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Modeling of Operating Speeds as a Function of Longitudinal Gradient in Local Conditions on Two-Lane Roads

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Abstract: The operating speed is the average value of the speed of traffic flow under normal conditions, i.e., the conditions of mutual interference of traffic participants. The operating speed serves as a gauge for how well a given roadway is performing under the applicable traffic conditions. All key decisions in the management of the growth and utilization of a road network, including planning, designing, evaluating, and implementing road projects, depend on accurate measures of capacity and level of service. This paper aims to develop a recommended model for operating speed on two-lane roads under local conditions by analyzing the operating speeds of the traffic flow on representative sections of such roads. Through the modeling process, the values of the 85th percentile of the operating speed were determined, and compared with relevant studies. The results show that the authors have successfully modeled operating speeds as a function of longitudinal gradient in local conditions on two-lane roads.

Keywords: Traffic flow; Section; Vehicle speed; Two-lane roads

1. Introduction

Traffic analyses are a crucial component of every road design, whether it is general, conceptual, executive, or archival. Three types of traffic analyses can be distinguished: operational, designing, and planning. Operating speed determination is a key element of traffic analyses. Improving the determination leads to more reliable indicators of operating speed, which is important for application in local conditions.

The crucial aim of speed control is to strike a balance between the needs of the social community and those of the individual road user. The social community fully understands the effects of speed and works to minimize the overall detrimental effects of traffic accidents.

Determining the actual operating speed reflects one of the most significant management strategies for achieving the objective. The capacity and level of service of the observed segment can be maximized by establishing the value of the true operating speed, which also minimizes the cost to the user and the risk of traffic accidents. The determination of traffic flow speed is mainly influenced by: the technical-operational characteristics of the road, the driving dynamics of the vehicle, the degree of realization of an uninterrupted flow (indirectly, the density of nodes and the method of management) and the position of the road in the network, i.e., the influence of the roadside environment [1].

This study examines and determines the operating speed on the Klupe-Tesli (Barii) portion of the main two-lane road M-I-108 as a function of the longitudinal gradient (ascent/descent). This is extremely important, given that an incorrect or unadjusted speed has a variety of detrimental effects. It is crucial for road engineering to reach the 85th percentile of the operating speed, which guarantees a constant flow of traffic [2].

2. Literature Review

Speed, one of the primary determining factors of traffic flow, is crucial for efficiency (quality of service, trip time), safety, and other factors (occurrence and consequences of traffic accidents). Speed has an impact on mobility, goods transport, fuel consumption, toxic substance emissions, noise, and the overall quality of life of society in terms of traffic process efficiency [1]. In theory, shorter travel times result from faster speeds. Higher speeds, nevertheless, also bring more traffic accidents, and accidents are a major contributor to congestion [3]. Operating speeds on two-lane highways depend on a variety of elements including side friction, visibility, longitudinal gradients, horizontal curve lengths, curvature change rate, radius of a horizontal curve, and pavement conditions [4].

The Speed Management manual also gives instructions for setting a specific speed limit and outlines the factors that should be taken into consideration while doing so. According to the World Health Organization, pedestrians are fatally injured in roughly 80 percent of cases when traveling at 50 kilometers per hour, although this danger drops to 10 percent at 30 kilometers per hour. According to this human aspect of influence, the ideal speed should be lower than 30 [km/h] in urban areas with a high concentration of pedestrian activity [5]. Driver adherence to the posted speed limit was quite poor in the UK. A questionnaire was employed to obtain these results. It was learned that the driver's self-reported driving speed, rather than any actual measurement of speed, is what determines how credible the answers are [6].

One of the key elements impacting the veracity of the speed restriction is whether or not a curve has a reduced radius [6]. According to research, radii greater than 200-300 [m] have little impact on speed. Only radii less than 200 [m] have an impact on speed [7]. Speeds on horizontal curves with radii of more than 800 [m] are nearly equivalent to those on long straights, whereas those on curves with radii of less than 250 [m] see a dramatic decline in speed with decreasing radii. Curves get smaller as traffic flow increases, according to research that was conducted on the investigation of the impact of traffic flow size in both directions on the flow speed distribution. In the research, Rossi et al. [8] evaluated endogenous traffic characteristics, which are thought to affect the speed distribution, flow rate, and flow composition. Ostrowski and Budzynski [9] demonstrated that the following road parameters have a substantial impact on travel time and flow speed on short and long road sections in Poland: variations in curvature, longitudinal slopes, as well as lane and shoulder width.

Many countries in Europe and North America already adopt variable speed limit systems, which lower listed speed limits when they detect hazardous weather or traffic circumstances. The extent to which drivers adhere to the imposed speed limit affects how successful these devices are [10]. Additionally, the High-Definition Monitoring System (HDMS) helps gather information on how specific cars are moving. The Variable Speed Limit (VSL) is the foundation for managing crash risk [11-13].

The reason for writing this paper is the frequent speed limit violations. Generally speaking, in European countries, more than 50% of drivers do not adhere to the posted speed limit on the entire road network [5], which calls into question the effectiveness of the entire speed control system. Differentiating the road hierarchy to make it evident to drivers what is a suitable speed for the road is one way to improve drivers' speed choice and enhance safety. Drivers are warned of higher speed limits by broader traffic lanes, while pedestrian walkways and close proximity to homes are indicators of reduced speeds [14].

