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Comparative Evaluation of Road Safety Level and Geometric Design Consistency

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Abstract: This paper investigates road safety levels and geometric design consistency in a road network in Greece concerning road alignment characteristics. Published literature has proved that road accidents and road safety, in general, are directly connected to the road network's geometrical design. Hence, there has been an attempt to select the optimum road design using modern computational systems in recent years. The present research aims to evaluate the risk level of the existing road network, identifying the road sections and road curves with a reduced provided level of road safety and, therefore, with an increased possibility for road accidents, and correlate the results between two widely used software. This research examines two discrete methodologies today for evaluating the provided road safety level based on a road network case study on Chios in Eastern Greece. The two methodologies present similar results, highlighting their advantages and disadvantages, and have a statistically significant correlation according to the level of road safety achieved. The research concludes that the correlation is proportionally higher in road segments with larger curve radii. A further research expansion topic could be the insertion of the number or severity of accidents in the analysis to get a holistic notion of the road safety condition.

Keywords: Alignment, Geometry, Road safety, Statistical analysis.

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1. Introduction

The execution of infrastructure projects in Greece has contributed significantly to the upgrade of the country's capacity to accommodate modern logistics needs, such as commercial ports, logistics hubs, and extensive road networks (Panas and Pantouvakis, 2014; Pantouvakis and Panas, 2013). Road safety is one of the most significant issues transportation engineers and society, in general, face. Published research has proved that the occurrence of road accidents (Hoye and Hesjevoll, 2020; Rengarasu et al., 2009) and road safety, in general, are directly connected to the geometric design of a road network. Road geometric design engineers have to provide an increased safety level to the users, with operational road networks, by serving the transportation needs of people and goods while considering soil conditions, environmental impacts, and socioeconomical factors. Besides, increased road safety should be evaluated through the lens of an ever-increasing demand for excellent service provision among organizations (Spyropoulou et al., 2021).

All mentioned above make road design a very complex process. The geometrical design of a road axis is conducted in three discrete stages: Horizontal alignment, Vertical alignment, and superelevation/cross-sections (Apostoleris et al., 2013, 2020, 2022). The synthesis of those three stages constituted the "road design," which has to abide by the restrictions posed by the established rules and regulations. Theoretically, the geometric road design may produce an infinite set of alternative solutions. That is why in recent years, there has been an attempt to select the optimum road design using modern computational systems (Liu et al., 2019). The present research opts to evaluate the risk level of the existing road network, based on its geometrical characteristics, with the aid of suitable software and the established legislation in Greece.

Over 50% of fatal road accidents in Greece occur in the peripheral road network, specifically on two-lane roads without a central median (rural highways) (HSA, 2019). A common characteristic of those accidents is the violation of the speed limit. Combined with the non-uniform geometric design often leads to a failure of the drivers' expectations and increases the possibility of an accident. This research examines two discrete methodologies supported by respective software used today to evaluate the provided road safety level applied to a case study for a road network within Chios island in Eastern Greece. The research objective is the characterization of the road segments and curves that present a low road safety level and conducts a comparative evaluation of the two applied methodologies through a correlation procedure. At the same time, the research categorizes all road segments that do not comply with the updated design guidelines concerning the risk they pose to the users.

The structure of the paper is as follows: first, there is background information on road safety guidelines in Greece to present the respective methodology for road safety characterization. Consequently, the software application described will serve as a second pillar of the comparative evaluation of road safety in an existing road network in Greece. Furthermore, the research methodology is described to explain the applied research approach and the selected data collection and management process. Finally, a case study is presented to evaluate the research results and the main inferences of the study along with proposals for future research directions to conclude the paper.

2. Background

2.1. OMOE guidelines in Greece

Two-lane rural highways that are not separated by a central median are the most dangerous, based on the high number of road accidents that occur on them (Intini et al., 2018; Richter et al., 2017). The lack of a reliable statistical connection between the geometric road characteristics and the recorded road accidents and their consequences makes it difficult for designers to improve road safety. In Greece, the main road geometric design guidelines were issued in 2001. Titled "Guidelines for Road Geometric Design" (abbreviation in Greek "OMOE"), they include the main principles, methodologies, and proposed values for the geometric design of new roads or the reconstruction of existing roads (OMOE, 2001). The basic road design principles address road horizontal alignment, vertical alignment, and superelevation/cross-sections and depend on road categorization (e.g., freeway, rural highway, local road, dirt road, etc.). In Greece, the three main safety criteria for achieving design consistency are (a) the study, (b) the operating speed, and (c) the dynamics of the vehicle's movement. This research focuses mainly on the second criterion, for which two main definitions of speed metrics exist:

