RSS 2022
8th Road Safety & Simulation International Conference
Road Safety and Digitalization
08-10 June 2022 • Athens, Greece

THE ROLE OF TRAFFIC SPEED RANGE IN ROAD SAFETY - THE CASE OF TWO-LANE RURAL HIGHWAYS

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Abstract

The idea for this research is based on the fact that the increased vehicle speed and its variability constitute a critical aggravating factor for the provided road safety level, especially regarding to two-lane rural highways. In this framework of reference, traffic speed measurements of travelling vehicles were carried out in 20 locations with automatic devices. These devices were mainly placed on horizontal curves while few of them was placed on tangents along a major two-lane rural highway with Average Daily Traffic exceeding 10,000 vehicles. Among these measurements, only the cases with a headway greater than 6 seconds were utilized in order to ensure free flow conditions. Subsequently, measurements were divided into speeds of passenger vehicles and speeds of heavy vehicles, which were further divided into daytime and nighttime speeds. At the same time, parameters such as mean speed, standard deviation and operating speed were determined and the road's geometric elements were utilized in order to determine elements that characterize the homogeneity of the geometric design (criterion II), the expected number of road accidents (via the IHSDM software) and the risk indicator (via the FM19 program). Utilizing all the above data, a variety of diagrams were made to correlate speed measurements data with the corresponding results obtained from the applications of software that evaluate the provided road safety level, as well as, with geometric elements related to road infrastructure. The results of the analysis show that the limited variability in traffic speed leads to an increased road safety level, highlighting the importance of homogeneity in geometric design.

Keywords: Road Safety; Traffic Speed; Road Geometry; Accident Factors

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1. Introduction

The aim of this research is to demonstrate the hazard correlation of a horizontal curve in relation to the variation of spot speed of travelling passenger cars and heavy vehicles. An additional purpose is to highlight the differences and similarities between passenger cars and heavy vehicles, as well as between daytime and nighttime speeds. Through this article's presented analysis, a critical factor exclusively related to traffic speed measurements statistic data is indicated.

2. The Relationship Between Speed and Safety

Speed can be described as one of the most important factors that road users consider while evaluating the convenience and efficiency of a certain route [1] and is one of the major parameters in geometric design and safety, synonymous with accident studies [2]. For example, Finch et al. [3] recently concluded that a reduction of 1.6 km/hr (1mph) in the average speed reduces the incidence of injuries by about 5%. Also, it is generally accepted that there are substantial safety benefits from lower speed limits. For example, reducing rural speed limits from 100 km/hr to 90 km/hr has been predicted to reduce casualties by about 11% [4].
Besides mean free-flow speed, the variability of speeds across drivers is also considered to be an important road safety factor. Despite the large number of past research on speeds, there is still much to learn about the factors of free-flow speeds and their variability. The existing models estimate a specific speed percentile and they do not distinguish between the mean speed factors and the speed dispersion factors, which leads to results that are sometimes difficult to interpret. It is possible that a road with high mean speed and low speed variability has the same 85th speed percentile as a road with a much lower mean speed but higher speed variability. Such a case is shown in Figure 1.

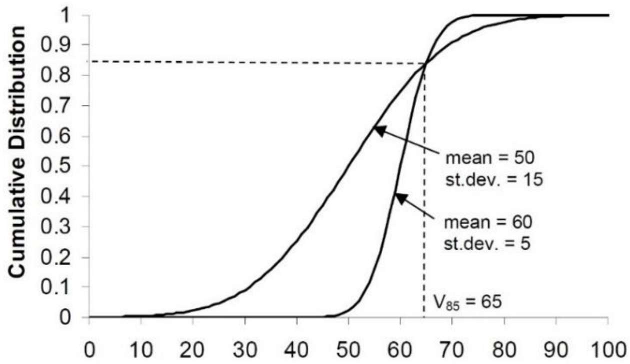

Figure 1: A case of two different speed distributions with the same 85th percentile speed

The relationship between speed and vehicle accidents has been studied with no irrefutable link. There is ongoing discussion as to which factor-the mean speed or the speed dispersion-has the most impact on safety. Either opinion is defendable. An increase in mean speed increases the crash severity, while an increase in speed variability increases the frequency of interactions between vehicles. Studies have shown that an increase in the deviation between a motorist's speed and the average speed of traffic is related to a greater chance of involvement in a crash. Garber and Gadiraju [5] found that crash rates from different highway types are increased with an increase in speed variation and that an increase in mean speed is not necessarily related to an increase in accident rates. They also found that speeds are increased regarding to better geometric conditions, regardless of the speed limit. Collins et al. [6] found low speed dispersion on horizontal curves with radii values of less than 100m, and that as the radii increases, the range of speed dispersion is also increased.

3. Data Collection

Road section and speed data

The analysis is based on spot speed measurements conducted on the road section Evangelismos-Leptokaria (a two-lane rural highway, section of the Athens–Thessaloniki National Road). The examined road section is approximately 35km length, while the daily traffic volume during measurements approaches approximately 10,000 vehicles (bidirectional traffic). Along the road section, 20 locations on horizontal curves were selected (Figure 2) in order to cover both section's entire range as well as each position's expected risk depending on the horizontal radius and the geometric design's homogeneity. Appropriate equipment was placed at each of the above locations in order to record the traffic volume and the spot speed of each passing vehicle for both directions.

