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Research Article

Models of Analysis of Credible Deviation from Speed Limits on Two-Lane Roads of Bosnia and Herzegovina

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Any deviation of speed in a traffic flow from a speed limit represents a potential risk of traffic accidents, so speed management appears as an imperative. However, an inadequately set speed limit often causes drivers' noncompliance to it in the conditions of real traffic flow. By determining the value of exceeding the speed limit according to vehicle classes, it is possible to recommend a credible speeding value that can be considered credible up to a value above the speed limit. In this paper, deterministic multistep mathematical models of speed deviation from the speed limit as a function of longitudinal gradient for the proposed vehicle classes were developed. A total of 11 measuring sections with different traffic flow types were analyzed. Based on a detailed analysis of speeding, models for the deviation of the 15th, 50th, and 85th percentiles were obtained, with the aim of adjusting the credible deviation to control measures. The results obtained in this study were compared with a survey of traffic flow speeding on two-lane roads conducted in Serbia.

1. Introduction

Roads represent significant resources and the most important public investments of a country, with significant funds allocated for the construction and maintenance with two fundamental tasks, to be efficient and to be safe. In real traffic flow, almost all functional dependencies are based on the relationship between flow, speed, density, number of traffic accidents, etc. as traffic parameters, and longitudinal gradient, road condition, minimum radius of horizontal curvature, etc. as road characteristics. Special attention in the analysis of the functional dependence of traffic and road parameters is expressed for two-lane roads since a large percentage of these roads make up the largest part of the road network of a country. By analyzing traffic parameters, it is evident that the speed of traffic flow is one of the main parameters, and, at the same time, a main indicator for sizing and functional and economic evaluation of project solutions. Any speeding in a traffic management system implies the application of an adequate speed management policy in order to ensure a harmonized traffic flow.

Deviation from a speed limit is mainly connected with the increased probability of traffic accidents. Additionally, determining a credible deviation from a speed limit of a real traffic flow is an imperative in the analysis of speeding, and thus reducing a potential occurrence of incidents. Commonly, the number of traffic accidents and the increase in risk are related to operating speeds. Operating speeds have been shown to be higher than design speeds for a speed limit of about 55 mph or less. Therefore, it is very important to analyze speed through five specific indicators of the dependence of speed on the geometric characteristics of the road. These are relationships between road geometry and operating speeds, influence of road geometry on operating speeds, influence of safety and security on road geometry, potential impacts on large vehicles, and nature of the speed-safety trade-off [1].

Analysis and determination of the value of appropriate speed limit exceeding represent the power in decision making in traffic engineering, which is often neglected. Any deviation from the speed limit is related to technical and exploitation characteristics of the road, driving and dynamic characteristics of vehicles in a flow, as well as to the psychophysical abilities of drivers. It was shown that after the 20 mph intervention, control of confounding variables for driver speeds declined [2, 3]. For example, on the slope ranging from −5.50% to 4.50% on the measuring plateau or terrain, it was found that the speed decreases with increasing the slope (ascent and descent), but the stress during driving increases on the descent and ascent [4]. Also, within this research, measuring sections on the ascent were identified as potential places with a high percentage of traffic accidents. According to the research [5], about 40% of drivers drive at free speed over the allowed speed limit, and this percentage of speeding varies from location to location. It was concluded that the 60 km/h limit was not appropriate for most of the locations selected. In traffic and operational analyzes conducted on two-lane roads, unadjusted speed is one of key indicators of traffic accidents. The importance of the 85th percentile of speed is especially emphasized in the scientific literature since it is a representative speed for design analyses in a traffic flow of road network users [5–9].

Modern HCM (Highway Capacity Manual) methodology [10], depending on the speed limit, can classify all two-lane suburban roads into three classes. Based on the recommendations from HCM, in this research, it has been analyzed two-lane class II roads in Bosnia and Herzegovina, where the speed limit does not exceed 80 km/h. The assessment of the qualitative measure of the Level of Service (LOS) has not been analyzed as it is based on the determination of the percentage of time losses and not on the mean value of speed or deviation from the speed limit [10]. The German methodology HBS 2001 [11] mainly expresses the problem of the functional dependence of travel speed on traffic lane width. This method defines a minimum lane width of 2.75 m, while on some sections in Bosnia and Herzegovina, the lane width can be 2.50 m.

The main contribution of this paper is reflected in the formation of deterministic models for predicting the deviation of real speeds of different vehicle classes from speed limits as a function of longitudinal gradients (ascent and descent). This enables the consideration of speed limit credibility in local conditions on specific segments of sections, i.e., the adoption of adequate engineering measures in terms of setting a credible limit in order to harmonize speeds in traffic flow and improve traffic efficiency and safety.

Further in the paper, a review of relevant literature is presented. Subsequently, Section 2 presents the methodology required for data analysis and synthesis, with the limitation and selection of adequate sites for empirical research. In Section 3, the results are provided with multistep empirical models, deterministic graphical models, and comparison of research results with surveys in Serbia. In Sections 4 and 5, the discussion and conclusion of the paper are given.