- **Design speed (V_e):** the design speed is based on the road's environmental and operational criteria. The design speed directly affects the design characteristics of the road, such as horizontal radii of curves, vertical radii of curves, vertical slopes, etc.
- **Operating speed (V_{85}):** the operating speed is a value used for the geometrical design characteristics critical for the provided road safety level, such as superelevation on curves, provided stopping sight distance, etc. By definition, the operating speed corresponds to the speed that does not exceed 85% of vehicles that travel in free-flow conditions on a clean and wet road surface.

The design speed (V_e) and operating speed (V85) must be kept constant for an adequate road length. In that respect, road alignment is formulated respectively and affects driving behavior. However, it may be necessary to amend the geometric characteristics of the alignment and the respective design speed (V_e) in a road segment of significant length (e.g., due to an obvious difference in the terrain characteristics). The design parameters must change smoothly, and the designers must consider a smooth transition between the different road segments. For the same reasons, the operating speed (V_{85}) has to be kept constant for most parts of the road as possible. These principles refer not only to high-speed roads (e.g. freeways, international roadways, etc.) but mostly to rural highways and local road networks. In the latter, driving behavior depends mostly on posted speed limits rather than vehicles' dynamic movement. The design quality of a road segment is associated with the difference between the design speed (V_e) and the operating speed (V_{85}), named criterion I, by determining three broad design quality categories (good, average, and non-acceptable), as shown in Table 1 below.

Table 1. Design quality categorization according to design speed (V_e) and operating speed (V_{85}) – Criterion I

Design quality	Evaluation formula	Description
Good	$\|V_{85} - V_e\| \leqslant$ 10 km/h	No further adjustments or corrections are necessary for the road alignment.
Average	10 km/h < $\|V_{85} - V_e\| \leqslant$ 20 km/h	In this case, the road inclinations have to be recalculated based on the V85, so the main design parameters are in accordance with the road safety requirements.
Non-acceptable	$\|V_{85} - V_e\|$ > 20 km/h	In this case, severe corrections are needed in order to restore the road safety level without the risk of causing serious road accidents.

The same procedure is made considering for the difference of the operating speed (V_{85}) for two consecutive road geometric elements, named as Criterion II, by determining three broad design quality categories (good, average, non-acceptable) as shown in Table 2. Similar methodological approaches exist in the respective German guidelines RAS-L (FGSV, 1995) issued by the Road and Transportation Research Association (FGSV), on which the respective Greek guidelines are based. Furthermore, similar approaches are also presented in the guidelines of AASHTO in cooperation with the FHWA in their publication Highway Safety Manual (NCHRP, 2017).

2.2. FM19 Software

Another approach for the evaluation of road safety level has been developed at the National Technical University of Athens in an attempt to utilize to the maximum the capabilities of modern computational systems and their processing power to evaluate the necessary elements of the road alignment and characterize the road segments along their road safety ranking.

Table 2. Design quality categorization according to the evaluation of the operating speed (V_{85}) for two consecutive road geometric elements – Criterion II

Design quality	Evaluation formula	Description
Good	$\lvert V_{85i} - V_{85i+1} \rvert \leq 10$ km/h	No further adjustments or corrections are necessary for the road alignment.
Average	10 km/h < $\lvert V_{85i} - V_{85i+1} \rvert \leq 20$ km/h	In this case, the road inclinations have to be re-calculated based on the V_{85}, so the main design parameters are in accordance with the road safety requirements.
Non-acceptable	$\lvert V_{85i} - V_{85i+1} \rvert > 20$ km/h	In this case, severe corrections are necessary to restore the road safety level without causing serious road accidents.