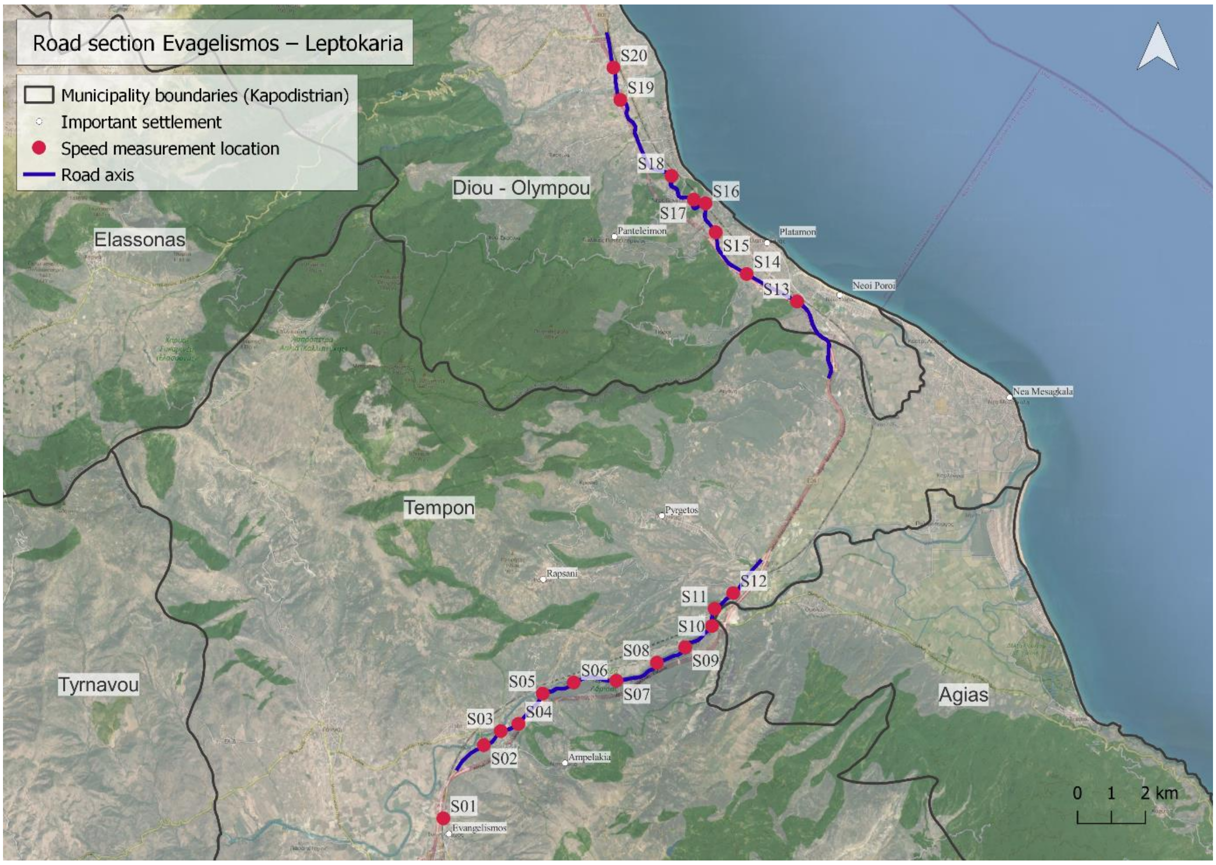

Figure 2: Road section Evagelismos – Leptokaria

Speed measurements were conducted on 17 to 20 May of 2016. METRO COUNT model 5600 instruments were used for the automatic 24-hour measurements due to their ability to measure the number of passing vehicles separately for each direction and classify them into 13 categories according to their type (traffic composition) while measuring their speed.

Figure 3: Indicative location of measurement procedure (counters placement)

4. Data Analysis

Speed data processing

For each of the 20 road locations where measurements were conducted, passing vehicles spot speed data was processed. Among these measurements, only the cases with a headway greater than 6 seconds were utilized, to ensure both free flow conditions and no influence from the preceding vehicles. From these data, measurements relating to passenger cars and heavy vehicles with more than 4 axles were isolated and grouped into segments with a speed step of 1km/h. In addition, a separation into daytime and nighttime data was held. Utilizing these data, statistical analysis was conducted in order to determine curvature, operating speed, mean speed and standard

deviation of speed, while the graphs in Figures 4 and 5 were generated for all days and locations where speed measurements were conducted.
The following indicative diagram (Figure 4) illustrates the relation between operating speed (V_{85}) and curvature (K_E) regarding to both passenger cars (PC) and heavy vehicles (HV) and according to time distinction.

