Impact of road alignment on fuel consumption and gas emissions – experimental and analytical research

Dražen Cvitanić[1], Deana Breški[1], Biljana Maljković[1]

[1] University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Department of Transportation, Matice hrvatske 15, 21000, Split, Croatia

Corresponding author:
Dražen Cvitanić
cvitanic@gradst.hr

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Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA

Abstract:
This research analysed the impact of road alignment on the fuel consumption and gas emissions of a vehicle driven at a free-flow speed by an 85th percentile driver. The field experiment included constant and free-flow speed rides by a personal car equipped with a high-performance (10 Hz) Bluetooth global position device and on-board diagnostics connector, with which the travel path, speed, acceleration, and consumption data were recorded. Regression analyses of the dependence of free-flow speed and fuel consumption on the geometric characteristics of the road (curvature, length, longitudinal slope, etc.) resulted in the formation of a reliable model that could compare alternative road designs for a given corridor in terms of route economy and safety. The main parameters contributing to the consumption on tangents were the slope and radii of adjacent curves. For constant speed, the slope was the only geometric parameter that had an impact on fuel consumption.

Keywords:
Two-lane road; fuel consumption; alignment characteristics; free-flow speed; design consistency; GPS

1 Introduction

The sectors that contribute the most to air pollutant emissions in Europe are transport, residential, commercial, institutional, energy supply, manufacturing and extractive industry, agriculture, and waste [1]. The transport sector produces approximately 30 % of the carbon dioxide emissions. Road transport produces 72 % of these emissions, of which passenger cars account for 60,7 %, whereas rural road traffic accounts for more than 50 % [2]. According to the aforementioned data, road traffic significantly affects air quality due to vehicle gas emissions; therefore, researchers from various fields have started to study the causes and possible countermeasures to reduce this negative impact on the environment. However, few researchers have analysed the impact of road alignment on fuel consumption and gas emissions, and those that have mainly focused on the impact of slopes. Boriboonsomsin and Barth [3] used analytical and experimental approaches to analyse the fuel consumption of a light-duty vehicle travelling at a constant speed in level, uphill, and downhill segments. The fuel consumption on level segments was up to 20 % less than that on the analysed hilly routes, which consisted of uphill and downhill segments with the same slope of 6 %. This means that at the same speed, fuel can be saved by selecting a longer but flat route, given that it is less than 20 % longer than a hilly route. Demir et al. [4] analysed a few emission models and concluded that the application of an appropriate slope design has a significant impact on reducing fuel consumption. Park and Rakha [5] analysed the impact of a slope in the range of -6 to +6 % when cruising at a constant speed. They used a simulation model to estimate the speeds and accelerations in the calculation of consumption and emissions because these are the most influential variables that determine the required engine power. They concluded that consumption and emission rates significantly increased, even for a 1 % increase in slope. Ko et al. [6] created vehicle speed profiles for various slope values (up to 9 %) and used a motor vehicle emission simulator to estimate consumption and emission. Their results showed that fuel consumption and gas emissions increased with increasing speed owing to the longitudinal slope.

Ko [7] also analysed the impact of the horizontal curve radius on fuel consumption. The study concluded that lowering the radius from the minimum value according to the Green Book [8] resulted in a significant increase in fuel consumption and gas emissions owing to larger speed changes.

Llopis-Castelló et al. [9] studied the impact of road alignment consistency on vehicular CO2 emissions. They used the continuous speed data recorded on 47 homogeneous road segments obtained in a previous study by Pérez-Zuriaga et al. [10]. Homogeneous road segments were distinguished according to their curvature change rate, whereas emissions were previously estimated by the same researchers [11] using the VT-Micro model [12]. According to their analysis, emissions decreased by up to 30 % as the consistency level increased from poor to good.

In conclusion, numerous studies have analysed the impact of road vertical alignment, whereas only a few studies have focused on the effects of horizontal alignment consistency on fuel consumption and gas emissions. However, many studies have analysed the impact of alignment consistency on road safety [13-16]. The common conclusion of these studies is that the main cause of accidents on two-way rural roads is inconsistent alignment. For consistent road alignment, there is no need for a sudden speed change, which contributes to greater road safety. According to several studies [5, 6, 17-19], a vehicle travelling at a uniform speed consumes less fuel than a vehicle travelling at a variable speed. Hence, it can be concluded that a horizontal alignment design with good consistency makes the road not only safer but also more economical and environmentally friendly.

2 Objective and hypothesis

According to the literature, several studies have dealt with the influence of vertical road alignment, especially slope, on consumption and emissions, but only a few studies have dealt with the impact of horizontal alignment. In addition to the slope, this research focused on different geometric characteristics of horizontal alignment (deflection angle, radius, curve length, tangent length, and radius before and after the analysed element) that could have an impact on driving speed and acceleration and consequently on consumption. Test drives with constant and free-flow speeds were conducted on a two-way state road, and the analysed data indicated higher fuel consumption for drives with fluctuating speeds than for drives with uniform speeds, which confirms the results from the literature. The hypothesis of this research is that it is possible to estimate the influence of alignment elements on the relative fuel consumption and gas emissions of a particular vehicle driven with a free-flow speed by the 85th percentile driver. The 85th percentile driver is defined as a driver whose average driving speed in the observed section is lower than the average speed of 15 % of the fastest drivers. The 85th percentile driver was selected from a previous field survey conducted by the authors [20], in which the continuous speed profiles of 20 drivers (performed with personal cars equipped with GPS devices) were recorded on a road segment that will also be considered in this research. The first difference from previous studies is that fuel consumption, as well as speed and acceleration profiles, are not estimated with the model but are actually measured in the field with an equipped test vehicle. These measured data, together with other geometric characteristics of road alignment, were used in regression analyses, which resulted in a fuel consumption model for free-flow speed on tangents for successive alignment elements. Therefore, the second difference is that the fuel consumption is related to a particular alignment element and not to road sections with a similar curvature change rate. The resulting model does not require complex measurements or simulations of the vehicle speed and acceleration profiles but only a few geometric characteristics of the adjacent road elements. Therefore, it can be used in road design processes in which different route variants can be compared in terms of fuel consumption. Using spreadsheet software, consumption can be calculated for different values of adjacent element dimensions, providing the option of choosing the elements that will have a less negative impact.