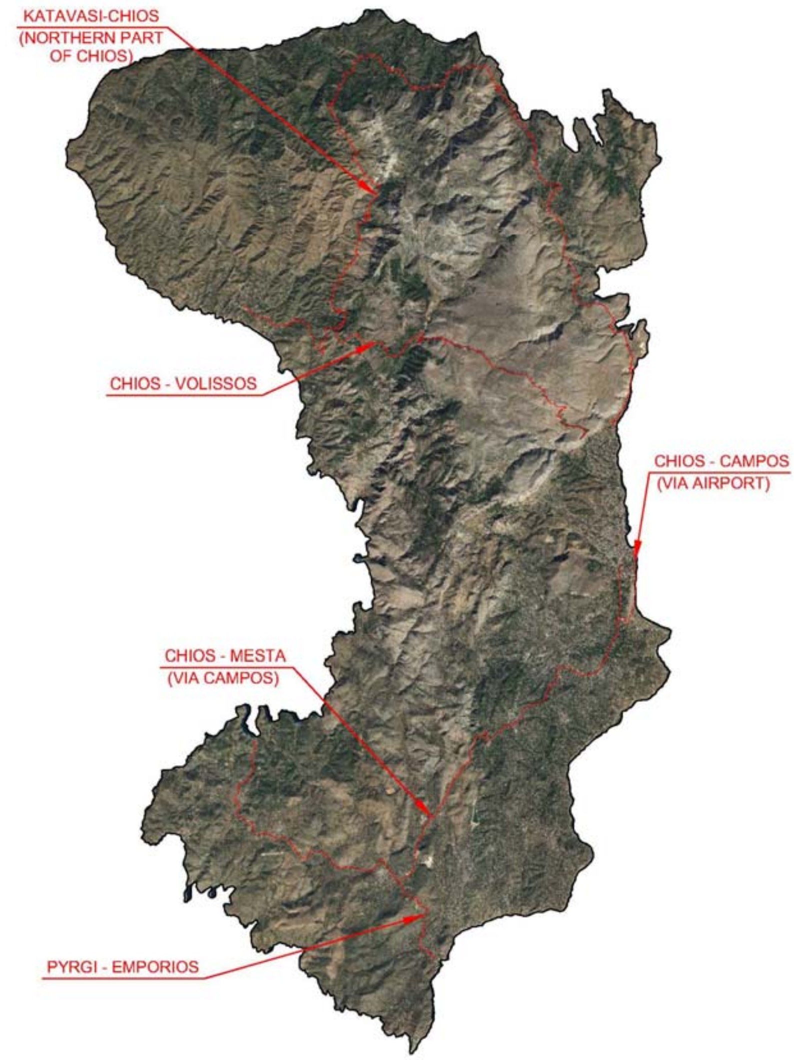

Fig. 1. Chios road network in Greece under investigation

The methodology is incorporated in the FM19 software (Mertzanis, 2022), which is based on the processing of a database management system that holds empirical data on the Greek road network. The FM19 software is based on the Fortran77 programming language combined with the object-oriented Visual Basic for Applications tool. The latter provides the necessary graphical user interface and may cooperate with different IT applications (e.g., Excel spreadsheets). In the FM19 software ecosystem, combined with the aforementioned programming languages, digital drawings were created using the AutoCAD software. Ancillary data that emerge during the alignment design and road safety characterization process are stored in a database created using the Excel spreadsheet program. The FM19 software includes a set of applications to estimate mathematical formulas that yield results for ranking the road segments and the individual curves and characterizing them from a road safety point view.

3. Research methodology

The research scope includes the application of the two previously presented approaches for processing and characterizing a 135 km long rural highway road network on Chios Island in Greece, as shown in Fig. 1 below.

The research purpose is the production of (a) the horizontal and vertical alignment as well as (b) separation into homogeneous sections and ranking according to the provided road safety level for all road segments that are presented in Table 3.

Table 3. Road segments under investigation

Axis	Points	Total Length
CHIOS–VOLISSOS	K1–K168	28.6 km
NORTH CHIOS KATAVASI CHIOS	K169–K746	57.2 km
CHIOS–KAMPOS (THROUGH THE AIRPORT)	K747–K764	4.4 km
CHIOS–MESTA (THROUGH KAMPOS)	K765–K954	37.9 km
PYRGI–EMPORIOS	K955–K996	5.5 km

The visualization of the road network was realized through the use of Google Earth software, through which the X and Y coordinates of the horizontal alignment were exported. The visualized information was subsequently fed into FM19 software as input data while the existing road geometric design elements were exported.

3.1. Data Collection Methodology

Using the FM19 software requires completing a series of steps for the correct and valid extraction of the requested results. First, the coordinates of a topographic survey of the road (longitude, latitude) are inserted in the program. Subsequently, the software automatically processes the coordinates, calculating tangents and curves (including radius), and exports a DXF (AutoCAD) file containing the horizontal road alignment, including the information on the horizontal radii and the chainage of the road, as shown in Fig. 2.