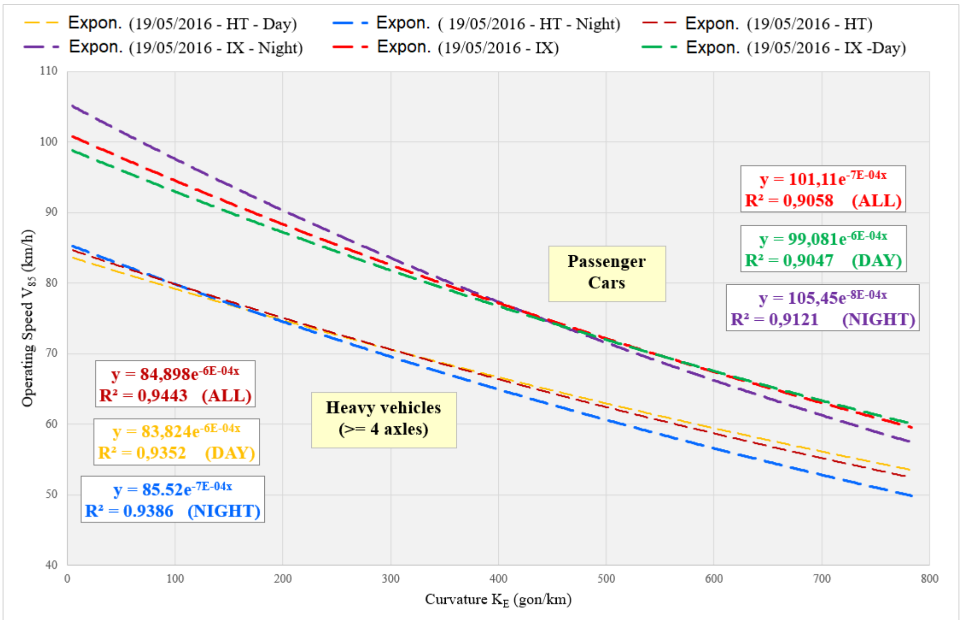

Figure 4: Correlation between K_E and V_{85}

According to Figure 4, passenger cars present higher speeds than heavy vechicles regarding to all curvature values (and by definition radius values). The difference is approximately 20 km/h at higher values of horizontal radius (and in tangents) and approximately 10 km/h at curves with higher curvature. It is also observed that speed of passenger cars during nighttime is significantly higher at higher value horizontal radius and about 5-6 km/h higher than those of daytime in tangents. It is noted that at smaller horizontal curves, recorded speeds during nighttime are lower than those of daytime for both passenger cars and heavy vehicles (approximately 3-4 km/h).
The diagrams presented in Figure 5 were generated for all measurement locations and for each diagram two indicators which are exclusively related to vehicles speed variation were defined and identified.

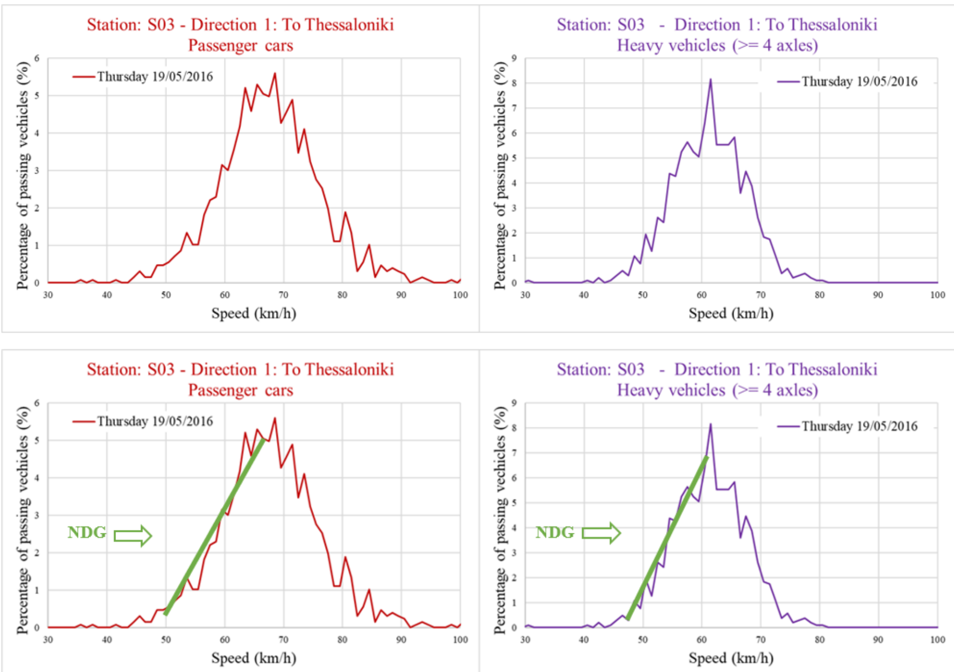

Figure 5: Indicative spot speed variation diagrams

CV Indicator

The first indicator examined is CV (Coefficient of Variation), which is defined as the ratio of the standard deviation of spot speed to the mean spot speed of the sample. As a coefficient it is dimensionless and is usually expressed as a percentage. CV indicator has been used in corresponding analyses which have shown that higher values, regarding to common or identical operating speeds (V_{85}), leads to a reduced provided road safety level [12]. The mathematical equation to approach CV is:

