there are other involved subjects that, despite their secondary roles, are for sure not marginal in the phenomenon quantification. Beyond users preferring more sustainable transport modes, the role of the road designer may be determinant in the environmental balance in terms not only of resource consumption, but also of emissions during construction and, mainly, in the use phase of the infrastructure. The construction phase, even if characterized by intense environmental impacts, represents only a small fraction of the overall life cycle of the road, typically lasting for several decades.

In truth, the relationship between the road profile and the vehicle performance has been studied for decades, with satisfactory results. In detail, these researches aimed to identify the ratio between length and grade of a road section to avoid slowing effects on heavy vehicles and, thus, to guarantee a specific quality level for traffic. Consequently, some considerations regarding road profile and emissions were provided in different studies.

The horizontal geometry of a road relies on design criteria that may balance needs of functionality and efficiency with users' safety. In this regard, the designers tend to define an alignment with good consistency between following elements in terms, mainly, of the driving speed. The strategy of assuring good consistency, imposed by all the road design standards, is perfectly in compliance with the emission issues. Indeed, the fewer the speed variations, the lower the fuel consumption and, thus, the GHG emissions. The studies by Llopis-Castelló *et al.* (2018a, 2018b, 2019) and Nobili *et al.* (2019), already discussed in the Section 1 (Introduction), rely on this hypothesis. Unfortunately, some of these conclusions are based on the validity of the operating speed models and on some consistency criteria that are acceptable only in road contexts very similar to those for which they were derived and must be carefully verified.

With these premises, an alignment representative of a common rural road type in Italy was defined, including some transition curves with sufficiently different radii (120, 180 and 240 m).

The simulated environment allowed the authors to accurately control the problem variables, such as the lighting conditions, the weather, the traffic flows, and the grade, to leave the driving behaviour (and thus the CO_2 emissions) related to the horizontal geometry only. The results are in part in compliance with literature, but suggest some considerations discussed in the following.

1st, the example in Figure 3, concerning the trend of the instantaneous CO_2 emissions of a single user along a curve, is strongly representative of the entire sample of drivers along the entire alignment, as confirmed by the following statistical analysis. Although this figure represents only a small part of the experimentation, it evidences a driving behaviour quite different from that considered in the road standards. Whether the previously listed hypotheses were confirmed in the tests, all the curves in the alignment would have been driven without longitudinal acceleration, with reduced CO_2 emissions. Instead, the driver, at the beginning of the spiral, when he can fully interpret the visual information from the curve, starts accelerating and keeps this regime beyond the end of the curve, up to one point of the following tangent. At this point, he perceives the following curve and, as he is not able to fully interpret it with so advance, decreases the vehicle acceleration up to a real deceleration, determining a minimum CO_2 emission. After entering in the next curve and having fully interpreted it, he restarts the cycle of acceleration and subsequent deceleration. This behaviour was statistically confirmed by 3 different one-way ANOVAs, but it is deductible only for roads with similar geometry and, therefore, cannot be generalized.

These analyses proved a different driving behaviour between the 1st curve (R = 120 m) and the others (R = 180 m and R = 240 m, respectively). This means that, below a certain radius, there is effectively a lower CO_2 emission. This value was not precisely identified (as it requires a more comprehensive experimental campaign) but, very likely, it is included in the 120…180 m range. Beyond this value, the curve does not condition the driving behaviour and, consequently, the CO_2 emissions are not influenced by it. This confirms the observed phenomenon, provided in Figure 3. The curve called C_1 (R = 120 m) is characterized by a radius such as to induce more cautious behaviour on the part of the driver who avoids sudden accelerations with the consequence of causing lower emissions than the other 2 types. The minor radius (C_1, 120 m) represents a constraint in developing excessive accelerations when the driver is along the tangent before the curve. While this tangent is driven, even though in acceleration, there are lower emissions than the other larger curves. This can be seen in Figure 7, where remarkably lower values of average CO_2 for C_1 are identified. The absolute CO_2 value is not investigated and further discussed, since it is an average value for the entire curve (in and out clothoids plus circular curve) and the research focuses on relative considerations among different elements.

With A_2, characterized by the independent variable Tangent, the hypothesis H0 was confirmed by the high p-value (0.4133). This means that differences among the averages are random. Then, this result requires deeper considerations, since it is expected that different lengths of tangents (from L_1= 146.58 m to L_3= 20.71 m) may determine different CO_2 values. On the contrary, along all the tangents the driver exhibited a 1st section in acceleration and a 2nd one at constant speed or in deceleration, determining a very limited average CO_2 emission, similar for the 3 tangents. This conclusion (currently limited for these lengths only) is partially in contrast with theoretical consistency studies, in which the tangent is considered as a critical geometrical element for CO_2 emissions, because it may determine high accelerations.