Given the aforementioned input data, the axis is divided into homogeneous segments. Then a further elaboration of data is conducted to extract a score for all segments and rank the road segments respectively. Lastly, the software produces a drawing with colored segments of the road alignment according to the calculated FM19 score. The dangerous curves (black spots) are highlighted with a dot, such as the orange dot for the position K-490, as shown in Fig. 3.

Similarly, the software can produce a respective colored alignment for the total road network under investigation along the four main categories presented in Table 4 and Fig. 4.

Table 4. Road segments safety coloring categorization

Characterization	Color	Score FM19	Criterion II
Good	Green	0–25	>0
Average	Orange	25–50	>–10
Bad	Magenta	50–75	>–20
Non-acceptable	Red	>75	<–20

4. Results

The comparative evaluation of the OMOE-X guidelines (Criterion II) and the FM19 software has been drafted in a table format. Due to the large size of the collected data, this paragraph will present the research results for a specific road segment (i.e., “Chios–Volissos,” in Table 1). For interoperability reasons, the cross-software characterization categories semantics are the following:

- Green color: segments that are “Good”
- Yellow color: segments that are “Average”
- Orange color: segments that are “Bad”
- Red color: segments that are “Non-acceptable.”

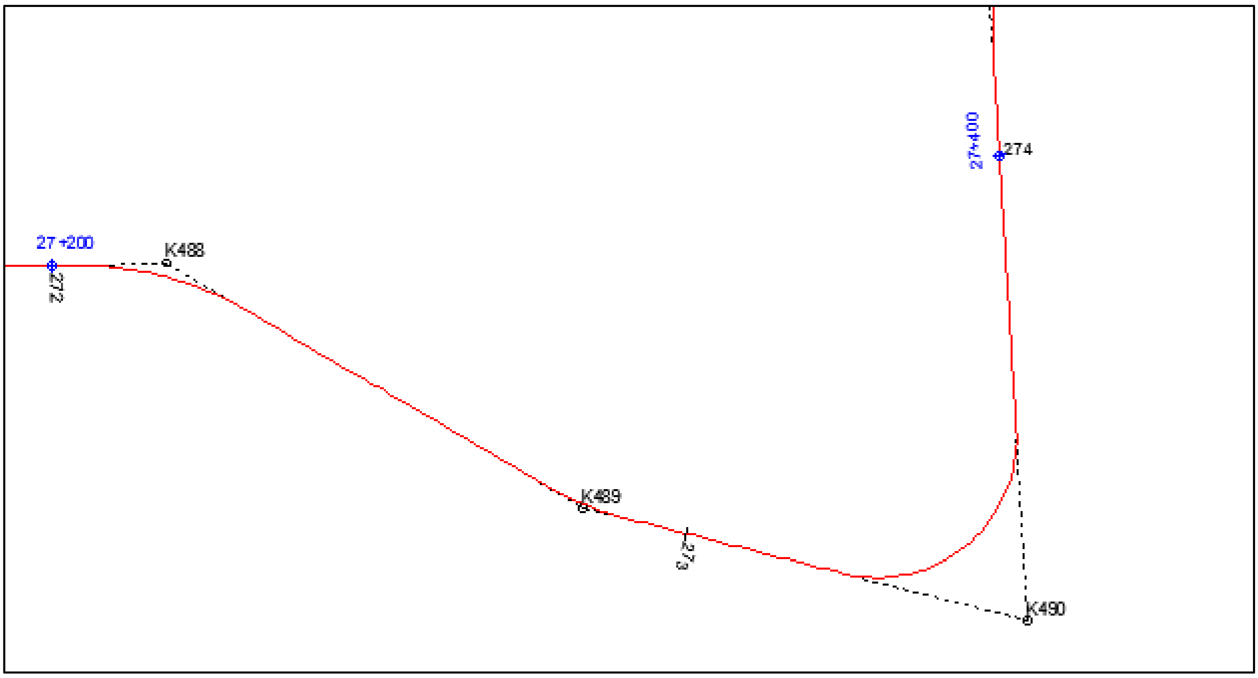