3. Methodology

The subject of the research in this paper is based on the research of the values of operating speeds on a two-lane road, i.e., to analyze the operating speed and, based on that, to mathematically verify the values of speeds for local conditions.

As part of this paper, the values of operating speeds of the traffic flow by vehicle classes were analyzed on the Klupe - Teslić (Barići) road section of the main road M-I-108 in Bosnia and Herzegovina. Empirical research in the field determined the values of the technical and operational characteristics of the considered section. The total width of the road on the entire section is 7.00 [m] (two traffic lanes with a width of 3.50 [m] each), and the condition of the road during all measurements was dry. Within this road section, it was necessary to measure vehicle speeds on three different longitudinal gradients (ascents/descents) which are: ±3.00%, ±5.70% and 4.06%. On the basis of the available data from the database of PE "Roads of RS", the values of the longitudinal gradients at the planned measuring sections were taken. Given that the speeds on a descent and ascent were measured separately, the research was carried out on six different sections, which are shown in Figure 1. Subgraph (a) of Figure 1 presents the section where the speed on an ascent of + 3.00% is measured, and subgraph (b) of Figure 1 is the section where the speed on a descent of -3.00% is measured. Analogously, subgraph (c) of Figure 1 presents the cross section on an ascent of +5.70%, subgraph (d) of Figure 1 presents the cross section on a descent of -5.70%, subgraph (e) of Figure 1 presents the cross section on an ascent of +4.06% and subgraph (f) of Figure 1 presents the cross section on a descent of -4.06%.

Vehicle speed is determined by measuring the time it takes for the vehicle to cross a marked road section of a certain length using the following expression:

$$V = 3.6 \cdot \frac{d}{t} \text{ [km/h]} \quad (1)$$

where,
V - speed [km/h],
d - length of measuring section [m],
t - time measured [s].

Figure 1. Sections where speed measurements were made

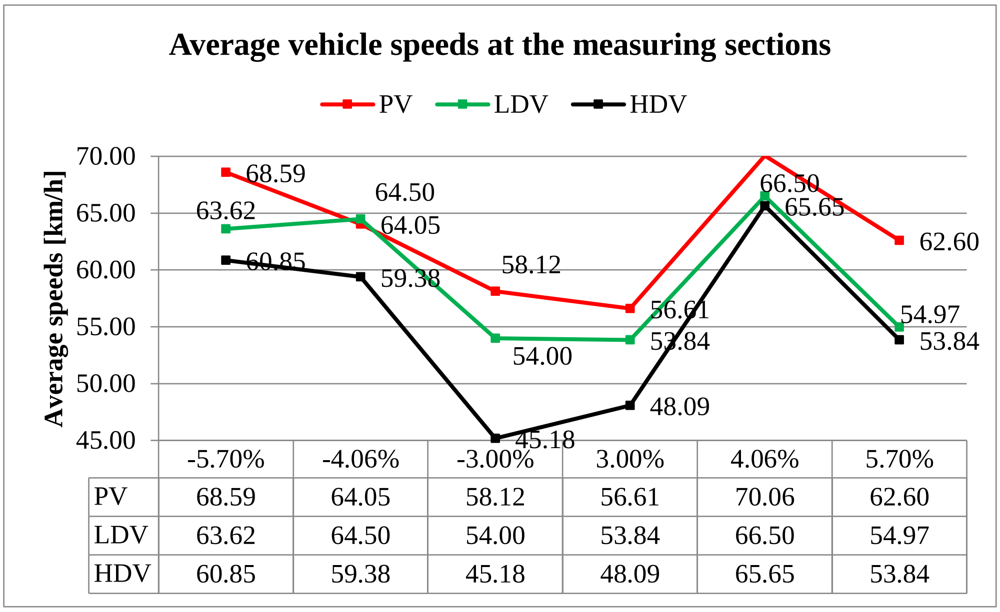
The number of accesses on the entire length of a gradient of 3.00%, which is 904 [m], is on average 6.64 [accesses/km], on the length of a gradient of 5.70% of 1000 [m] is 15 [accesses/km], and on the length of a gradient of 4.06% of 796 [m] is 26.38 [accesses/km]. That is, on the segment of the Klupe - Teslić section with a gradient of 3.00%, there is one access point every 150.00 [m] on average, on the segment with a gradient of 5.70% there is one access point every 66.67 [m], and on the road segment with a gradient of 4.06%, there is one access point every 37.90 [m] on average.

The method of measuring speeds on the observed cross sections and the statistical method were used as the main methods of data collection for the research. In order to obtain the results, it was conducted empirical research on measuring speeds in real road and environment conditions with a handheld radar manufactured by Bushnell NSN 5840-01-620-6670. It has been determined a required sample size which is at least 410 vehicles at each of the six observed measuring sections, and the total sample for analysis is 2563 measured speeds of different classes of vehicles. In the paper, it has been given the main hypothetical assumption that the values of operating speed deviation from those limited in practically ideal road conditions are primarily dependent on the structure of the traffic flow and the driving-dynamic characteristics of vehicles.