3 Field experiment

Field rides on a segment of the two-way, two-lane state road were conducted to collect speed, vehicle path, acceleration, and consumption data. Rides were made on weekdays under good weather conditions. Road alignment data were derived from the main road design and verified using survey data. The analysed segment contained 87 horizontal curves with tangents between them (Table 1).

Table 1. Road segment characteristics

Element	Geometric characteristics	Min.	Max.	Mean	Standard Deviation
Curve	Radius (m)	75	1010	300	225
	Length (m)	40	440	147	99
	Deflection (º)	3	142	37	28
	Superelevation (%)	2	7	3,4	1,4
Tangent	Length (m)	4	683	95	103
Vertical alignment	Slope (%) - one direction	-5,5	7,0	0,2	2,2

To achieve free-flow conditions, data were recorded on the road segment with a low traffic volume and with no intersections. This segment of the road was previously used to gather the data required for the development of operating speed prediction models on tangents and curves [20]. Because the goal of this research was to analyse the relative impact of alignment characteristics on fuel consumption, it was decided to conduct a few test drives with a personal car. The 85th percentile driver from the aforementioned research drove his own car (Suzuki SX4 S-Cross) on the selected road segment in both directions. The data relevant to this study included speed, acceleration, deceleration, mass air flow (MAF), and alignment characteristics (curve radii, superelevations, slopes, deflection angles, and lengths of horizontal alignment elements). A block diagram of the experiment and data analysis is shown in Figure 1.

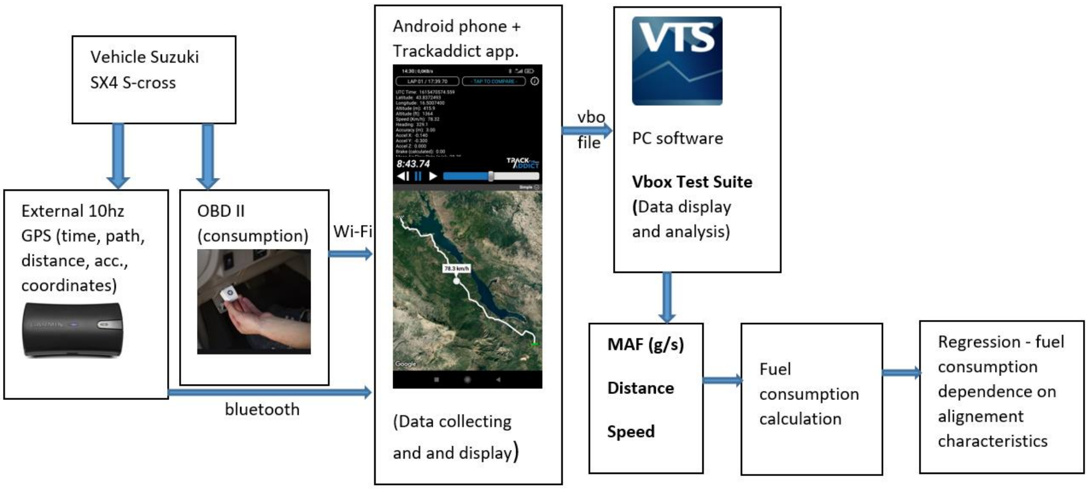


Figure 1. Block diagram of the research architecture

The test rides were performed using a high-performance (10 Hz) GPS device and on-board diagnostics (OBD II) connector. The OBD II unit was connected to the vehicle and monitored real-time data from the vehicle sensors. The data were collected on an Android tablet via the Trackaddict application [21] using OBD II and a 10-Hz GPS and then exported to VBO format files.

Data from the VBO files were analysed in the office using the VBOX Test Suite PC software [22]. The VBOX Test Suite presented all the data collected on one screen, that is, it showed the vehicle path, elevation, speed, acceleration, deceleration, radii of curve, MAF, and many other indicators (Figure 2). The coordinates at the beginning and end of each horizontal alignment element (tangents and curves) were marked with signs on the vehicle paths. For each element, the average MAF and speed were recorded, where MAF is the mass of air consumed in grams per second. The MAF data were obtained via the OBD II from the sensor and were used by the engine control unit to deliver the proper amount of fuel. Therefore, knowing the speed and MAF made it possible to estimate the vehicle fuel flow FF (l/h) and fuel consumption FC (l/100 km, l/km) as well as CO_2 emissions, as shown by Meseguer et al. [23]:

$$FF(l/\mathrm{h}) = (MAF \cdot 3600)/(AFR \cdot FD) \tag{1}$$

Where:

MAF is the mass air flow (g/s),
AFR is the air-to-fuel ratio,
FD is the fuel density (g/l) presented in Table 2.

Table 2. Fuel type characteristics [23]