$$\mathrm{CV} = \frac{\sigma}{\mu} \qquad (1)$$

where μ= mean speed
σ= standard deviation of the speed

NDG Indicator

The second indicator examined is NDG (Normal Distribution Gradient) which is introduced in the context of the present research and is essentially defined as the gradient formed in Figure 5. Theoretically, while NDG obtains higher values i.e. for smaller variation of spot speed range, the provided level of road safety is reduced. Using the normal distribution equation to approximate the diagrams in Figure 5, as well as mathematical science (the first and second derivatives of normal distribution), the mathematical formula of NDG is calculated according to the following equation:

$$\mathrm{NDG} = \pm \frac{\alpha}{\sigma^2 \cdot \sqrt{2 \cdot \pi}} \cdot \mathrm{e}^{-0.5} \qquad (2)$$

where μ= mean speed
σ= standard deviation of the speed
α= the step selected

The following indicative diagram (Figure 6) illustrates the relation between NDG indicator and radius (R) regarding to both passenger cars (PC) and heavy vehicles (HV) and according to time distinction.

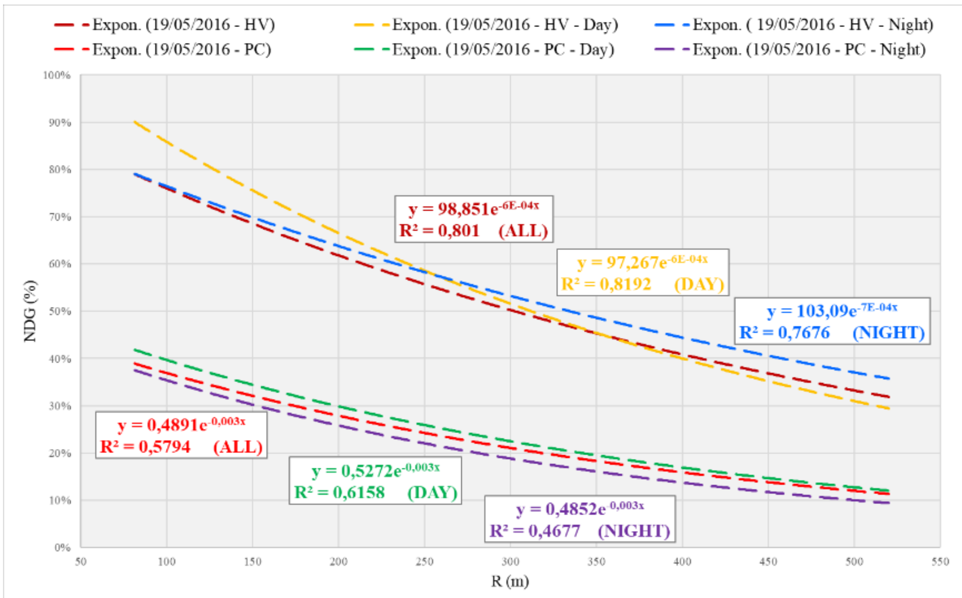

Figure 6: Correlation between R and NDG

It appears that NDG values are particularly high in the case of heavy vehicles (almost doubled) compared to passenger cars. It is worth noting that NDG values during daytime are higher than those of nighttime regarding to passenger cars. This observation is confirmed for heavy vehicles only at larger horizontal radii. Consequently, the dispersion of heavy vehicles speeds is remarkably lower than dispersion of passenger cars speeds, which is also confirmed by standard deviation's values presented in Table 1.

Methodologies and software used for evaluating provided road safety level

Once the two indicators reflecting spot speed variation of passing vehicles had been defined and identified, an attempt was made to assess their correlation with the provided road safety level of each location. Within this framework, current methodologies and software which highlight critical locations, in terms of road safety, for a two-lane road network were used. Specifically:

- Criterion II, which concerns the difference in operating speeds V_{85} between two successive independent road elements (straight or curves).
- Predicted accidents for each horizontal curve of the road, as determined by the Crash Prediction Model (CPM) method using the IHSDM software.
- FM19 ranking method, which indicates provided road safety level of each horizontal curve of the road.

Criterion II

A fundamental parameter influencing the safety of a road section is the operating speed of passing vehicles. It is noted that the V_{85} operating speed has been used in the literature to evaluate the road safety level of every horizontal curve based on the deviation between operating speeds (V_{85}) of two consecutive and independent geometric elements of the road (two successive curves or a curve and an independent tangent) [7-13]. The limits established internationally are defined as follows:

Criteria II - Correlation between the operating speed V_{85} of two consecutive geometric elements on the road

Cluster 1:	Good quality design	$\mathbf{|V_{85i} - V_{85i+1}| \leq 10km/h}$
Cluster 2:	Medium quality design	$\mathbf{10km/h < |V_{85i} - V_{85i+1}| \leq 20km/h}$
Cluster 3:	Poor quality design	$\mathbf{|V_{85i} - V_{85i+1}| > 20km/h}$

Based on the above methodology each individual curve of every road section is evaluated (considering the long tangents counted as independent element) and the spots with a deviation of more than 20 km/h are defined in order to propose measures to improve them. The philosophy of the methodology lies in the fact that roads with better consistency leads to smaller operating speed differences occurring along each road section and therefore to a better provided road safety.