Fig. 2. Road alignment provided by FM19 software

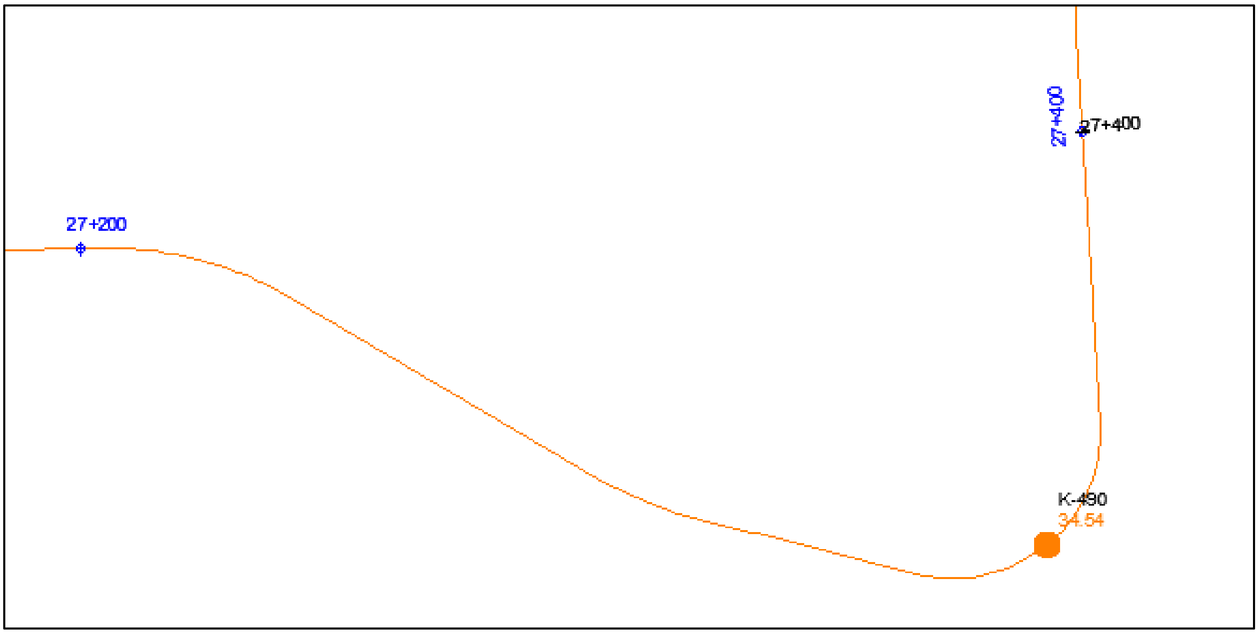

Fig. 3. Road segment characterization according to the FM19 software

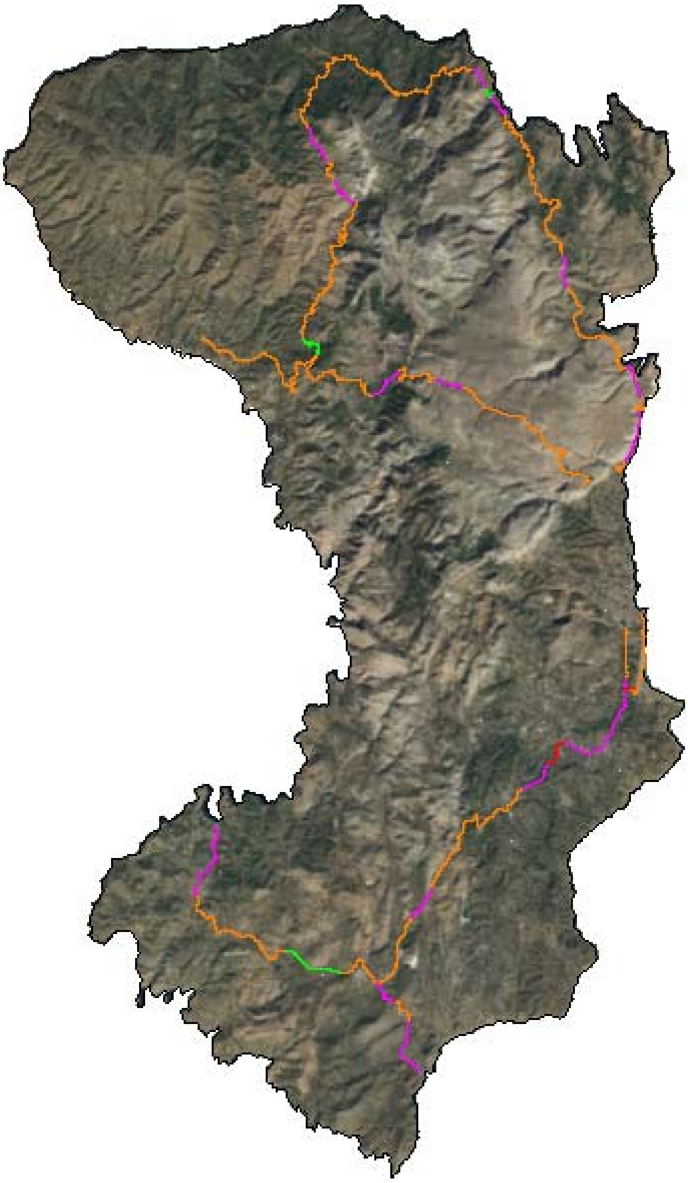

Fig. 4. Road map for provided safety level colored according to the results of FM19 software

An excerpt of the comparative evaluation's results is presented in Table 5 below. At first, the two methodologies seem to have an optical consistency. For example, in the section "Chios–Volissos" for the nine curves presented in Table 5(a/b) the characterizations are somewhat similar. It is characteristic that curve K12 is characterized as "non-acceptable" by both criteria, while a "good" characterization is unanimously yielded for curve K17.

Table 5a. Comparative evaluation of "Chios–Volissos" (Segment 2) - OMOE-X

		OMOE-X Criterion II	
Nr.	**R [m]**	**Forward**	**Forward**
K 9	50	−47,69	−4,49
K 10	60	4,49	−29,07
K 11	250	29,07	0,00
K 12	23	−51,53	−40,18
K 13	130	40,18	−7,93
K 14	200	7,93	−5,07
K 15	100	−18,61	−8,44
K 16	150	8,44	−20,90
K 17	1.000	20,90	15,79

Table 5b. Comparative evaluation of "Chios–Volissos" (Segment 2) -FM19 software

		FM19 software	
Nr.	**R [m]**	**Forward**	**Forward**
K 9	50	55,48	63,93
K 10	60	51,52	59,48
K 11	250	22,17	26,57
K 12	23	75,99	87,09
K 13	130	22,92	29,34
K 14	200	25,27	30,07
K 15	100	37,42	43,70
K 16	150	30,38	35,81
K 17	1.000	12,12	15,98