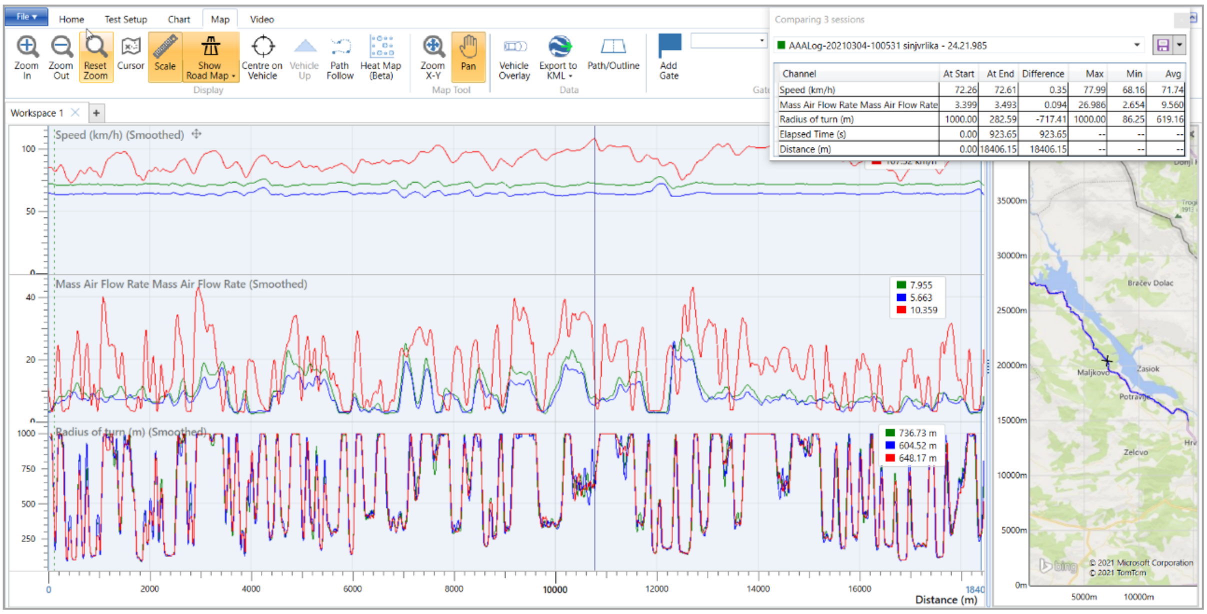
Fuel type	**Ratio by mass - *AFR***	**Fuel Density** (g/dm^3)
Gasoline	14,7:1	820

Fuel consumption can be expressed in litres per 100 kilometres or as instantaneous fuel consumption (IFC) in l/km.

$$FC\left(\frac{l}{100km}\right) = \frac{FF(l/h)}{V(km/h)} \cdot 100 \tag{2}$$

$$IFC\left(\frac{l}{km}\right) = \frac{FF(l/h)}{V(km/h)} \tag{3}$$

The amount of CO_2 generated when burning fuel can be calculated using the atomic masses of carbon and oxygen for a known carbon content in the fuel [23]. This implies that CO_2 emissions are proportional to fuel consumption; therefore, the results of this study are applicable to both parameters. Hence, all the parameters needed for the calculation of average fuel consumption and gas emissions for each alignment element were obtained.



Comparing 3 sessions

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Channel	At Start	At End	Difference	Max	Min	Avg
Speed (km/h)	72.26	72.61	0.35	77.99	68.16	71.74
Mass Air Flow Rate Mass Air Flow Rate	3.399	3.493	0.094	26.986	2.654	9.560
Radius of turn (m)	1000.00	282.59	-717.41	1000.00	86.25	619.16
Elapsed Time (s)	0.00	923.65	923.65	--	--	--
Distance (m)	0.00	18406.15	18406.15	--	--	--

Figure 2. VBOX Test Suite - Graph of data recorded

4 Analysis and results

Table 1 summarises the statistical data of the geometric characteristics (radius, curve and tangent length, slope, superelevation, deflection angle) of a 22 km long road section. The design speed was 60 km/h, and the posted speeds ranged from 60 to 80 km/h, depending on the road curvature. First, two test rides with constant speeds were conducted to analyse the dependence of fuel consumption on the geometric characteristics of the road. The speeds of the test rides were selected between the values of the design and the maximal posted speed limit, that is, 64 km/h and 72 km/h. Subsequently, three free-flow speed drives were conducted using the selected 85th percentile driver to analyse the most significant variables causing the difference in fuel consumption.

Figure 2 presents a graphical display of the data obtained using GPS and OBD II units. The path of the vehicle obtained by GPS is shown on the right-hand side of the figure. On the left side is a diagram with the distance on the X-axis and radius of turn (m), MAF (g/s), and speed (km/h) on the Y-axis. The red lines in the diagram represent the speed, MAF, and path radii for a free-flow speed, while the blue and green lines represent the recorded values for rides with constant speeds of 64 and 72 km/h, respectively. The average values of the recorded data for these rides in the analysed section are presented in Table 3.

One can see that the fuel consumption (l/100 km) was the lowest for a uniform drive with the smallest speed and speed dispersion, whereas it was the highest for a ride with a free-flow speed. The fuel consumption for driving at a 12 % higher constant speed (72 km/h vs. 64 km/h) increased by approximately 8 %. The consumption for driving with a higher constant speed increased for each element of the entire analysed segment.

Table 3. Recorded data statistics

Average Speed (km/h)	**64,28** (uniform drive)	**71,84** (uniform drive)	**90,86** (free-flow drive)
Speed Stand. Dev. (km/h)	1,04	1,06	8,10
Average *MAF* (g/s)	7,96	9,56	17,09
Average *FC* (l/100 km)	3,70	4,00	5,60

Geodetic surveys of roads, highway projects, and aerial images made it possible to obtain recorded data for each road element. The VBOX Test Suite allowed for the marking of a particular section of the road. The software showed the recorded data at the first and last points of the marked region as well as the calculated differences and average values for each ride. The calculated average FC (l/100 km) for every 500 m length of the analysed segment is shown in Figure 3. The average consumption consistently increased as the constant speed increased, whereas the dispersion of FC values was similar for both constant speeds. The positive and negative FC peaks were located on the uphill and downhill segments, respectively.