As part of data analysis and synthesis, after conducting the measurement, it was created a database in Microsoft Office Excel v. 2010, where the data were analyzed, and the graphs of the distribution of the relative frequency of certain classes of vehicles on different gradients along the section of the M-I-108 main two-lane road, Klupe - Teslić (Barići), and the calculation of the 85th percentile were obtained with the statistical software package TableCurve 2D V5.01. By entering the values from tables created in Microsoft Office Excel into the TableCurve 2D V5.01 statistical program, it was obtained the speed distribution graphs which were mostly distributed by Normal (Gaussian) or Logarithmic-Normal distribution. For each measuring point, the speeds of individual vehicles in each class were measured, and then the arithmetic mean (AM), standard deviation (STDEV) and variation coefficient were calculated. Vehicles in each class (PC, LDV and HDV) were then grouped by speed into 2 [km/h] wide speeding classes to obtain a speed distribution.

4. Research Results

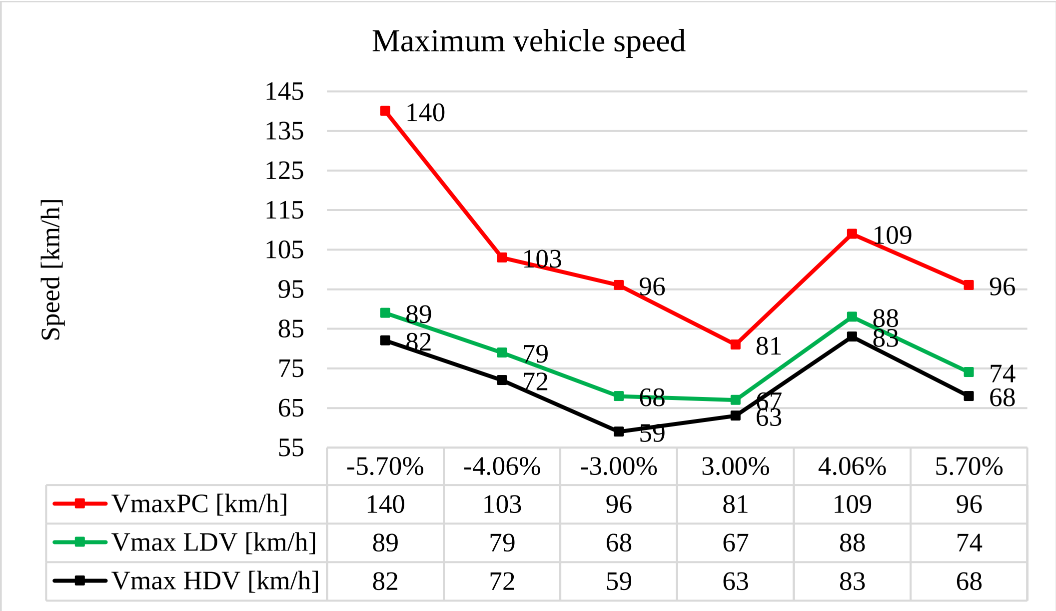
The operating speed is an average value of traffic flow speed under normal conditions, i.e. conditions of mutual interference of traffic participants. Figure 2 shows the average speeds of all vehicles (taking into account drivers who drive at extremely high speeds, over 40 [km/h] from the limit).



	-5.70%	-4.06%	-3.00%	3.00%	4.06%	5.70%
PV	68.59	64.05	58.12	56.61	70.06	62.60
LDV	63.62	64.50	54.00	53.84	66.50	54.97
HDV	60.85	59.38	45.18	48.09	65.65	53.84

Figure 2. Average operating speeds of vehicles on the M-I-108 road

It is also important to show the maximum vehicle speeds recorded during the research. Based on the research, it can be concluded that the speeds on a descent are predominantly higher than the speeds on an ascent, except for a gradient of 4.06% where the speeds are higher on an ascent, and this can be explained by the fact that all classes of vehicles that drive on that descent have to slow down because they encounter a curve. The maximum obtained speed values for all vehicle classes can be observed on a descent of -5.70% and ascent of +4.06% because that part of the section is straight. Namely, it is important to note that the number and width of traffic lanes and the condition of the road were the same on all slopes along the observed section. As can be assumed, the highest speeds were driven by passenger cars, and the slowest by heavy duty vehicles, which can be seen in Figure 3.



	-5.70%	-4.06%	-3.00%	3.00%	4.06%	5.70%
VmaxPC [km/h]	140	103	96	81	109	96
Vmax LDV [km/h]	89	79	68	67	88	74
Vmax HDV [km/h]	82	72	59	63	83	68

Figure 3. Maximum vehicle speeds on measuring segments of M-I-108 Klupe – Teslić (Barići) section

Figure 4 shows the distribution of the individual class of vehicles (PC) that exceed the speed limit on a descent of -3.00%, where passenger cars have a distribution that is in accordance with the Gaussian distribution, and the distribution of heavy duty vehicles corresponds relatively well to the aforementioned distribution.