2. Literature Review

Studies based on an analysis of individual drivers' attitudes and behaviors while driving can predict the level of compliance with speed limits including the perception of speed limit credibility and the perception of road risks [12]. The harmonization of the geometrical characteristics of the road with the expectations of drivers is performed according to their own perception of the road, and not according to the designer's perception (projected speed) [7]. In general, the geometry of the road, the characteristics of drivers, and weather conditions are important factors that influence the drivers' decision to adhere to the existing speed limit. However, the establishment of credible restrictions is possible only if the factors that affect drivers' compliance are identified [2, 13, 14]. Additionally, some studies show that a deviation from a speed limit for drivers is realistically acceptable if it is 10% higher than the speed limit on the roads [15, 16]. Lee et al. analyzed the average speed and standard deviation according to the speed limit using driving record data and confirmed the effect of reducing the average speed [17].

The main reason for exceeding speed limits, by some authors, refers to the credibility of set speed limits because drivers do not consider them realistic [18–20]. However, some authors have investigated the functional dependence of speed, length of individual geometric elements of the road, radius of curvature, transverse/longitudinal gradient, and traffic accidents [21–24]. Also, the research presents the problem of reducing speed due to the geometric characteristics of the road. The reduction in the speed of heavy-duty vehicles was specifically analyzed in the study [25], where a longitudinal gradient of 9.0% at 1.20 km of the road was taken into account, which significantly reduced the speed of heavy vehicles. According to this study, in order to increase speed due to influential road factors, the mass/power ratio must be improved [25]. Based on a report conducted in Texas [26], regression analysis identified that the following variables affect the prediction of traffic accidents: AADT (Annual Average Daily Traffic), lane width, shoulder width, and section length. The use of wider longitudinal markings on the road leads to a reduction in the speed of vehicles, and thus a reduction in the number of traffic accidents. The analysis of speed reduction in day and night driving conditions at average traffic load resulted in the following reduction of vehicle speed: by 2.24% in the day and by 1.96% at night for light vehicles, and 2.46% in the day and 2.15% at night for heavy vehicles [27]. In the analysis of the Bayesian network for predicting the probability of the influence of traffic and road factors on the occurrence of traffic accidents, the following are especially emphasized: vehicle speed, horizontal curve radius, vehicle type, adhesion coefficient, and longitudinal slope [23]. Also, the results of a study [24] show that the continuous use of several limit indexes and the excessive average slope of long and steep sections of roads were one of the major causes of frequent accidents on a section of HeXi road in China. In their study, Silvano et al. assessed the impact of technical and exploitation characteristics of the road and changes in speed limits on the speed of free traffic flow using an extensive dataset of urban roads [28]. Based on a survey conducted in Poland, it was found that for a speed limit of 90 km/h in free traffic conditions, 38% of light vehicles exceed the speed limit during the day and 42% at night. For heavy vehicles with a limit of 70 km/h, speed limit exceeding of this class of vehicles in same traffic flow conditions is 83.5% in the day and 86% at night [29]. Research focused on the credibility of the 80 km/h speed limit of two-lane rural roads, where drivers verified the proposed speed for each of 27 road situations, which shows that there were large differences in drivers' attitudes for different road and environmental characteristics related to (non) compliance with the limits in given situations [16]. In addition, based on research in Malaysia, two experiments were conducted where photographs of a situation were presented to drivers, without a speed limit, based on which drivers chose speeds. The second experiment was based on the assessment of appropriate speed of drivers created according to a subjective attitude for a given situation. Experiments have concluded that there are limits within which drivers can modify their estimates of appropriate driving speed, based on speed limits [30]. According to a study [31] conducted in the UK, 30 mph (Urban Road) and 70 mph (Rural Motorway) limits were characterized as credible, 40 mph (Urban Motorway) as too slow, and 60 mph for a measuring rural location (Rural single carriageway) as a too high-speed limit. In our region, a study [32] was conducted in Serbia based on the examination of the value of speeds on highways and two-lane roads in a function of longitudinal gradient. Within this research, models of free traffic flow speeds as a function of longitudinal gradient were developed.

The research in Bogotá reduced the speed limit from 60 km/h to 50 km/h for 3 different periods starting from 2017 to 2019. The average speed reduction in the corridors with speed management was 1.48 km/h during daytime and 3.04 km/h during nighttime, and without speed management, the average speed reduction was 0.7 km/h during daytime and 2.2 km/h during nighttime. By reducing the speed limit, the average number of driving accidents was reduced by 10% [14]. Similar research was conducted in Boston where the speed limit was reduced from 30 mph to 25 mph. It was concluded that setting a speed limit of the 85th percentile of free flow speed can be a hurdle for local communities looking to lower speed limits [9]. By analyzing studies of posted speed limit (PSL) from 50 to 40 or 60 km = h, the results showed that a reduced PSL to 40 km/h was a significant reduction in the mean free-flow speed and speed variance, while an increased PSL to 60 km/h resulted in an increase in the mean free-flow speed, but without a change in speed variability. [33].

Also, the analysis of transport networks has established that during early morning hours with very light traffic, the impact of lowering speed limit was significant. During congested time periods, the travel speed reduction from lowering speed limit was not significant. [20].

Based on variable speed limit (VSL) research, it was shown that under medium and lower traffic density conditions, different VSL values can always reduce the mean traffic speeds and under similar traffic conditions, most VSL values reduced the speed differences between consecutive vehicles, thereby reducing the speed discretions in the traffic stream [34].