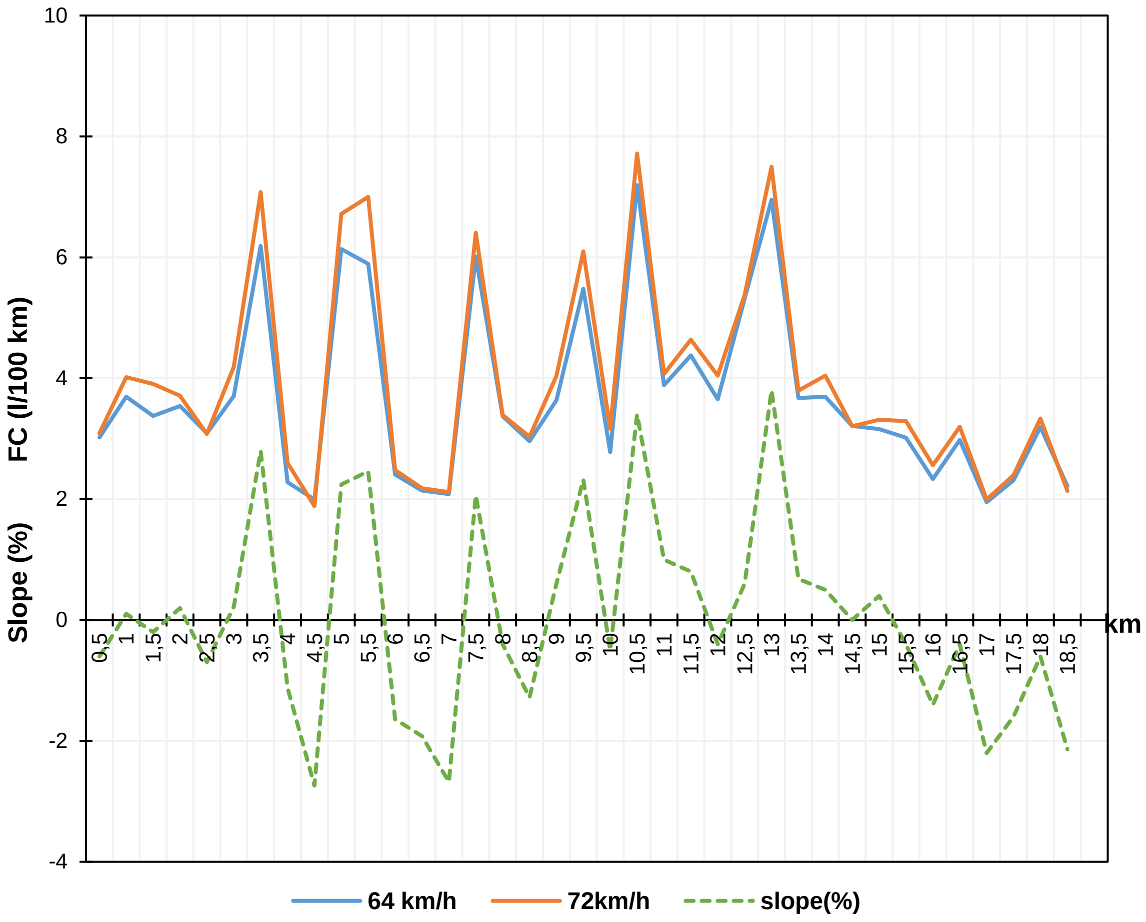

Figure 3. Fuel consumption for constant speeds vs. slope

Figure 4 presents the average FC (l/100 km) vs. slope (%) for each 500 m segment length for all driving speeds. One can see that the FC was significantly higher when driving at free-flow speeds (FFS); however, the shapes of the peak FC values were similar, implying that the slope had a significant impact on FC. The fuel consumption for driving with a free-flow speed, with great speed dispersions caused by the characteristics of alignment, was higher by more than

50 % in comparison to the ride with a constant speed of 64 km/h. This suggests that the consumption for driving at a free-flow speed is indirectly related to the alignment characteristics.