At this point, the FM19 software also gives another possibility. Apart from characterizing each curve, FM19 can also characterize every section in total. For a more realistic approach, each road section has been divided into smaller sections of 2 to 3 kilometers, as the specific methodology dictates. The results for fourteen segments of the "Chios–Volissos" section are presented in Table 6 (according to the color categories of Table 2). The numerical results have been plotted on an x-axis and y-axis to graphically represent the comparative evaluation of OMOE-X and FM19 methodologies. Subsequently, a trend line was created with the spreadsheet functions. The statistical metric used a measure of fit is the R-squared (R2) index, which indicates how much variation of a dependent variable (OMOE-X) is explained by the independent variable (FM19) in a regression model. The R-squared metric in that case is equal to 0,3011 or 30,11%, which is not high, but the significant correlation of the two methodologies is being visually confirmed by examining Fig. 5. A specific statistical analysis of the results could be a subject for further research.

Table 6. FM19 total segment characterization

		Road "Chios–Volissos" FM19	
Segment	**Curves Number**	**Forward**	**Backward**
1	7,00	213,11	256,01
2	8,00	160,57	187,99
3	8,00	201,97	239,94
4	11,00	206,86	252,16
5	6,00	244,49	300,57
6	12,00	217,68	256,23
7	8,00	193,08	225,26
8	14,00	260,54	310,69
9	6,00	159,04	184,90
10	15,00	176,54	206,50
11	22,00	242,40	286,59
12	15,00	158,69	185,80
13	17,00	191,35	223,42
14	18,00	237,09	281,06