Predicted accidents according to Crash Prediction Model (CPM) of IHSDM software

A related tool used to evaluate a road network in terms of consistency and road safety, which is particularly popular in USA, is the IHSDM software [14]. This software performs five different analyzes, two of which concern the evaluation of design consistency and the geometric design of the road. The first analysis, under the heading "design consistency model", concerns the utilization of the methodology outlined above regarding to Criterion II as applied through the US design guidelines. The second analysis, under the heading "crash prediction model" CPM, determines, based on a mathematical model, the accidents that are expected to occur per geometrical element of the road (tangent, clothoid, circular arc) in the next 5 years.

FM19 Software

The use of the Criterion II methodology was undoubtedly useful in assessing the homogeneity of road sections with the aim of upgrading the road safety. However, there are few researchers that have expressed their objections to the fact that the above methodology exploits only the operating speed, which is determined by two to three geometric parameters, while the evaluation of the road safety by road section should take advantage of many more elements such as geometry and configuration of intersections, pavement condition, roadside clearance widths, safety barriers, road lighting, traffic volume, etc.

The FM19 software is based on the same philosophy with Criterion II but is taking into account more parameters for the evaluation of the road safety level, such as horizontal radius, superelevation of the curve, longitudinal gradient of the road and the adequacy of stopping sight distance [15]. The main keys regarding to FM19 software has the following novelty features:

- Includes distinct mathematical expressions for each parameter that affects road safety, including the severity of each parameter, as determined by reference to the literature and recorded accidents.
- The final evaluation is not based on each parameter individually but considers all the influencing parameters.
- The methodology is based on the concept of hazard level where road sections/curves with lower score correspond to a high level of road safety while road segments with higher score correspond to poor of road safety level.

The above methodologies/software were applied on the entire road section and the indicators/ranks characterizing each horizontal curve where speed measurements were conducted.

Results analysis and hierarchy

As mentioned in previous paragraphs, NDG and CV indicators, as well as the software indicators evaluating the provided road safety level were determined with discrete daytime and nighttime, for 20 road locations where speed measurements were conducted and for two vehicle types (passenger cars, heavy vehicles). The results of the performed analysis, as well as the horizontal radius of each curve, the operating speed (V_{85}), the mean speed (V_{μ}) and the standard deviation of speed (S) are presented in Table 1, which is indicative and refers to the aggregated results of passenger cars and heavy vehicles.

Based on the variation of indicators, an attempt was made to establish a range of values for the results in order to create a first hierarchy of estimated risk. This hierarchy was based on the following reasonable assumptions:

- CV indicator: As the value increases, an increased risk is expected.
- NDG indicator: As the gradient decreases, an increased risk is expected.
- FM19: For higher software's value, the provided road safety level is reduced (and therefore an increased risk is expected).
- Criterion II: For higher difference between the successive operating speeds, the provided road safety level is reduced (and therefore an increased risk is expected).
- Predicted accidents IHSDM: For higher number of predicted accidents, the provided road safety level is reduced (and thus an increased risk is expected).