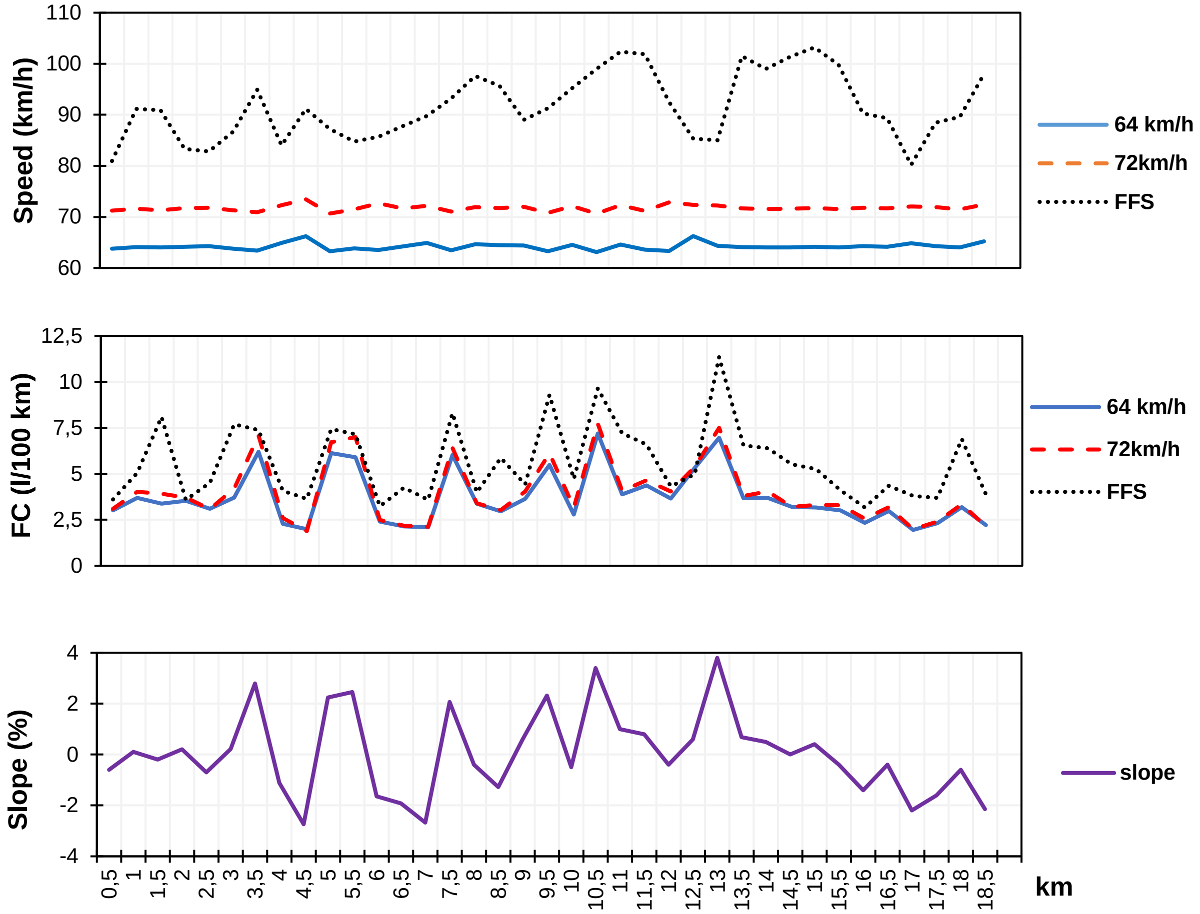

Figure 4. Slope, fuel consumption, and speed for different driving styles

The impact of speed, acceleration, and slope on MAF can be seen in Figure 5.

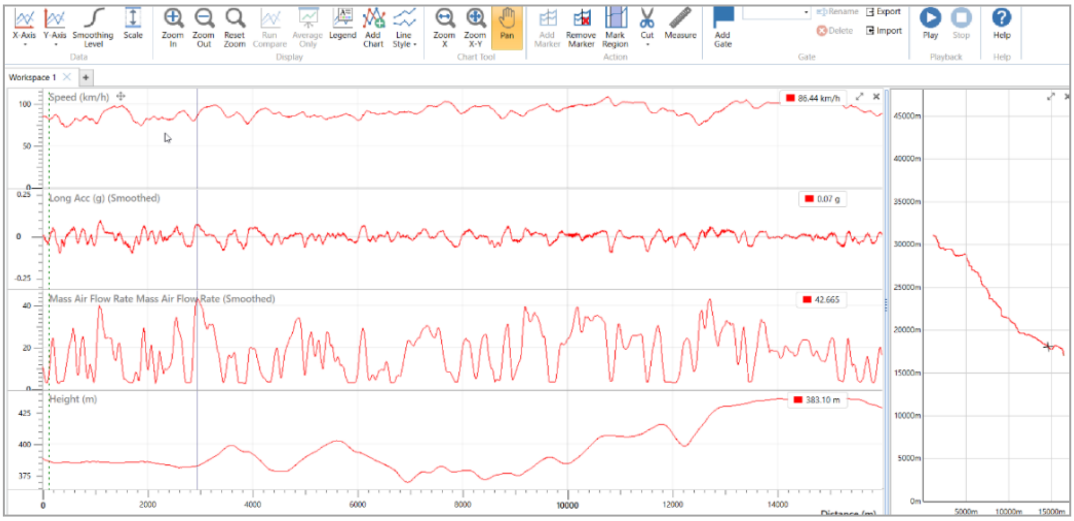

Figure 5. Recorded speeds, accelerations, MAF, and slopes on road segments

The peaks of MAF coincided with the peaks of positive accelerations, and they were higher for uphill segments than for downhill segments. To confirm that fuel consumption is influenced by acceleration, speed, and slope, a regression analysis was performed with the peak value of FC (l/km) as a dependent variable. The resulting coefficient of determination R^2 was high (0,86), and all independent variables had a significant influence, whereas slope and acceleration had the most significant impact on fuel consumption peak values.

4.1 Impact of alignment geometric parameters on fuel consumption

To analyse the possible impact of various geometric characteristics, the MAF (g/s) data for rides with constant speed were collected for each element and imported into the spreadsheet software, together with the geometric characteristics. Subsequently, the average FC (l/km) for each element was calculated. A multiple linear regression analysis on recorded data for a uniform speed of 64 km/h was conducted. The longitudinal slope was the only significant independent variable among all the analysed alignment geometric characteristics (*slope*, deflection angle α, radius R, curve length L, previous tangent length L_{tgb}, radius before and after the analysed element, R_{bef}, and R_{aft}). A summary of the model is presented in Table 4, and the statistics are shown in Table 5.

Table 4. Model summary for the FC regression model (64 km/h - uniform speed)

R	R^2	$\bar{R}^2$	$RMSE$
0,888	0,789	0,786	0,009

Table 5. Statistical analysis results for the FC regression model (64 km/h - uniform speed)

Parameter	Estimate	Standard Error	Standardized Estimate	*t*-statistic	*p*-value
(Intercept)	0,041	0,001	-	38,112	< 0,001
slope	0,008	4,819e-4	0,888	16,618	< 0,001

Dependent Variable: $FC = 0{,}041 + 0{,}008 \cdot slope$

Note: The following covariates were considered but not included: α (º), R (m), L (m), L_{tgb} (m), R_{bef} (m), R_{aft} (m)

After determining the existence of dependence, the study attempted to determine the optimal functional dependence of fuel consumption on the slope. The exponential function described this dependence well, with a high coefficient of determination R^2 of 0,88. This is because fuel consumption increases with a similar intensity for positive slopes as it decreases for negative slopes (Figure 6). This implies that fuel consumption is higher on uphill segments, followed by downhill segments of the same length and slope, than on level segments, as concluded by Boriboonsomsin and Barth [3] and Ko et al. [6].