Through the 3rd one-way ANOVA (A_3), instead, curves and following tangents have been studied together, to identify eventual "couple" phenomena. The result, provided in Figure 8, does not provide any further advantage in the phenomenon understanding respect to A_1. In this case too, there is a difference between the average CO_2 emissions of the 1st couple (C_1&L_1) and the others. Considering that the tangents themselves do not provide significant statistical contributions, this difference can be related to the curves only.

From the experimentation and, mainly, from the statistical analyses some doubts regarding the "blind" application of the design consistency models raise. In fact, they cannot be accepted and applied slavishly, but should be critically verified in any specific case. The excessive speed may be limited by the presence of the curve, only whether the circular arc radius has quite low values. Otherwise, the acceleration and, in turn, the CO_2 emissions remain high. However, as already said, the deduced results cannot obviously be generalized.

In the future steps of this research, the authors might investigate different geometries to identify specific radius ratios, lengths of curves and tangents, for directing the designers towards the definition of a sustainable road.

However, the experimentation in a simulated environment was confirmed as an optimal instrument to validate a road, because, as in this case, it assures full control of the interested variables. In any case, parallel verifications and checks on real roads may also be interesting and helpful for further confirmation of the outcomes.

Furthermore, it should be considered that the regulations containing road design criteria aim to guarantee users' safety and reach a certain level of functionality. Their main goal is determining a succession of suitable geometric elements that may ensure a certain consistency in speeds and visibility and, in parallel, reliable and safe completion of the main manoeuvres (stopping, passing, lane change). This guarantees traffic flows below the road capacity and may avoid sudden manoeuvres that can cause potential accidents.

Very often, especially in rural areas, to avoid huge environmental impacts for a road infrastructure - in terms of pollution, earthworks, bridges, consumption of non-renewable resources, etc., its construction is constrained by further rules, sometimes in contrast with the primary safety and functionality requirements.

Unlike other impacts, however, the aim of limiting emissions is perfectly coordinated with these primary goals, since sections characterized by very limited speed variations, as seen, may reduce the GHG emissions and, at the same time, guarantee a better level of service and higher safety standards.

However, any development or extension of the design procedures and criteria must always take into account all the relevant aspects to assure a comprehensive achievement of both project goals and infrastructure benefits, in a perfect balance of all the involved variables.

5. Conclusions

This research aimed to evaluate the eventual influences of the road horizontal geometry on GHG emissions and, in particular, on CO_2.

The obtained results evidence the influence of different configurations of the horizontal geometry on CO_2 emissions and, mainly, a certain approximation of traditional models for determining road consistency. The curves, traditionally considered as constant speed elements, determine the higher CO_2 emissions, while the tangents, generally considered as responsible for the main speed variations and, thus, of emissions, are instead driven in 2 different ways. The 1st part is driven in acceleration, while the 2nd in a conservative way, to adequate the speed to the following curve. Whether this driving behaviour is confirmed even in other experiments, some existing models for calculating the operative speed should be revised.

The problem evidenced in this research is that the traditional procedures for operative speed evaluation, on which the international standards rely, are based on very simplistic hypotheses (as, for instance, constant speed along curves).

The proposed methodology could be codified in the road standards, to constitute a reference procedure for verifying the design of novel roads or maintenance activities of existing infrastructures, in terms of environmental compliance of the infrastructure.

Although this research verified that the value of some geometric features (radii, lengths of curves and tangents) influences the driving behaviour, specific threshold values, beyond which the performance is critical, were not identified.

Consequently, the future developments of the research will consider a large-scale experimental phase in a simulated environment, to determine CO_2 emission in the most frequent configurations of the horizontal geometry. Once some generally valid laws are defined, the same model will be verified in a real context. The following study will also focus on the quantification of the emissions in terms of the various components of the Green House Gases, since they may be more dangerous than carbon dioxide.

Further, the relevant introduction in the vehicle market of ADASs could guarantee a higher control of consumptions and, thus, of emissions. Evaluating whether and how much these systems can influence driving behaviour and, thus, reach the fixed goals will be interesting for the development of the research.

Declaration

This research was based on an experiment carried out in a simulated environment with drivers. We did not require prior approval from our IRB for the following reasons:

- the sample is made up of adult users who have signed the consent to the trial;
- a questionnaire administered before the trial ascertained any negative dispositions of the user towards driving, a further questionnaire administered after the experiment was aimed at highlighting any negative repercussions on the psycho-physical state of drivers (car sickness);
- the purpose of the research was clearly stated in the questionnaire administered before the trial;
- the type of experimentation would not have had any negative consequences on the psycho-physical conditions of the users;
- all data was processed anonymously, without making any personal reference to individual drivers.

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