3. Research Methodology

Monitoring speeding is an integral part of speed management policy. However, setting speed limits on a road network does not mean compliance with it by drivers who exploit the road. The main goal of the research, which is based on the examination of speeding on sections of two-lane roads, is given in this section of the paper. Within the methodology, measuring sections were selected, the values of speed deviations from speed limits were determined, and then the necessary analysis and synthesis of collected data were carried out. The hypothetical framework of this research is based on the assumption that with increasing the longitudinal gradient (ascent/descent) in real conditions, the deviation of traffic flow speed values from the speed limit increases. This statement is based on all classes of vehicles, Passenger Vehicles (PV), Light Duty Vehicles (LDV), Heavy Duty Vehicles (HDV), Buses (BUS), and depends on a large number of influencing environmental factors. Also, in accordance with the hypothetical framework, the research [4] has shown that with increasing a slope (ascent/descent) increases the deviation of speeds beyond the speed limits, which also applies to the level of stress. Credible speed deviation from the speed limit implies a credible deviation if it corresponds to road and environmental conditions and if most drivers comply with it as a deviation. If road and environment conditions are not in accordance with the speed limit (favorable technical and exploitation characteristics of the road, and low speed limit), it cannot be considered credible. Relevant literature for the analysis of the values of credible speed deviation from the speed limit provides quite contradictory views, so that the deviation values are verified from values where there is no deviation from the speed limit to extreme values of deviation [5, 28, 35].

In this paper, we conducted a survey on eight measuring sections (11 cross-sections–S_1–S_{11}) in order to define the values of credible deviation from the speed limit on two-lane class I roads on the basis of a reference sample, and in a form of a recommendation. The use of the model for calculating a credible deviation from the speed limit is based on deterministic mathematical modeling, with the aim of adapting the model to real road conditions in Bosnia and Herzegovina. Research methodology and techniques, site selection, and data processing methods are given in Table 1 and were used by the following criteria:

Determining a credible deviation involves classifying vehicles (PV, BUS, LDV, and HDV) on 11 sections as a function of longitudinal gradient (ascent/descent). At each measuring section given in Table 2, it was determined by empirical research that more than 65% of vehicles exceed the

Table 1: Criteria for obtaining the values of a credible deviation from the speed limit.

Applied methodology	The basic method of defining credible speed deviation from the speed limit ($\Delta V = V_{real}$- V_{lim}), observation of four classes of vehicles and their grouping (PV, BUS, LDV, and HDV)
Recording technique	Using a special measuring device (handheld radar) bushnell NSN 5840-01-620-6670
Site selection	Road class: Standard two-lane roads (class I highway)—two-lane class II roads (according to HCM-2016) [10] Traffic lane width: from 2.75 m to 3.5 m Distance from side disturbances: <2.50 m Access density (on one side): <13 access points/km Terrain: flat or hilly suburban road Speed limit: 50–80 km/h Free flow speed: speed limit + 10–20 km/h Overtaking lane length (if any): location specific Road condition: good condition Longitudinal gradient: $-5.70 \leq G \leq 7.00$ Length of measuring section from a cross section: min 1000 m Traffic light intersection: none There is no impact of pedestrian flows
General information on traffic requirements	Traffic criteria: medium traffic load; higher percentage of commercial vehicles (15 and more); relevant flow according to the 200th hour criterion ≤12% AADT; percentage of traffic requests by directions: 60/40; lack of influence of parking or bus stops, recording in a peak and nonpeak period
Data processing	Based on the average values of individual locations and the summary average values, the values of speeds that do not exceed the speed limit are ignored in the analysis.

Table 2: Percentage of speeding as a function of difference between free and speed limit.

Two-lane road section		Section mark	Section length	Ascent/descent at 1000 m in %	AADT 2017 (veh/day)	V_{fr} (km/h)	Speed limit vlim (km/h)	% Speeding
S_1	Klupe–Teslić	M-I-108	16.734	−5.700	6498	**63**	**50**	90.12
S_2	Klupe–Teslić	M-I-108	16.734	−4.060	6498	**66**	**50**	89.42
S_3	Klupe–Teslić	M-I-108	16.734	−3.000	6498	**61**	**50**	80.91
S_4	Maglaj–Ozimica	M-I-110	10.520	−2.760	10086	**82**	**70**	87.00
S_5	Maglaj–Ozimica	M-I-110	10.520	−1.700	10086	**90**	**80**	67.42
S_6	Maglaj–Ozimica	M-I-110	10.520	−1.350	10086	**79**	**70**	75.37
S_7	Šepak–Karakaj 3	M-I-115	20.950	1.000	6408	**69**	**50**	65.28
S_8	Teslić–Klupe	M-I-108	16.734	3.000	6498	**60**	**50**	75.98
S_9	Teslić–Klupe	M-I-108	16.734	4.060	6498	**71**	**50**	93.40
S_{10}	Teslić–Klupe	M-I-108	16.734	5.700	6498	**64**	**50**	86.34
S_{11}	Border (RS/FBIH)–Donje Caparede	M-I-110	3.140	7.000	4305	**64**	**50**	73.22

speed limit on selected measuring sections of two-lane roads. Also, based on the insight into the database on traffic flows of PE "Roads of RS" and PE "Roads of BiH" for 2017, the section of the two-lane road M-I-108 shows a representative value of hourly load $q_{\mathrm{m200}} = 545$ (veh/h), which is 8.38% of AADT. The shortest section M-110 Border (RS/BIH)—Donje Caparde has a low value of hourly load $q_{\mathrm{m200}} = 346$ (veh/h), which is 8.03% of AADT.