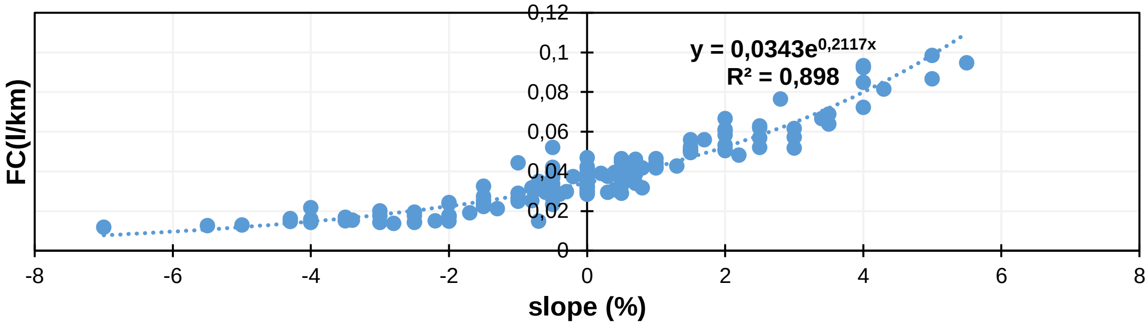

Figure 6. Fuel consumption for rides with constant speed vs. slope

For example, Figure 6 shows that the consumption (measured and estimated) on level segments was approximately 3,5 l/100 km. On uphill segments with a slope of 4 %, the consumption was approximately 2,3 times higher, whereas on downhill segments with the same slope, it was approximately 2,3 times lower than on level segments. This means that the average consumption on the uphill segment, followed by the downhill segment of the same length and slope (4 %) was 4,8 l/100 km; which was 37 % higher than that on the level segment. The difference is small for slopes up to 2 %, after which it increases, as shown in [3], which is probably due to the need to shift gears on steeper uphills; hence, the increased consumption of the uphill segment dominates the downhill consumption savings.

4.2 Development of the FC dependence model of alignment characteristics for driving with a free-flow speed

The next goal was to analyse the hypothesis that fuel consumption depends on the geometric characteristics of the road while driving at a free-flow speed. The hypothesis was based on the fact that there is a dependence of 85 % driving speed and acceleration on the geometric characteristics of road alignment (mostly on curve radius and tangent length). Considering that fuel consumption is related to speed, acceleration, and deceleration, it was assumed that there was also a dependence of fuel consumption on the geometric characteristics of an 85th percentile driver. To determine this, the 85th percentile driver from a previous study [20], which dealt with the development of operating speed models on tangents and curves, conducted three test rides. For safety reasons, rides were performed under temporary signal control; the light signal was placed a few hundred meters before the beginning of the section. The test vehicle waited on the green signal for a few minutes to clear the road section in front. This enabled the test vehicle to drive at a free-flowing speed for the entire segment.

First, the dependence of the average tangent speed on the alignment characteristics was analysed. Stepwise multidimensional regression analyses showed the dependence of tangent speed on the tangent length and radii of the curves before and after the tangent, as expected. The model showed a high adjusted coefficient of determination R^2 = 0,74 (Table 6). Table 7 presents the model statistics.

Table 6. Model summary for the average tangent speed regression model (free-flow speed)

R	R^2	$\bar{R}^2$
0,866	0,750	0,743

Table 7. Statistical analysis results for the average tangent speed regression model (free-flow speed)

Parameter	Parameter	Standard Error	*t*-statistic	*p*-value
(Intercept)	22,713	3,459	6,57	< 0,001
$\ln(L)$	1,751	0,4	3,80	< 0,001
$\ln(R_{aft})$	3,893	0,589	6,60	< 0,001
$\ln(R_{bef})$	6,943	0,581	11,96	< 0,001

A logarithmic function was used because it describes the impact on speed well, as shown in [20].

Subsequently, the fuel consumption on the curves and tangents was analysed for free-flow speed rides (Table 8). The average consumption for the 22,8 km length segment was 5,63 l/100 km. On tangents, the average consumption was 5,94 l/100 km, whereas on curves, it was 5,44 l/100 km.

Table 8. Fuel consumption on the analysed road segment

	Total	Tangents	Curves
Length (km)	22,779	8,252	14,527
FC total (l)	1,28	0,49	0,79
FC average (l/100 km)	5,63	5,94	5,44

The fuel consumption was approximately 10 % higher on tangents than on curves because most speed changes occur on tangents. Therefore, a fuel consumption prediction model for tangents was first developed.

The analysed road segment included too many short tangents, which are not allowed according to recent Croatian guidelines for road design [24]. To ensure horizontal alignment consistency, Croatian guidelines define the minimum tangent length (in m) as twice the project speed in km/h ($2 \cdot V_p$). The minimum tangent length for the analysed road segment would therefore be 120 m. Additionally, after analysing the records of test drives, it was noticed that the driver did not notice short tangents and adjusted the speed according to the curvature of the road. The observed driver behaviour was in line with Lamm's design alignment consistency concept [25], according to which short tangents should be ignored when checking the consistency of the operating speed of adjacent elements. Given that the proposed concept is intended for analysing planned roads, the model should be developed using data with tangents not shorter than the minimum prescribed by the guidelines [24]. Therefore, data for tangents shorter than 100 m were eliminated from the *FC* model development process to obtain a usable model.

Multidimensional stepwise regression showed *FC* dependence on radii before and after the tangent (R_{bef} and R_{aft}) as well as on the slope. Hence, the dependence of the average *FC* on the free-flow speed on the tangents for successive alignment elements was established. The best fit yields a natural logarithm model in the following form:

$$FC = 0{,}15575 + 0{,}01194 \cdot \ln R_{aft} - 0{,}02831 \cdot \ln R_{bef} + 0{,}00691 \cdot slope \tag{4}$$

The data and model statistics are presented in Tables 9, 10, and 11.

Table 9. Descriptive statistics for the FC regression model (free-flow speed)

	R_{bef}	R_{aft}	slope
N	41	41	41
Mean	450	464	0,22
Standard deviation	264	272	2,74
Maximum	1010	1010	5,00

Table 10. Model fit measures for the FC regression model (free-flow speed)

R	R^2	$\overline{R}^2$	*RMSE*	Overall Model Test			
				F	*df1*	*df2*	*p*-value
0,942	0,888	0,879	0,0116	97,8	3	37	< 0,001

The obtained results show that there was a significant explanation ($R^2 = 0{,}88$) for the variability of the response data around its mean. The residual variability can be explained by the different times and locations of the changing gear and speed for each of the test drives and for each direction of the drive (SN and NS) as well as by other factors causing variations in the fuel consumption rate, such as pavement roughness, air, and other resistance forces, which are difficult to record and use in practical models.