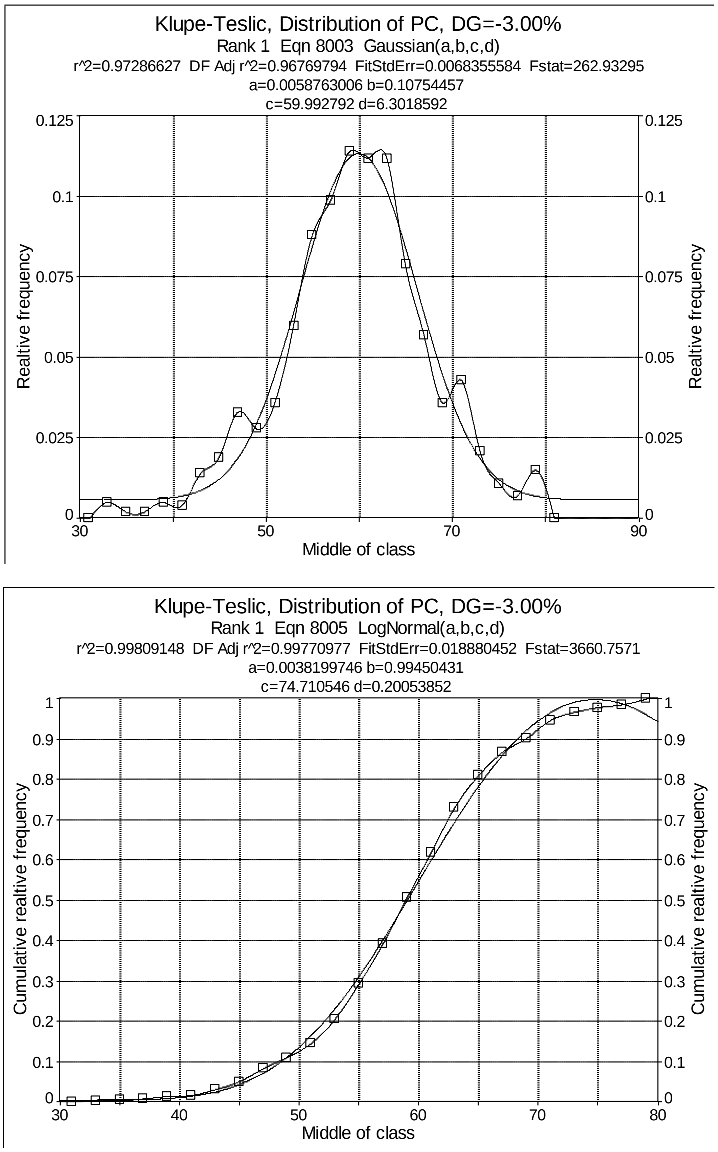
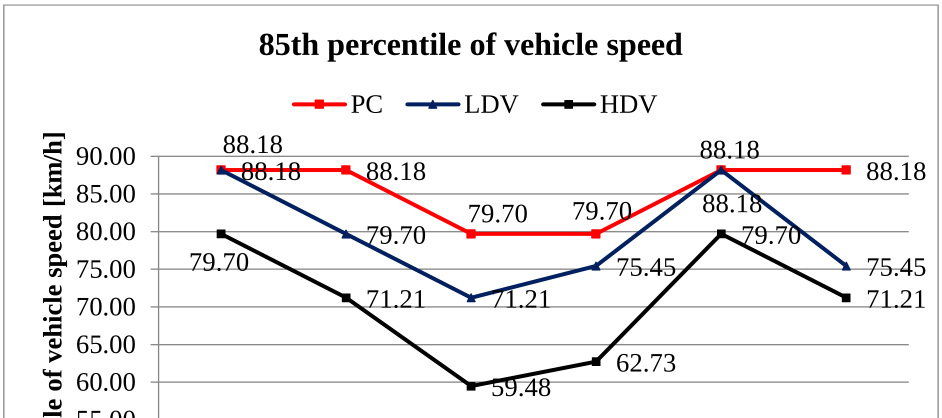


Figure 4. Determining the relative and cumulative frequency of PC speeds on a descent of -3.00%



	-5.70%	-4.06%	-3.00%	3.00%	4.06%	5.70%
PC	88.18	88.18	79.70	79.70	88.18	88.18
LDV	88.18	79.70	71.21	75.45	88.18	75.45
HDV	79.70	71.21	59.48	62.73	79.70	71.21

Figure 5. Values of the 85th percentile of vehicle speed in the traffic flow on the M-I-108 road

Table 1 shows the detailed speeding values of the considered vehicle classes.

Based on the obtained values, it can be concluded that the existing speed limit of 50 [km/h] on the Klupe-Teslić (Barići) section is not credible. In case that the speed limit is not credible, one of two possible solutions to the problem is resorted to: redefining the existing speed limit based on a system analysis, which means increasing or decreasing the existing values, or changing the elements of the road and the environment by applying certain design measures in accordance with the conditions of the traffic flow [15]. For this reason, it was calculated the 85th percentile value. The value of the 85th percentile of speed was obtained using the statistical software TableCurve 2D V5.01. This means that with a certainty of 85.00% it can be claimed that vehicles on the Klupe - Teslić (Barići) section will drive at the speeds shown in Figure 5.

Table 1. Speeding of certain classes of vehicles according to speed classes on observed gradients

Longitudinal gradient [%]	Vehicle classes	Speeding classes [km/h]			
		up to 10 [km/h]	10 – 20 [km/h]	20 – 30 [km/h]	30 – 40 [km/h]
-5.70%	PC	24.22%	30.75%	27.95%	17.08%
	LDV	35.71%	39.29%	14.29%	10.71%
	HDV	41.18%	35.30%	11.76%	11.76%
-4.06%	PC	29.60%	37.07%	24.42%	8.91%
	LDV	27.27%	54.55%	18.18%	0.00%
	HDV	44.45%	44.44%	11.11%	0.00%
-3.00%	PC	46.98%	44.30%	8.05%	0.67%
	LDV	84.21%	15.79%	0.00%	0.00%
	HDV	100.00%	0.00%	0.00%	0.00%
+3.00%	PC	50.88%	40.35%	8.42%	0.35%
	LDV	62.50%	37.50%	0.00%	0.00%
	HDV	94.12%	5.88%	0.00%	0.00%
+4.06%	PC	18.29%	30.79%	26.83%	24.09%
	LDV	11.11%	38.89%	38.89%	11.11%
	HDV	16.00%	52.00%	28.00%	4.00%
+5.70%	PC	31.14%	42.81%	20.96%	5.09%
	LDV	47.62%	42.86%	9.52%	0.00%
	HDV	55.56%	44.44%	0.00%	0.00%