Determining the deviation from the speed limit selected according to vehicle classes appearing on the measuring sections implies the calculation according to the following equation:

$$\Delta V = V - V_{\mathrm{lim}}\left(\frac{\mathrm{km}}{\mathrm{h}}\right), \tag{1}$$

where V is the measured vehicle speed, V_{lim} is the speed limit on a measuring section.

The speed limits that were analyzed are also the most common limits set on class I highways in Bosnia and Herzegovina (50 km/h, 70 km/h, and 80 km/h). It is assumed that the values of the speed deviation from the speed limit on an ascent/descent range from 10 km/h to 20 km/h, so a speed class range of 2 km/h was adopted for data synthesis.

Also, when measuring speeds and determining speed deviations from the limited value, it is necessary to identify the characteristics of the basic population based on the sample. The probability that the sample represents the basic population depends on the errors made during data collection and the size of the sample. Errors most often occur due to imperfections in the measuring equipment, sampling methods, or accidently. Sampling errors increase due to recording only a part of a traffic flow (unrepresentative). Using a larger sample reduces the possibility that the characteristics of the sample may differ from the characteristics of the population. By analyzing the deviation of real speeds from the speed limit, the distribution was approximated by a Gaussian distribution, which is symmetric with respect to the mean and asymptotically approaches the ordinate axis.

Table 3: K and U values for a certain level of reliability.

Level of reliability (%)	K	ΔV values in percentage	U
90.0	1.65	50%	0.00
95.0	1.96	15% or 85%	1.04

Table 4: Necessary and sufficient sample size.

The sample size for the acceptable deviation value $e = 1$ (km/h)								
Reliability level (%)	K	U	Standard deviation σ (km/h)					
			2	4	6	8	10	12
90	1.65	0.00	11	44	98	174	272	392
95	1.96	1.04	24	95	213	379	592	852

By analyzing the sample size for the required level of accuracy and reliability, its values from a general form were determined:

$$n = \frac{K^2 \cdot \sigma^2 \cdot \left(2 + U^2\right)}{2 \cdot e^2} \, (-), \tag{2}$$

where σ is the standard deviation of the sample, K is the number of standard deviations around the mean of normal distribution, $e$is the acceptable deviation limit, and U is the coefficient for a certain level of reliability.

The coefficient U for the percentage speed is given in Table 3 for 15%, 50%, and 85%.

If the standard deviation value of $\sigma = 2$, 4, 6, 8, 10, and 12 km/h is specified, and the limit value of acceptable error $e = 1$ km/h, the value of the sample size given in the following Table 4 is determined for the reliability levels.

3.1. Limits and Research Site Selection. In this paper, measurements were performed in real road and environmental conditions, using a speed measuring device (Bushnell NSN 5840-01-620–6670). Measurement of speeds in free traffic flow was performed by the "local measurement method," on the basis of which the synthesis of the mentioned data was started. The local measurement method implies that the free flow speed of the vehicle is measured on the cross section of the observed section of road over a length of 1000 m. On the observed cross section of the measuring section of the road, the free flow speeds of the vehicles moving towards the cross section were measured. The measured speed values were entered into the database. The research was conducted in daily driving conditions, under optimum weather conditions (there was no snow, rain, fog, or reduced visibility). The research excludes public transport vehicles, special vehicles, fire trucks, and similar vehicles for other purposes. The research was conducted in May, June, and July, 2021 on selected measuring sections, and the empirical measurement was performed on relevant working days from 8 a.m. to 8 p.m. A longitudinal gradient (ascent/descent) on measuring section length of 1000 m was identified by determining the arithmetic mean (based on the database of public enterprises Roads of Republic of Srpska and Roads of Bosnia and Herzegovina) of values of longitudinal gradients of a given section, which were measured every 200 m. The measuring

Figure 1: Position of measuring sections (S_1–S_{11}).

cross section is placed at the end of the measuring section with a length of 1000 m, and with a determined ascent/decent. These locations can be considered representative in order to obtain adequate data. It is also important that when doing measurements on measuring sections of two-lane roads, on all longitudinal gradients (ascent/descent) and on flat terrain, there is no lane for slow driving. Figure 1 shows the locations of the marked measuring sections (S_1–S_{11}) on the road map in Bosnia and Herzegovina.

Measuring points on two-lane roads were selected on the sections of the main roads Klupe–Teslić M-I-108, Border (RS/BiH)–Donje Caparde M-I-110, Šepak–Karakaj M-I-115, and on the section of the main road M-I-110, Maglaj–Ozimica.

Before starting the analysis of the credible speed deviation from the speed limit, it is necessary to determine the structure of the traffic flow on the mentioned measuring sections. The analysis includes four classes of vehicles, with Table 5 showing commercial vehicles (CV), i.e. vehicles other than passenger vehicles (BUS + LDV + HDV).

This structure of traffic flow on the analyzed road network S_1–S_{11} makes approximately 80% of passenger vehicles and 20% of commercial vehicles. From Table 3, it can be concluded that this heterogeneous structure of traffic flow has a relatively low value of AADT on section S_{11}, and over 10,000 veh/day on sections S_4, S_5, and S_6.