The Fisher *F* test showed that the overall model was significant ($p < 0{,}05$). The coefficient statistics of the model show that all the independent variables were significant at the 5% level. The standardised estimated coefficients indicate that the radius before tangent R_{bef} and the slope had the highest impact on fuel consumption, while the radius after tangent R_{aft} had the smallest impact. The representativeness of the obtained model was proven by testing the assumptions of the linear regression model. The assumption that random errors are distributed over a normal distribution was proven by the probability distribution paper and frequency histogram of the standardised residues. The assumption of homoscedasticity was tested, and the standardised residuals were evenly and randomly scattered around zero, from which it can be concluded that the error variances did not increase with the increasing value of the dependent variables.

Table 11. Regression coefficients for the FC regression model (free-flow speed)

Parameter	**Parameter Estimate**	**Standard Error**	**Standardized Estimate**	***t*-statistic**	***p*-value**
(Intercept)	0,15575	0,02937		5,30	< 0,001
ln(R_{aft})	0,01194	0,00324	0,217	3,69	< 0,001
ln(R_{bef})	-0,02831	0,00305	-0,538	-9,28	< 0,001
slope	0,00691	7,41e-4	0,540	9,32	< 0,001

After developing a fuel consumption model for tangents, an attempt was made to develop a model for curves, but no statistically significant relationship was found between the FC and the analysed alignment characteristics because of the low intensity of speed changes on the curves. However, because the intensity of speed changes on tangents depends on the radii of adjacent curves, all horizontal alignment elements were included in the developed fuel consumption prediction model.

5 Discussion

There are few guidelines for the design of environment-friendly highways. Few models for the estimation of fuel consumption and gas emissions, which can be used in road design, have been proposed [6, 7, 9, 11, 26]. Some of these models used the average speed, whereas others used second-by-second speed and acceleration as input data. These input data are obtained in different ways: by using a traffic microsimulation model or vehicle dynamic models. These studies analysed fuel consumption or gas emissions per trip or per homogenous segment; however, this research analysed consumption per element. All studies showed the same trend: consistent road design reduces acceleration, generating lower fuel consumption and emissions.

In this study, a simple model was developed for estimating fuel consumption on tangents depending on the geometric characteristics of the alignment elements, which is theoretically sound and explains most (88 %) of the variability of the response data around its mean. The model does not require complicated measurements or simulations of second-per-second vehicle speed and acceleration; therefore, it can easily be used by road designers to estimate the fuel consumption for alternative road design variants in a given corridor. Every road design includes reports of successive element dimensions and slopes, which can be imported into spreadsheet software, where the calculations can be performed easily. Designers can try various combinations of successive element dimensions and slopes, calculate fuel consumption or CO_2 emissions, and compare construction costs in a cost-benefit analysis for a road design period.

The form of the FC regression model is very similar to that of the tangent operating speed model (they both depend on the natural logarithm of R_{bef} and R_{aft}, while the fuel consumption model also includes a slope as an independent variable). Therefore, using the FC model with or without conjunction with the operating speed model would result in not only an economically and ecologically better road design but also one with a safer road, because minimising fuel consumption implies that there is less speed dispersion around the mean value, that is, harmonised successive elements. For the given alignment, the measured average fuel consumption (l/100 km) on the analysed longer tangents was 6,06 l/100 km, whereas when estimated by the model, it was 6,03 l/100 km, which is a negligible difference. The developed model is promising but cannot be used generally, as it was developed from data of only a few rides. Therefore, there is a need for a detailed study on more segments with more drivers and rides to cover other percentile driving styles and obtain detailed insights into the relative fuel consumption dependence on alignment characteristics.

6 Conclusions

Most policy measures that address the problem of fuel consumption and emissions focus on vehicle technology, not road design. The most significant parameters of fuel consumption and gas emissions for a given slope are speed and acceleration, which depend on the alignment characteristics. Therefore, this study attempted to determine the impact of alignment characteristics on vehicle fuel consumption, that is, gas emissions. To obtain consumption data, a few test rides with an equipped vehicle were made, and data on path, distance, speed, and MAF were collected on the state road segment. Test drives with uniform speeds were first fabricated and then analysed. The results show that the fuel consumption for driving at a 12 % higher constant speed (72 km/h vs. 64 km/h) increased by approximately 8 %. It is worth noting that the consumption increases for higher constant speeds on all elements of the analysed road segment. Regression analyses showed that the vehicle consumption for driving at a constant speed depends only on the slope, among all other analysed geometric characteristics. The impacts of positive and negative slopes are almost identical, that is, as much as consumption increases with increasing positive slope, it decreases with an increasing negative slope. This could be explained by the identical value of the resistance force in opposite directions of driving and in the same direction of driving. This implies that the fuel consumption/emission on uphill segments is not completely compensated for by downhill segments of the same length and slope, that is, the slope is an important factor in ecologically friendly road design. A ride with a free-flow speed results in 50 % more fuel consumption; this indicates that alignment consistency has a significant impact on vehicle dynamics, that is, consumption. As a result, a regression model of fuel consumption for test rides with a free-flow speed by an 85th percentile driver on tangents was developed for tangents longer than 100 m. The developed model has a significant R^2 of 0,88, which explains most of the variability by the geometric independent variables: R_{bef}, R_{aft}, and slope. As CO_2 emissions are related to vehicle fuel consumption, this study is also applicable to the calculation of CO_2 emissions. The initial results are promising, but there is a need for more detailed research, which would include more drivers and more segments with a wide range of alignment element dimensions as a next step towards including environmental aspects in alignment design guidelines.