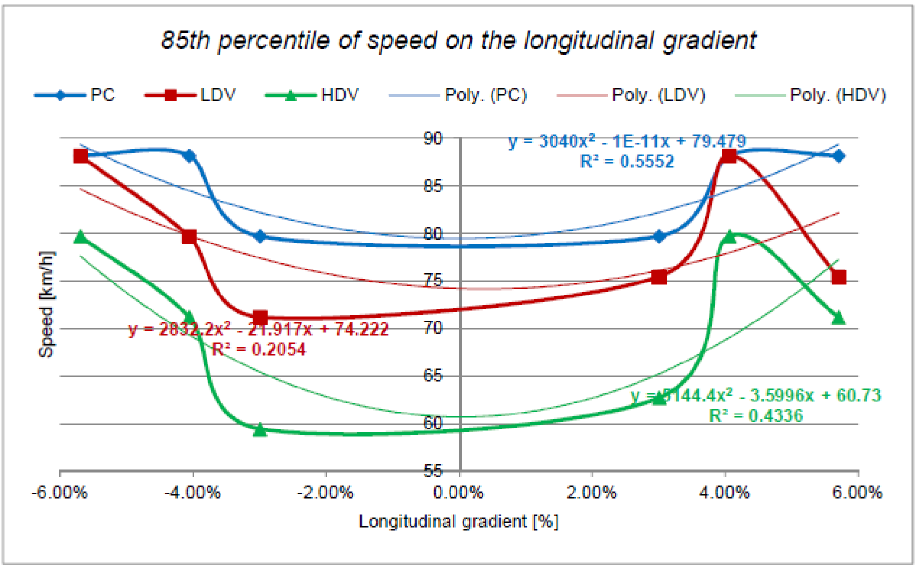


Figure 6. Model of the 85th percentile of speed of different classes of vehicles on a slope

Based on the results obtained with the statistical software package TableCurve 2D V5.01, it was also obtained a regression model of the 85th percentile of speed, shown in Figure 6. For passenger cars and heavy duty vehicles, the correlation of medium strength was identified due to the coefficient of determination, which is 0.56 and 0.43, respectively, and for light duty vehicles, this coefficient is 0.21, which is weak correlation according to Chadock's scale of values.

The research conducted on the observed section Klupe-Teslić (Barići) provided the mean values of the measured speeds for all three classes of vehicles. Figures 7-9 show a comparison of those average speed values with research results obtained in Serbia [16]. It can be seen that the results obtained on the Klupe-Teslić section deviate from the measured values in Serbia. By synthesizing the data, the obtained values of the measured speeds match for light duty vehicles for the approximate values of LG = - 5.00%, LG = +4.00% and LG = +5.00%, and when it comes to the average speeds of heavy duty vehicles, it is observed that the speed values match for approximate values of LG = -4.50% and LG = +3.50%.

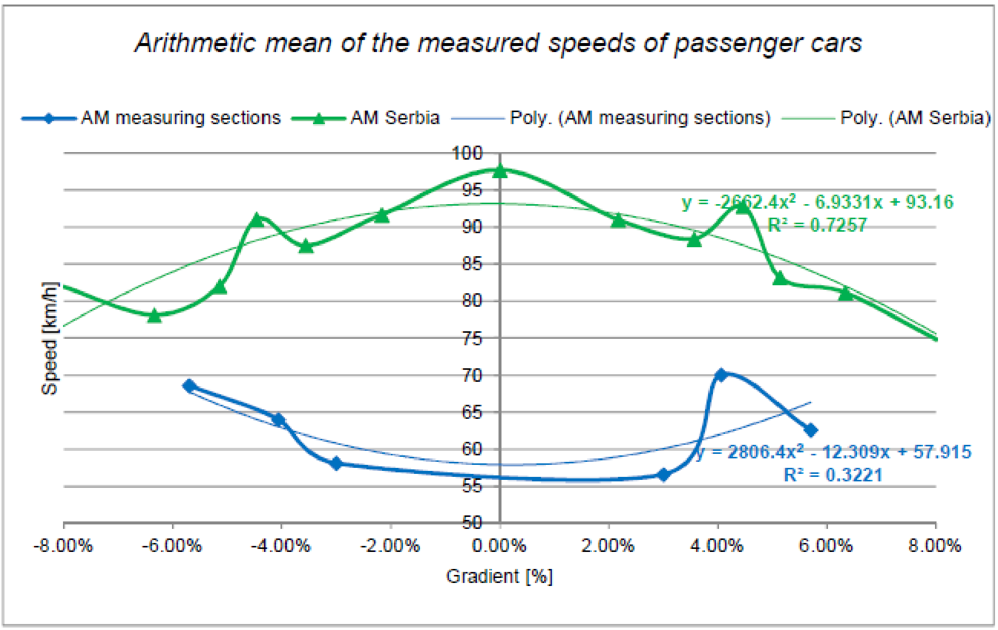


Figure 7. Comparison of arithmetic means of measured speeds of passenger cars [16]