4. Synthesis and Analysis of the Research Results

Empirical measurement on the measuring sections was performed using a handheld radar Bushnell NSN 5840-01-620–6670, and data entry and processing was performed on a notebook computer Intel Pentium Dual CPU 2.16 GHz 2 GB. Based on empirically measured values of speeds classified in 5 classes, the values of deviations were obtained from speed limits, which were further processed in Microsoft Office Excel

Table 5: Determined value of measuring sample according to vehicle classes.

Two-lane road section		Section mark	Section length (km)	Ascent/descent at 1000 m in %	Size of measuring sample by speed deviation classes (% error ± 2.0%)					
					PV	BUS	LDV	HDV	CV	Σ all vehicles
S_1	Klupe–Teslić	M-I-108	16.734	−5.70	1805	100	145	75	320	2125
S_2	Klupe–Teslić	M-I-108	16.734	−4.06	1763	47	53	87	187	1950
S_3	Klupe–Teslić	M-I-108	16.734	−3.00	1497	75	98	108	281	1778
S_4	Maglaj–Ozimica	M-I-110	10.520	−2.76	588	84	133	105	322	910
S_5	Maglaj–Ozimica	M-I-110	10.520	−1.70	530	171	121	89	381	911
S_6	Maglaj–Ozimica	M-I-110	10.520	−1.35	415	97	141	105	343	758
S_7	Šepak–Karakaj 3	M-I-115	20.950	1.00	735	106	171	103	380	1115
S_8	Teslić–Klupe	M-I-108	16.734	3.00	1428	58	92	91	241	1669
S_9	Teslić–Klupe	M-I-108	16.734	4.06	1746	79	98	137	314	2060
S_{10}	Teslić–Klupe	M-I-108	16.734	5.70	1691	77	105	92	274	1965
S_{11}	Border (RS/FBIH)–Donje Caparede	M-I-110	3.140	7.00	782	84	104	77	265	1047
TOTAL					12980	978	1261	1069	3308	16288

in accordance with (1), after which further statistical processing was performed.

In the conducted empirical research, the values of speeds for 4 classes of vehicles were measured, and the measured speed values where there is no exceeding of the allowed speed were rejected from the research. By extracting only the exceeded speeds in relation to the traffic flow, it was analyzed the sample size of exceeded speeds, which is greater than 65% of the measured speeds on all measuring sections (Table 2). For each category of vehicles, the values of the arithmetic mean (AM) of speed value deviation from the speed limit, standard deviation (SD), and the coefficient of variation (Cv) were determined on the measuring sections of two-lane roads. The classification of obtained values was performed with a class width of 2 km/h. By classifying, it was obtained the distribution of speed deviation values for each vehicle category (PV, BUS, LDV, and HDV). Tabular data were used for further statistical analysis and definition of adequate distribution of obtained values. Also, tabular data were used to determine $\Delta V_{15\%}$, $\Delta V_{50\%}$, and $\Delta V_{85\%}$ percentile values, using statistical software Table Curve 2D v5.01. Empirically and tabularly obtained values of AM, SD, and Cv were used for the purpose of developing deterministic mathematical models for determining the deviation of free flow speed from the speed limit as a function of longitudinal gradient (ascent/descent). The research in this study was conducted during periods of low traffic (up to a two-way flow of 200 km/h), and the speed measurement of all vehicles was carried out in free-flow conditions on every tenth vehicle, arbitrarily.

Statistical research of the obtained values at the cross sections of the measuring sections was tested by the Gaussian (normal) distribution. Based on statistical analysis, tabularly obtained values of the deviation from the speed limit according to the class layout shows the distribution by Gaussian distribution with an adequate correlation coefficient ($R2 > 0.50$), which is given in Figure 2. The assumption is that the empirical distribution of speed deviation values in the case of a sufficiently large statistical sample for given vehicle classes can be theoretically approximated by the normal distribution (although this was not relevant to the scope of this study). Also, it was determined the values of cumulative relative frequency, which in all cases can be approximated by the cumulative Gaussian distribution (Figure 3).

By obtaining the values of the empirical arithmetic mean (AM) for each cross section of measuring sections for all predicted vehicle classes, it was started the development of multistep mathematical models. Also, the values of standard deviation (SD) were determined, where it was shown that all coefficients of variation (Cv) for the given cross-sections were less than 0.50. The models were developed with the aim of obtaining the functional dependence of the credible speed deviation of certain vehicle classes (PV, LDV, HDV, and BUS) on the longitudinal gradient (ascent/descent) of two-lane roads.

The general form of the multistep model is given in the following form:

$$\Delta V = A + B \cdot G^{\pm 1} + C \cdot G^{\pm 2} + \cdots + X \cdot G^{\pm n}, \tag{3}$$

where A, B, C, ... X is the regression curve coefficients rounded to three decimal places, G is the longitudinal gradient [%] (ascent/descent).

Based on the previously given equation, empirical mathematical models have been developed to determine the functional dependence of the credible speed deviation on the longitudinal gradient. The models are given in a form of higher degree polynomials in Table 6. The precision and high accuracy of the models according to vehicle classes (PV, LDV, HDV, and BUS) processed are confirmed by high coefficients of correlated speed dependence on a longitudinal gradient ($R^2 > 0.8$).