Table 1: Indicative results table

Direction	Location	R (m)	KE (gon/km)	Criterion II	FM19 Rank	Predicted accidents IHSDM	Passenger cars					Heavy Vehicles (>= 4 axles)				
							V85 (km/h)	Vμ (km/h)	S (km/h)	CV	NDG	V85 (km/h)	Vμ (km/h)	S (km/h)	CV	NDG
1	S4	250	254,8	-17,37	41,78	1,33	90,01	77,62	12,19	15,70%	16,29%	74,15	68,20	6,13	8,99%	64,33%
1	S5	160	398,125	-17,19	65,17	1,44	72,76	66,13	7,10	10,74%	47,94%	66,28	60,96	5,07	8,31%	94,28%
1	S6	180	353,88889	-14,51	53,56	1,74	76,14	67,68	8,82	13,03%	31,13%	67,59	61,58	5,78	9,39%	72,36%
1	S7	600	106,16667	-0,57	14,47	0,84	86,71	76,69	11,06	14,42%	19,78%	74,44	67,79	6,52	9,62%	56,87%
1	S8	120	530,83333	-26,48	76,89	2,07	63,54	56,26	7,96	14,14%	38,23%	60,10	52,86	7,98	15,09%	38,01%
1	S9	120	530,83333	-15,72	63,19	3,42	68,64	60,57	8,29	13,69%	35,18%	59,55	53,98	5,44	10,08%	81,69%
1	S10a	135	471,85185	-15,95	62,85	1,47	74,87	65,65	9,24	14,08%	28,32%	63,84	58,35	5,37	9,20%	83,93%
1	S10b	135	471,85185	-15,95	62,85	1,47	78,70	68,86	10,37	15,05%	22,51%	67,50	61,83	5,67	9,17%	75,26%
1	S11	230	276,95652	-13,59	54,45	0,93	77,90	69,75	8,58	12,30%	32,90%	69,61	63,86	5,72	8,95%	74,02%
1	S12a	280	227,5	0,00	42,94	1,07	79,79	69,40	11,11	16,01%	19,59%	72,51	65,77	6,79	10,32%	52,51%
1	S12b	170	374,70588	-7,78	40,30	2,59	76,34	66,25	11,65	17,59%	17,82%	70,82	64,25	6,58	10,23%	55,97%
1	S13a	520	122,5	-6,48	34,97	0,69	96,23	83,00	12,10	14,58%	16,52%	80,57	73,45	7,24	9,86%	46,11%
1	S13b	13000	4,9	0,92	0,67	0,53	97,21	83,00	13,64	16,44%	13,00%	81,90	75,03	7,00	9,33%	49,42%
1	S15	370	172,16216	-10,51	17,91	0,80	91,65	78,07	13,60	17,42%	13,08%	75,10	65,09	10,39	15,96%	22,41%
1	S16	81,3	783,51784	-21,35	64,33	1,67	64,17	57,12	7,04	12,33%	48,79%	51,73	46,90	4,86	10,36%	102,48%
2	S4	250	254,8	-17,37	41,78	1,33	86,56	75,40	11,20	14,85%	19,29%	71,66	65,18	6,70	10,27%	53,98%
2	S5	160	398,125	-17,19	65,17	1,44	74,01	66,27	8,08	12,19%	37,06%	66,15	61,02	5,25	8,60%	87,88%
2	S6	180	353,88889	-14,51	53,56	1,74	76,43	68,69	8,60	12,53%	32,69%	67,82	61,82	5,74	9,29%	73,40%
2	S7	600	106,16667	-0,57	14,47	0,84	83,30	74,18	10,97	14,79%	20,11%	73,13	66,72	6,27	9,40%	61,54%
2	S8	120	530,83333	-26,48	76,89	2,07	68,78	60,40	8,51	14,09%	33,40%	59,14	53,67	5,27	9,81%	87,22%
2	S9	120	530,83333	-15,72	63,19	3,42	69,35	61,82	7,75	12,54%	40,29%	59,50	54,36	5,42	9,96%	82,52%
2	S10a	135	471,85185	-15,95	62,85	1,47	74,66	65,01	10,12	15,57%	23,63%	62,60	56,51	6,26	11,08%	61,69%
2	S10b	135	471,85185	-15,95	62,85	1,47	80,42	70,76	10,35	14,63%	22,59%	68,28	61,97	6,34	10,23%	60,18%
2	S11	230	276,95652	-13,59	54,45	0,93	80,33	70,97	10,30	14,52%	22,79%	67,41	61,10	6,75	11,05%	53,13%
2	S12a	280	227,5	0,00	42,94	1,07	82,23	71,97	10,45	14,51%	22,17%	71,43	64,35	6,98	10,84%	49,73%
2	S12b	170	374,70588	-7,78	40,30	2,59	88,30	76,52	11,80	15,42%	17,37%	75,73	68,28	7,39	10,83%	44,27%
2	S13a	520	122,5	-6,48	34,97	0,69	101,42	86,41	14,52	16,80%	11,48%	85,28	77,28	7,41	9,58%	44,11%
2	S13b	13000	4,9	0,92	0,67	0,53	106,62	91,40	15,42	16,87%	10,17%	88,49	81,36	7,58	9,31%	42,15%
2	S15	370	172,16216	-10,51	17,91	0,80	90,03	76,10	14,11	18,54%	12,16%	71,46	62,34	10,30	16,52%	22,83%
2	S16	81,3	783,51784	-21,35	64,33	1,67	59,86	53,57	6,47	12,09%	57,72%	53,29	47,30	5,87	12,42%	70,17%

In order to create a first visual correlation of the results according to the estimated risk, ranges of values were determined for each parameter, at the discretion of the research team and the corresponding literature [8, 15] (Table 2). Meanwhile, colors were introduced for each level of risk in order to visualize the results, as shown in Table 1.

Table 2: Indicators limit values

	Criterion II	FM19 rank	Predicted accidents IHSDM	CV	NDG - Passenger vehicles	NDG - Heavy vehicles
Low risk - green	> 0	< 25	< 1	< 0,13	> 0,3	> 0,75
Moderate risk -yellow	Between 0 and -10	Between 25 and 50	Between 1 and 2	Between 0,13 and 0,16	Between 0,3 and 0,2	Between 0,75 and 0,5
High risk - orange	Between -10 and -20	Between 50 and 75	Between 2 and 3	Between 0,16 and 0,19	Between 0,2 and 0,1	Between 0,5 and 0,25
Very high risk - red	< -20	> 75	> 3	> 0,19	< 0,1	< 0,25

The first visual perception, generated by observing color uniformity of Table 1 in relation to the locations, leads to the conclusion that there is a connection between the indicators obtained from the statistical analysis of speed measurements (CV, NDG) and the results concerning the provided road safety level (Criterion II, FM19 rank, Predicted accidents IHSDM) for both passenger cars and heavy vehicles. Similarly, a connection seems to exist between the results concerning the provided road safety level. Finally, it seems that NDG and CV indicators are colored evenly regarding to vehicle type.
Therefore, it was considered necessary to elaborate the results more extensively through graphical correlations and small-scale statistical analysis, in order to reveal the existence or the absence of a connection between the indicators obtained from the statistical analysis of speed measurements and other parameters written in Table 1.