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References

[1] European Environment Agency (EEA). Air quality in Europe - 2020 report (EEA Report No 9/2020). Accessed: 15.03.2021. Available at: https://www.eea.europa.eu//publications/air-quality-in-europe-2020-report
[2] European Parliament. CO2 emissions from cars: facts and figures. Accessed: 09.04.2021. Available at: https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics
[3] Boriboonsomsin, K.; Barth, M. 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, 2009, 2139 (1), pp. 21-30. https://doi.org/10.3141/2139-03

[4] Demir, E.; Bektaş, T.; Laporte, G. A comparative analysis of several vehicle emission models for road freight transportation. *Transportation Research Part D: Transport and Environment*, 2011, 16 (5), pp. 347-357. https://doi.org/10.1016/j.trd.2011.01.011

[5] Park, S.; Rakha, H. Energy and environmental impacts of roadway grades. *Transportation Research Record: Journal of the Transportation Research Board*, 2006, 1987 (1), pp. 148-160. https://doi.org/10.1177/0361198106198700116

[6] Ko, M.; Lord, D.; Zietsman, J. Environmentally conscious highway design for vertical grades. *Transportation Research Record: Journal of the Transportation Research Board*, 2013, 2341 (1), pp. 53-65. https://doi.org/10.3141/2341-06

[7] Ko, M. Incorporating Vehicle Emissions Models into the Geometric Highway Design Process. *Transportation Research Record: Journal of the Transportation Research Board*, 2015, 2503 (1), pp. 1-9, https://doi.org/10.3141/2503-01

[8] American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*. 6th edition, Washington DC, USA: AASHTO, 2011.

[9] Llopis-Castelló, D.; Camacho-Torregrosa, F. J.; García, A. Analysis of the influence of geometric design consistency on vehicle CO2 emissions. *Transportation Research Part D: Transport and Environment*, 2019, 69, pp. 40-50. https://doi.org/10.1016/j.trd.2019.01.029

[10] Pérez Zuriaga, A. M.; García, A.; Camacho-Torregrosa, F. J.; D'Attoma, P. Modeling operating speed and deceleration on two-lane rural roads with global positioning system data. *Transportation Research Record: Journal of the Transportation Research Board*, 2010, 2171 (1), pp. 11-20. https://doi.org/10.3141/2171-02

[11] Llopis-Castelló, D.; Pérez-Zuriaga, A. M.; Camacho-Torregrosa, F. J.; García, A. Impact of horizontal geometric design of two-lane rural roads on vehicle co2 emissions', *Transportation Research Part D: Transport and Environment*, 2018, 59, pp. 46-57. https://doi.org/10.1016/j.trd.2017.12.020

[12] Ahn, K.; Rakha, H.; Trani, A.; Van Aerde, M. Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. *Journal of Transportation Engineering*, 2002, 128 (2), pp. 182-190. https://doi.org/10.1061/(ASCE)0733-947X(2002)128:2(182)

[13] Abdel-Aty, M. A.; Radwan, A. E. Modeling traffic accident occurrence and involvement. *Accident Analysis and Prevention*, 2000, 32 (5), pp. 633-642. https://doi.org/10.1016/S0001-4575(99)00094-9

[14] Cafiso, S. et al. Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables. *Accident Analysis and Prevention*, 2010, 42 (4), pp. 1072-1079. https://doi.org/10.1016/j.aap.2009.12.015

[15] Hassan, Y. Highway design consistency: Refining the state of knowledge and practice. Transportation *Research Record: Journal of the Transportation Research Board*, 2004, 1881 (1), pp. 63-71. https://doi.org/10.3141/1881-08

[16] Polus, A.; Mattar-Habib, C. New consistency model for rural highways and its relationship to safety. *Journal of Transportation Engineering*, 2004, 130 (3), pp. 286-293. https://doi.org/10.1061/(ASCE)0733-947X(2004)130:3(286)

[17] Chang, D. J.; Morlok, E. K. Vehicle speed profiles to minimize work and fuel consumption. *Journal of Transportation Engineering*, 2005, 131 (3), pp. 173-182. https://doi.org/10.1061/(ASCE)0733-947X(2005)131:3(173)

[18] Ehsani, M.; Ahmadi, A.; Fadai, D. Modeling of vehicle fuel consumption and carbon dioxide emission in road transport. *Renewable and Sustainable Energy Reviews*, 2016, 53, pp. 1638-1648. https://doi.org/10.1016/j.rser.2015.08.062

[19] Kang, M.-W.; Shariat, S.; Jha, M. K. New highway geometric design methods for minimizing vehicular fuel consumption and improving safety. *Transportation Research*

Part C: Emerging Technologies, 2013, 31, pp. 99-111. https://doi.org/10.1016/j.trc.2013.03.002

[20] Cvitanić, D.; Maljković, B. Operating speed models of two-lane rural state roads developed on continuous speed data. *Tehnički vjesnik - Technical Gazette*, 2017, 24 (6), pp. 1915-1921. https://doi.org/10.17559/TV-20150304133437

[21] HP Tuners. Trackaddict application. Accessed: 11.03.2021. Available at: https://www.hptuners.com/product/trackaddict-app

[22] VBOX Automotive. VBOX Test Suite software. Accessed: 11.03.2021. Available at: https://www.vboxautomotive.co.uk/index.php/en/software-overview

[23] Meseguer, J. E.; Calafate, C. T.; Cano, J. C.; Manzoni, P. Assessing the impact of driving behavior on instantaneous fuel consumption. In: *2015 12th Annual IEEE Consumer Communications and Networking Conference (CCNC)*. 09-12 January 2015, Las Vegas, NV, USA, IEEE; 2015. pp. 443-448. https://doi.org/10.1109/CCNC.2015.7158016

[24] Narodne Novine. Pravilnik o osnovnim uvjetima kojima javne ceste izvan naselja i njihovi elementi moraju udovoljavati sa stajališta sigurnosti prometa. Ministarstvo Pomorstva, Prometa i Veza. NN 110/2001, 2001. Accessed: 12.03.2021. Available at: https://narodne-novine.nn.hr/clanci/sluzbeni/2001_12_110_1829.html [In Croatian]

[25] Lamm, R.; Choueiri, E. M.; Hayward, J. C. Tangent as an independent design element. *Transportation Research Record*, 1988, 1195 (1), pp. 123-131.

[26] Rakha, H.; Ahn, K.; Trani, A. Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. *Transportation Research Part D: Transport and Environment*, 2004, 9 (1), pp. 49-74. https://doi.org/10.1016/S1361-9209(03)00054-3