It is especially important to point out that for the PV class for empirically measured speeds, deviations from the speed limit range from the lowest value of the deviation from the speed limit for $G = +3.00\%$, which is 9.743 km/h, to the deviation value for $G = +1.00\%$, which is 22.490 km/h. The

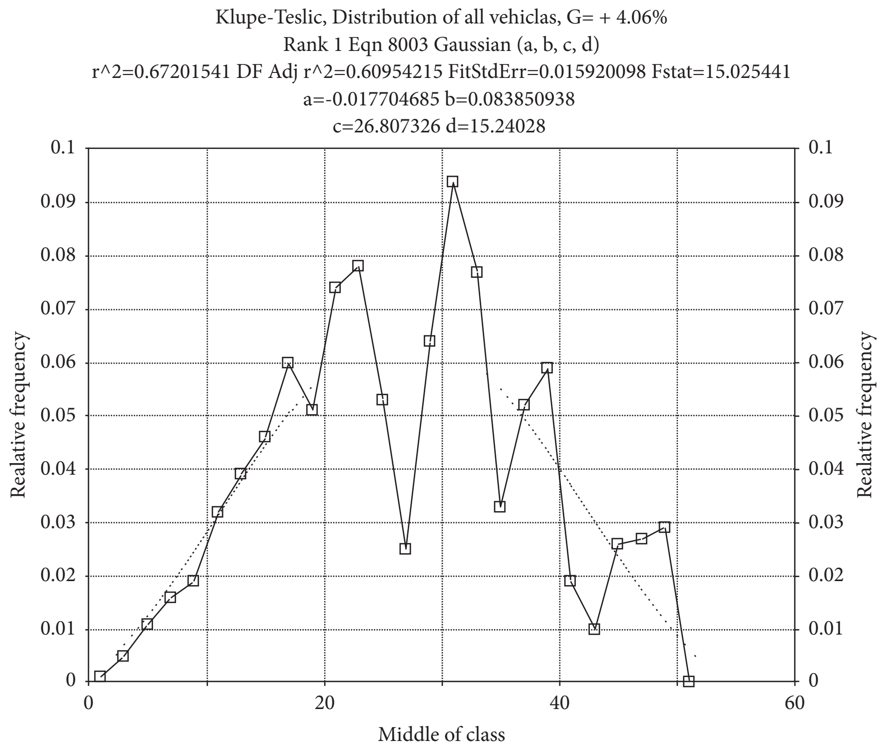

Figure 2: Example of relative frequency of obtained values of speed deviation from the speed limit for all vehicles in traffic flow.

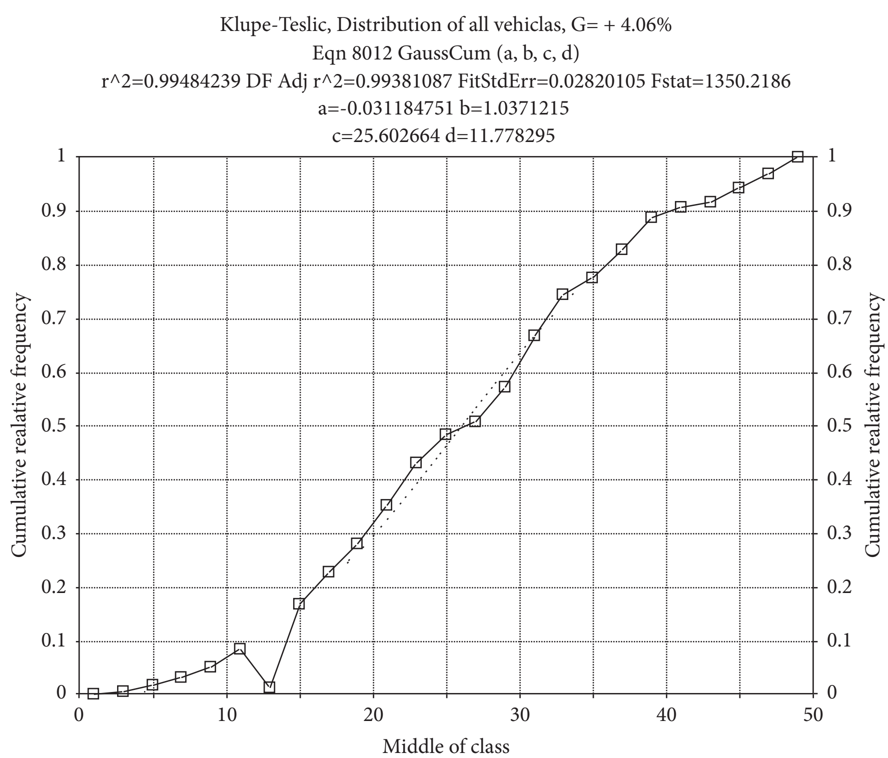

Figure 3: Example of cumulative relative frequency of obtained values of speed deviation from the speed limit for all vehicles in traffic flow.

deviation for PV is balanced on flat terrain, but progressively increasing on the descent. This shows a large dispersion of speeds on individual measuring sections for PV. For LDV, the dispersion of speed deviations towards the longitudinal gradient is slightly lower than that for PV and ranges from 7.417 km/h $\leq \Delta V \leq$ 15.316 km/h. The highest deviation from the speed limit on the ascent for PV occurs on the measuring section of a gradient $G = +4.06\%$. Significantly lower

Table 6: Empirical mathematical models of functional speed deviation dependence on a longitudinal gradient.