5. Correlation of speed variation with the provided road safety level

Previous research regarding to the connection of NDG and CV with the provided road safety level, indicates that NDG seems to follow more sufficient correlations with the parameters examined. Therefore, only NDG indicator will be utilized in the correlations of the present research [16,17].
Subsequently, NDG graphical correlations with the FM19 software results, the values of Criterion II and the Predicted Accidents as determined from the IHSDM software according to operating speed (V_{85}) variation are presented for both passenger cars (Figure 7) and heavy vehicles (Figure 8).

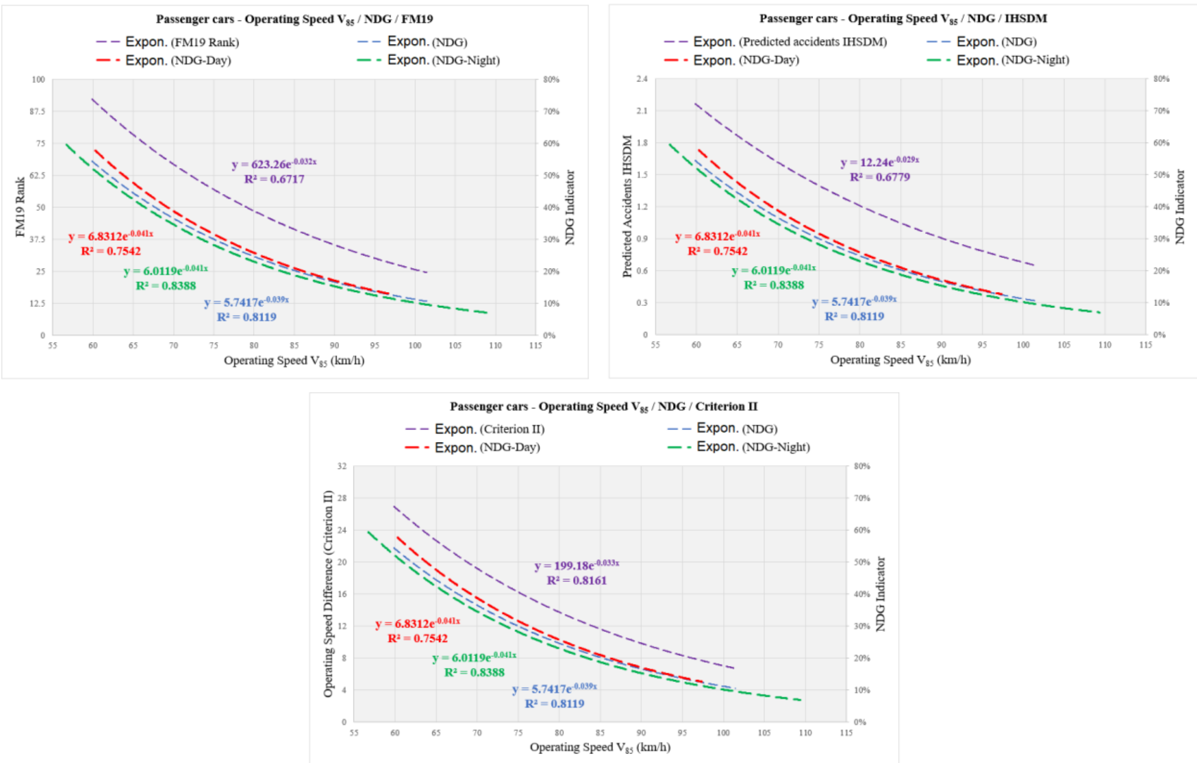

Figure 7: Passenger cars – Correlation between NDG and FM19 rank, Criterion II and predicted accidents IHSDM according to V_{85} variation

The diagrams of passenger cars regarding to all cases (FM19 rank, predicted accidents IHSDM, Criterion II) are parallel and seem to develop a particularly strong correlation with NDG indicator. More specifically, reliability coefficients (R^2) have values higher than 0.75. This similarity confirms that NDG can be used as an indicator to evaluate or estimate the provided road safety level. Indicator's values (NDG) concerning to passenger cars appear to be higher during daytime and lower during nighttime, which shows that the speeds dispersion is more intense during day than night.
Referring to the following diagrams (Figure 8) of heavy vehicles, it is noted that the results of FM19 and IHSDM software, as well as the values of Criterion II were not determined by considering heavy vehicles data but taking into consideration passenger vehicles data. However, it was considered suitable to correlate NDG with them, to create a sense of compatibility (or absence of compatibility) between these parameters. The diagrams of heavy vehicles regarding to all cases (FM19 rank, predicted accidents IHSDM, Criterion II) indicate a relatively parallel direction, but without developing a strong correlation with NDG (reliability coefficients R^2<0,45). This fact is probably based to the small sample that was unutilized. Finally, in the case of heavy vehicles, a similarity between NDG and the software results also occurs. Indicator's values concerning to heavy vehicles appear to be significantly higher during daytime and lower during nighttime, which indicates that speeds dispersion is particularly stronger during day than night.