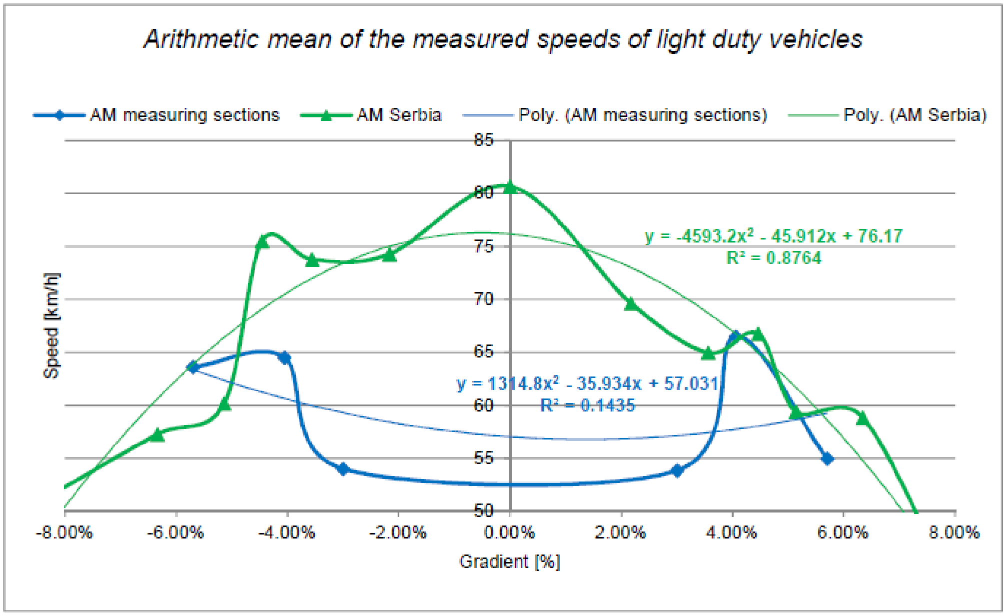


Figure 8. Comparison of arithmetic means of measured speeds of light duty vehicles [16]

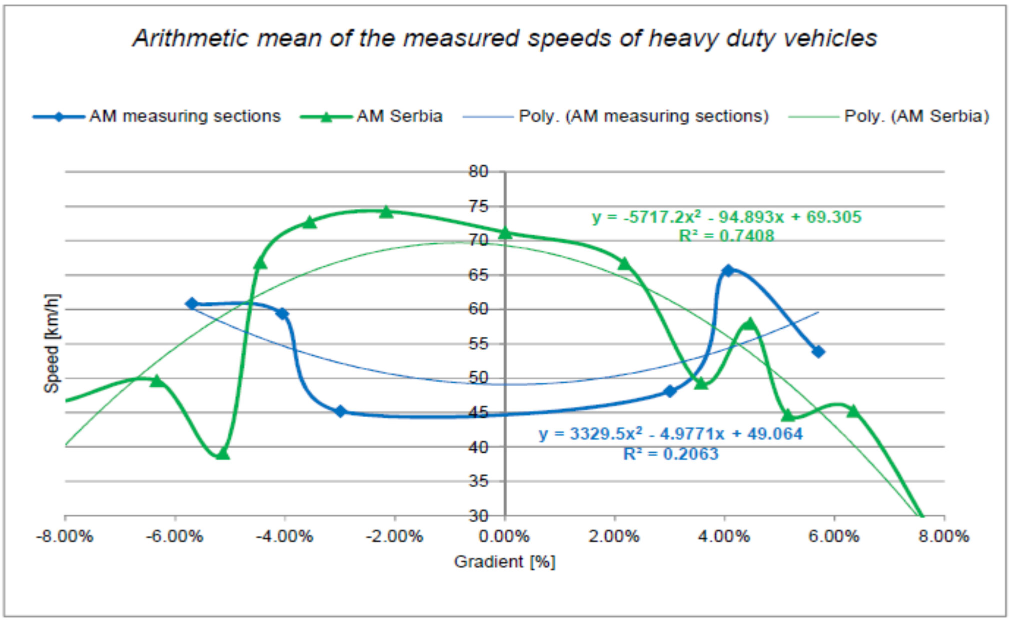


Figure 9. Comparison of arithmetic means of measured speeds of heavy duty vehicles [16]

The calculation of the 85th percentile of vehicle speed has been compared in Figures 10-12. In most cases, higher speeds for the 85th percentile were obtained for all classes of vehicles recommended for the territory of Serbia, with the exception of the speeds of light and heavy duty vehicles on sections with approximate gradients, LG = -5.70% to -4.50% and LG = +3.50% to +5.70%.

Figure 13 shows the average measured speed values for three classes of vehicles on sections in Croatia compared to the Klupe-Teslić section.

Observing speeding by vehicle classes, it was observed that 87.40% of PCs, 79.58% of LDVs and 67.79% of HDVs exceed the speed limit. Based on the results of the research conducted in Serbia [17], in daily conditions 64.10% of passenger car drivers drive the vehicle at a speed higher than the limit for the urban area, and 36.80% of the drivers of heavy duty vehicles exceed the speed limit for the urban area, which is 50 km/h. It can be concluded that there is significantly higher speeding on the analyzed section Klupe - Teslić (Barići).