Vehicle category: PV	Correlation coefficient: $R^2 = 0.997$
$\Delta V = 14.845 + 18.524.G - 119.496.G^{-1} + 1.16.G^2 - 124.945.G^{-2} - 0.866.G^3 + 104.888.G^{-3} - 0.03.G^4 + 128.398.G^{-4} + 0.012.G^5$ (km/h)	
Vehicle category: BUS	Correlation coefficient: $R^2 = 0.995$
$\Delta V = 28.118 + 7.292.G - 47.413.G^{-1} - 0.602.G^2 - 127.083.G^{-2} - 0.325.G^3 + 29.764.G^{-3} + 0.005.G^4 + 119.38.G^{-4} + 0.004.G^5$ (km/h)	
Vehicle category: LDV	Correlation coefficient: $R^2 = 0.834$
$\Delta V = 29.12 + 22.622.G^2 + 7.664.G^4 - 1.053.G^6 + 0.064.G^8 - 0.002.G^{10}$ (km/h)	
Vehicle category: HDV	Correlation coefficient: $R^2 = 0.928$
$\Delta V = 7.515 + 3.472.G + 1.784.G^2 - 1.571.G^3 - 0.513.G^4 + 0.202.G^5 + 0.038.G^6 - 0.01.G^7 - 0.001.G^8$ (km/h)	

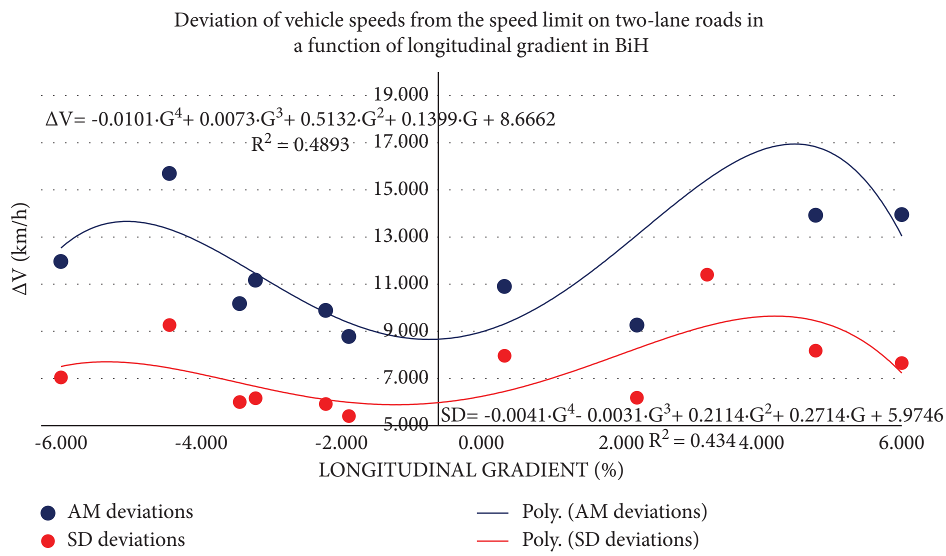

Figure 4: Deviation of traffic flow speeds as a function of longitudinal gradient.

dispersion occurs for BUS and in the functional dependence on the longitudinal gradient, it ranges from 7.143 km/h ≤ ΔV ≤ 13.250 km/h. Also, for BUS, the largest scattering of speed deviations from the speed limit is for $G = +4.06\%$. If it is taken the deviation for HDV, the smallest deviation is with the largest longitudinal gradient $G = +7.00\%$ and it is 3.467, and deviations over 10 km/h occur on flat terrain and downhill for this class of vehicles. Such an unbalanced trend of scattering of speeds that deviate from the speed limit on selected measuring sections can be justified by the characteristics of the terrain, driving and dynamic characteristics of vehicles, psychophysical abilities of drivers, and technical and exploitation characteristics of the two-lane roads. Due to these influencing factors, AM and SD values of speed deviations were identified for the mentioned measuring sections, with the aim of obtaining adequate statistical regressivity.

Figure 4 shows a graphical generalization of the model for determining a credible speed deviation from the speed limit in a form of a fourth-degree polynomial, but for all vehicle classes on the measuring sections of two-lane roads. By calibrating the model for all vehicle classes, two extreme values of speed deviation from the speed limit can be noticed, one lower on the descent and one higher on the ascent. The correlation coefficient $R^2 \approx 0.50$ shows that the arithmetic means of speed value deviation from the speed limit vary from one measuring section to another measuring section, so the fourth-degree polynomial was used as an instrument to simplify the model.

Considering that in the previous model in Figure 4, only speeds deviating from the speed limit were analyzed and that the AM and SD of the stated deviations on the measuring sections are shown; based on the proposed model, there is the smallest speed deviation for all classes of vehicles on flat terrain $G = 0 \pm 1.00\%$, where this value does not exceed 10 km/h. The analysis of the model on class I roads in Bosnia and Herzegovina, and the review of the previously calibrated model shows the apparent conclusion that the deviation of the flow speed from the speed limit increases on the ascent and descent for all classes of vehicles, but it must be taken into account all 4 previously mentioned vehicle classes (PV, LDV, HDV, and BUS).

Also, in order to obtain more precise values of the previously mentioned model, it was further developed a calibrated model for $\Delta V_{15\%}$, $\Delta V_{50\%}$, and $\Delta V_{85\%}$, as a function of longitudinal gradient. Deviations of values on measuring sections by 15%, 50%, and 85% of speed deviations from the limit value are more than 10 km/h, which can be seen according to the model in Figure 5. For analytical generalization of the model for the values of speed deviation from the speed limit for all vehicle classes by 15%, 50%, and 85%, analytically developed mathematical models given in Table 7 were obtained.