5. Conclusions

The present paper aimed to evaluate the provided road safety level on five main road axes on the island of Chios, Greece and highlight the road sections and curves where the provided road safety level is reduced. The main parameter investigated was the geometrical design characteristics of each road and their design consistency. An evaluation was conducted by applying the safety criteria of OMOE-X and the FM19 software. The comparative evaluation opted for indicating the positions and sections that present a reduced level of road safety and have to be mitigated and restored. As a first research inference, the two methodologies present—in principle—similar results and have a statistically significant correlation. A closer examination of the results denotes that the correlation is proportionally higher in road segments with a higher curve radius. Similarly, segments with smaller curve radii present a smaller correlation. The OMOE-X guidelines have been drafted for road networks that have a maximum speed of 50–90km/h, namely roads with smooth geometry and larger curve radius. As such, it can be inferred that the OMOE-X criterion overestimates the safety risk of existing roads with a small curve radius. Besides, on such roads, the developed vehicle speeds are relatively low. Therefore, for roads with the aforementioned characteristics, the FM19 should be regarded as a more reliable methodology for safety risk evaluation.

As a further research expansion topic, evaluating a larger amount of road segments is suggested to enhance the statistical sample. In addition, other parameters could be inserted in the analysis, such as the number or severity of accidents, and derive respective correlation metrics for those as well. In that fashion, the analyst could have a more detailed and holistic notion of the road safety condition in the investigated road networks.

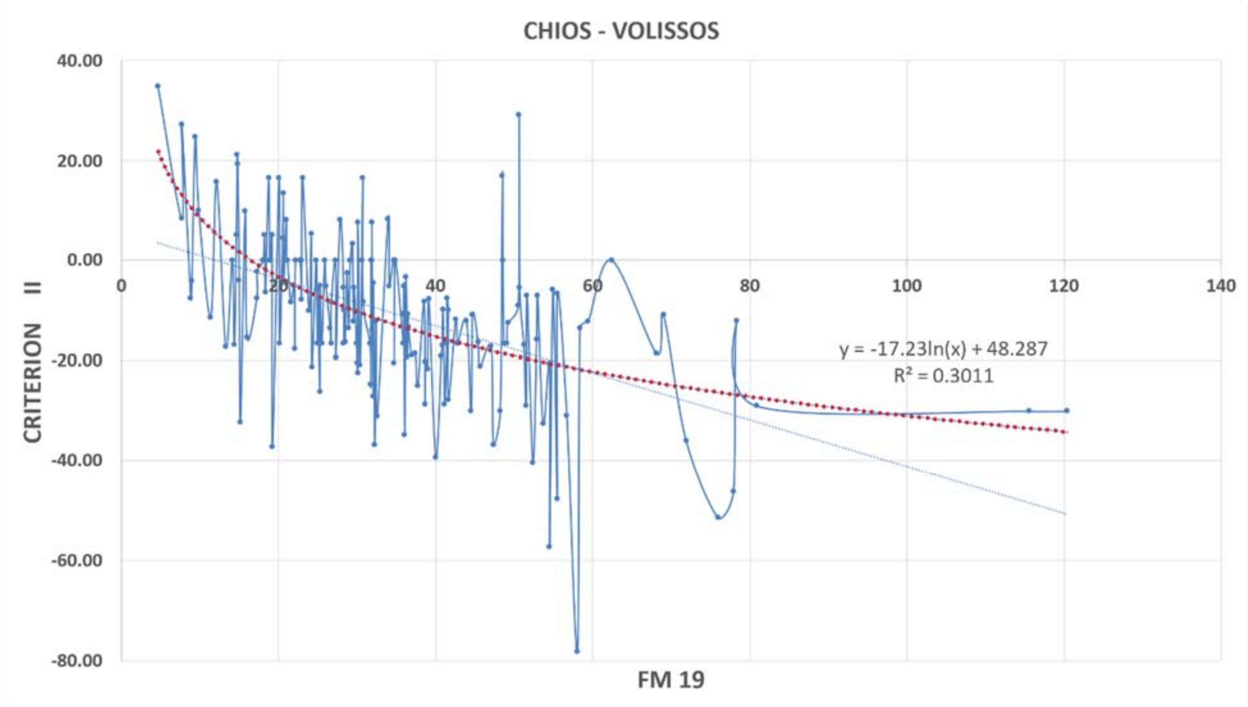

Fig. 5. Correlation graph between OMOE-X and FM1

Author Contributions

Antonis Panas conceived the research and contributed to conceptualization, methodology, data collection and analysis, draft preparation, and manuscript editing. Eirini Kavouria contributed to draft preparation, manuscript editing, and supervision. John-Paris Pantouvakis contributed to draft preparation, manuscript editing, and supervision. All authors have read and agreed with the manuscript before its submission and publication.

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