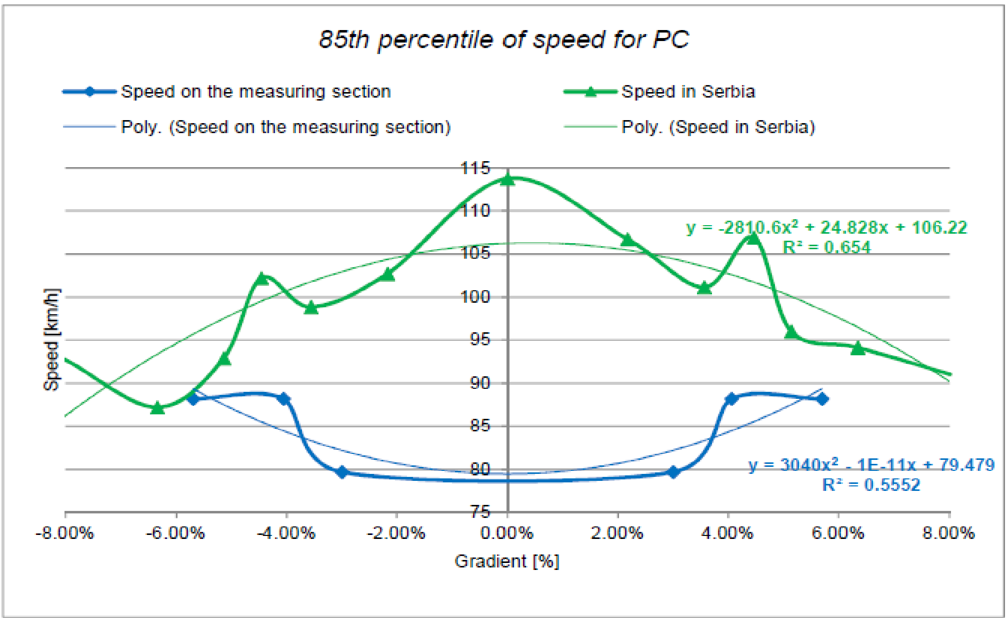


Figure 10. Comparison of 85th percentile of speed for passenger cars [16]

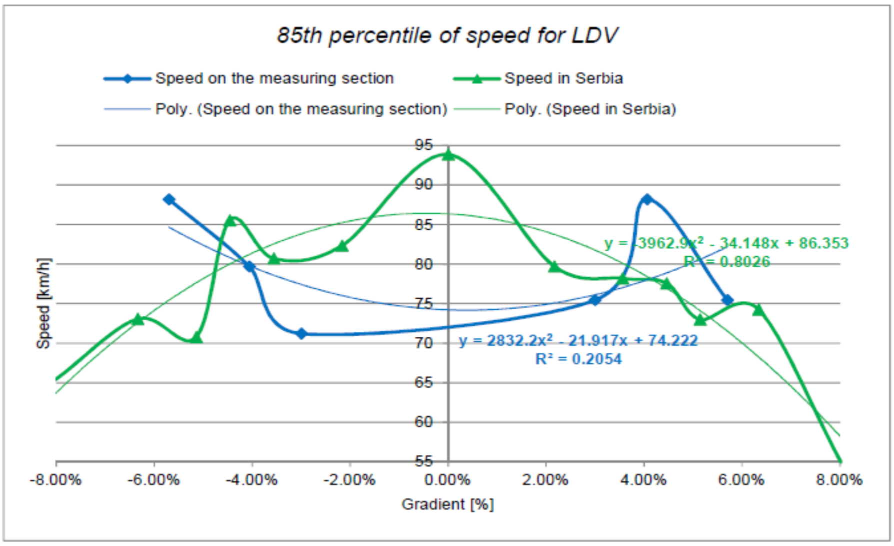


Figure 11. Comparison of 85th percentile of speed for light duty vehicles [16]

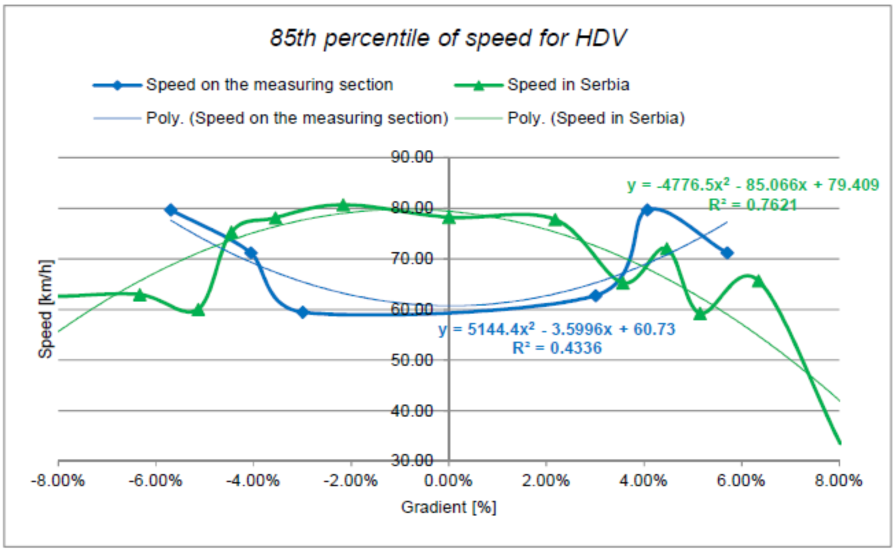


Figure 12. Comparison of 85th percentile of speed for heavy duty vehicles [16]