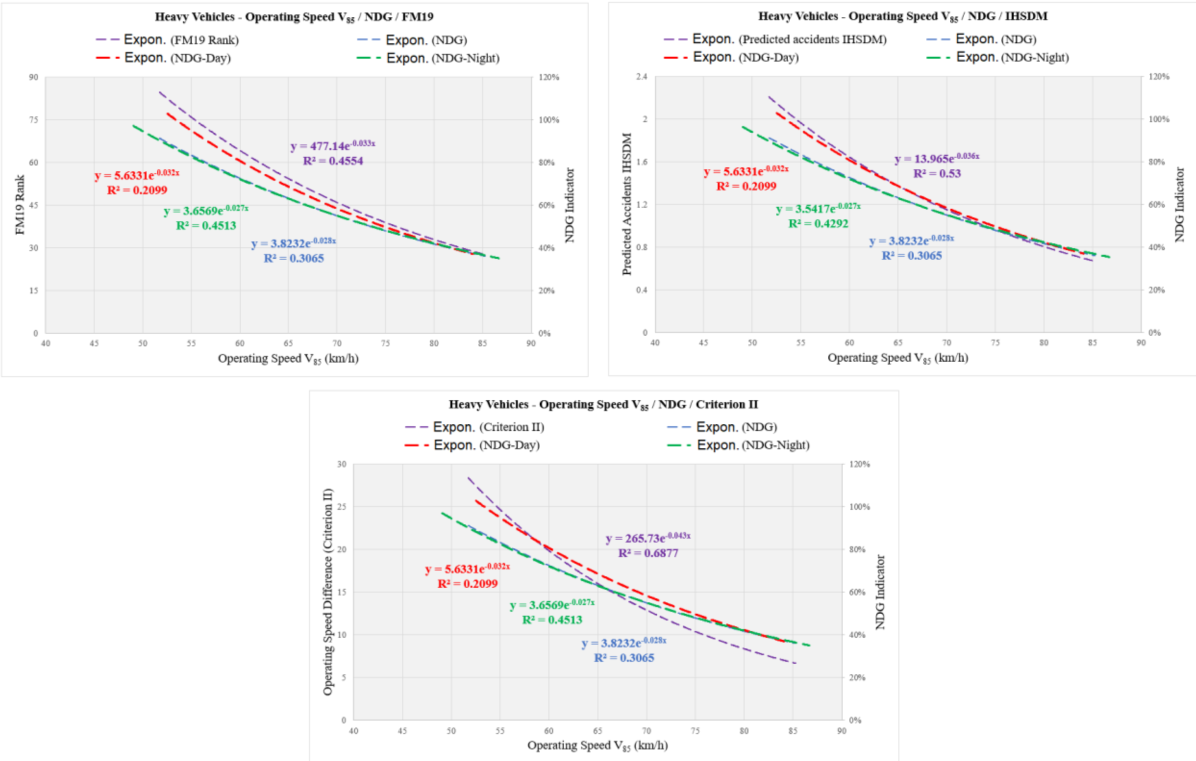

Figure 8: Heavy vehicles – Correlation between NDG and FM19 rank, Criterion II and predicted accidents IHSDM according to V_{85} variation

6. Conclusions

From the analysis presented, very important conclusions derive, which are:

- The correlation NDG achieved with all software evaluating the provided road safety level seems particularly strong in the case of passenger cars and important in the case of heavy vehicles, which indicates that it can be used as an indicator for estimating/evaluating the provided level of road safety for a single curve or an individual location of a road section. This is very important as it becomes possible to evaluate an individual point/location exclusively by speed measurements and their statistical processing and analysis.
- The difference in operating speed between heavy and passenger vehicles is about 20km/h in large horizontal curves and tangents and 10km/h in small value radii.
- Speed during nighttime hours seem to be significantly higher for passenger cars in larger radii and tangents, while at small radii values regarding to both types of vehicles speed is slightly lower during nighttime hours.

- The form and trend in the diagrams of NDG indicator are similar to the corresponding forms and trends of all software evaluating the provided road safety level (FM19, IHSDM, Criterion II), which demonstrates its correlation with the provided safety level of a road section.

7. Subject for further research

The results obtained from the conducted analysis indicate that there is a significant correlation between the dispersion of traffic speed and the provided road safety level. From the achieved progress, several aspects emerged that could not be explored in the framework of this research. Therefore, these aspects are suggested below in order to provide ideas for further research that could be implemented:

- Confirmation of the present research results by using a larger sample of measurements and for more two-lane road categories (national, provincial roads, etc.).
- Evaluation of corresponding speed measurements for highway sections in order to demonstrate correlation similarities and differences between operating speed and critical risk indicators, as well as with the expected and reported accidents.
- Evaluate differences of research results for other type of vehicles e.g. motorcycles.
- Correlate research's results and available data in order to establish mathematical relationships/equations in order to define severity of accidents (fatalities, serious/light injuries, PDO) and not only their expected number.

Author Contributions Statement

The authors confirm contribution to the paper as follows: study conception and design: K. Apostoleris, S. Sarma, B. Psarianos; data collection: K. Apostoleris, S. Sarma, S. Mavromatis; analysis and interpretation of results: K. Apostoleris, S. Sarma, S. Mavromatis; draft manuscript preparation: K. Apostoleris, S. Sarma, S. Mavromatis, B. Psarianos. All authors reviewed the results and approved the final version of the manuscript.

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