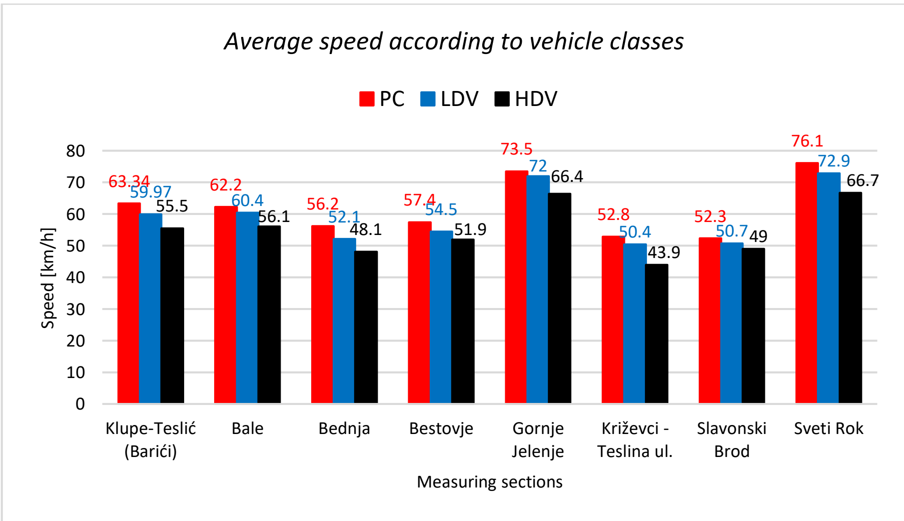


Figure 13. Comparison of average speeds in Croatia and on the observed section

5. Discussion of Research Results

A scatter diagram was used to determine the form of regression of the arithmetic mean of speeding, standard deviation and 85th percentile of speed. On those diagrams, it can be seen that the curve of measured speed values for heavy duty vehicles is below the curve for light duty vehicles, and the curve of light duty vehicles is below the curve for passenger cars on the basis of which it can be claimed that it is relatively lower the arithmetic mean of speeding, standard deviations and 85th percentile of speed for light and heavy duty vehicles compared to passenger cars, i.e. passenger cars have the highest values, light duty vehicles have slightly lower values, and heavy duty vehicles have the lowest values. It is also observed that the arithmetic mean of speeding, standard deviation and 85th percentile of speed of all classes of vehicles are lower on sections with a longitudinal gradient from -3.00% to + 3.00%.

Based on the analysis carried out, the following measures are proposed: implement more rigorous controls and ensure compliance with the existing fixed limit as a short-term solution or change the existing speed limit on the observed section as a long-term solution.

6. Conclusions

The subject of the research in this paper is based on the analysis of operating speeds and the creation of a model to determine their values, and based on that, to examine the adequacy of the credibility of limited speeds. It is the lack of appropriate models of operating speeds that is a problem in real design solutions, which is also what this research is based on. In the empirical part of the research, it was necessary to measure operating speeds on several measuring sections of two-lane roads (ascent/descent), define speed limits by vehicle classes, and compare the gained values with the values obtained by other researchers.

Based on the analysis conducted, it has been confirmed the main hypothetical assumption that the values of deviations of operating speeds from those limited in practically ideal road conditions depend primarily on the structure of the flow and the vehicle's driving-dynamic characteristics. The confirmation of the hypothetical assumption refers to the deviations of speed values for different classes of vehicles in real and at the same time in ideal conditions. The empirical arithmetic means of speeds and 85th percentile values of speeds of different vehicle classes on all observed gradients actually represents a model recommended for local conditions for determining speed values on two-lane roads as a function of the percentage of longitudinal gradient. The model equations are given in Table 2. Good pavement condition and greater distance of lateral obstructions from the pavement also contribute to higher driving speeds.

Table 2. Analytical model recommended for local conditions to determine the 85th percentile of speeds on two lane roads

Vehicle class	Model
PC	$y = 3040x^2 - 1E\text{-}11x + 79.479$
LDV	$y = 2832.2x^2 - 21.917x + 74.222$
HDV	$y = 5144.4x^2 - 3.5996x + 60.73$

The total percentage of drivers who exceed the speed limit on the observed section is 85.78%. On all observed gradients, only a small percentage of drivers respect the posted speed limit. Those sections of the road are straight, so drivers have no objective reason why they should reduce their speed. Favorable road and traffic conditions allow vehicles to move at speeds that are higher than the speed limit. Drivers drive at higher speeds on roads with wider traffic lanes and on sections of roads that are straight.

As part of the direction of further research, it is important to continuously carry out measurements of operating speeds on all road sections in Bosnia and Herzegovina, which, with appropriate monitoring, would lead to indicators for risky sections, as well as to a significantly more accurate model that is recommended for local conditions for determining exceeded speeds on two-lane roads. Improving the database with additional analysis of speeds in different time periods (weekdays, weekends, peak and off-peak periods) would create a valid basis for setting credible limits and dynamic speed management.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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