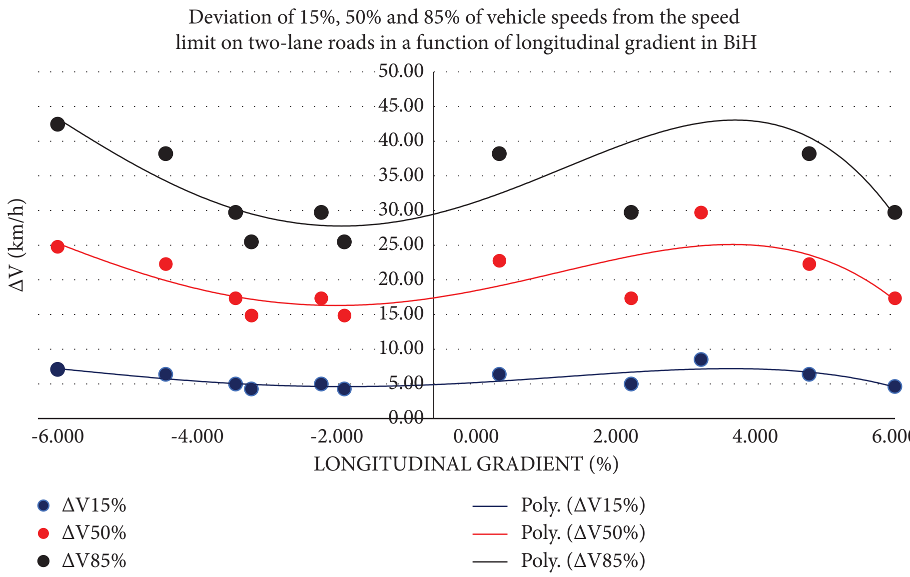

FIGURE 5: ΔV 15%, 50%, and 85% as a function of longitudinal gradient.

TABLE 7: Analytical model of 15%, 50%, and 85% speed deviations from the speed limit on two-lane roads in BiH.

15% deviation of values ΔV $\Delta V_{15\%} = -0.002.G^4 - 0.014.G^3 + 0.126.G^2 + 0.397.G + 4.884$ (km/h)	Correlation coefficient: $R^2 = 0.614$
50% deviation of values ΔV $\Delta V_{50\%} = -0.006.G^4 - 0.048.G^3 + 0.394.G^2 + 1.403.G + 17.391$ (km/h)	Correlation coefficient: $R^2 = 0.586$
85% deviation of values ΔV $\Delta V_{85\%} = -0.010.G^4 - 0.079.G^3 + 0.712.G^2 + 2.341.G + 29.462$ (km/h)	Correlation coefficient: $R^2 = 0.596$

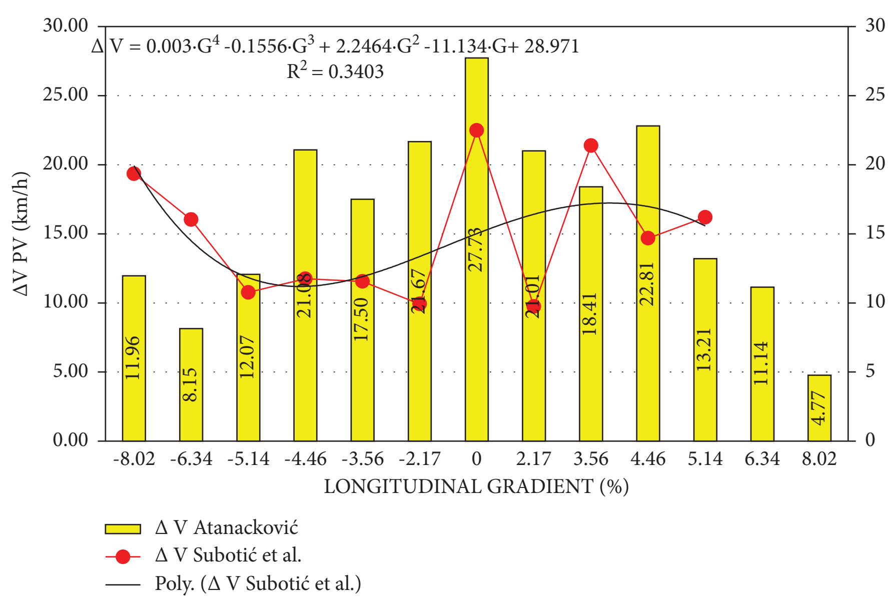

FIGURE 6: Comparative overview of ΔV for PV in Serbia (ΔV Atanacković) and BiH (ΔV Subotić et al.).

Since analytically developed mathematical models are given in Table 7, Figure 5 shows deterministic models for the deviation of traffic flow speed from the speed limit by ΔV 15, 50, and 85 percentiles as a function of longitudinal gradient. These values show a significant scattering of the deviation values by 85 percentiles and minimum by 15 percentiles.

Figures 6 and 7 compare the empirically obtained ΔV values for passenger vehicles and commercial vehicles obtained on the basis of research conducted in Bosnia and Herzegovina (Subotić et al.) and Serbia (Atanacković). Also, the research conducted in Serbia [32] was given with a speed limit, so that on the suburban sections of two-lane roads, where a speed limit of 70 km/h is provided, the value of AM

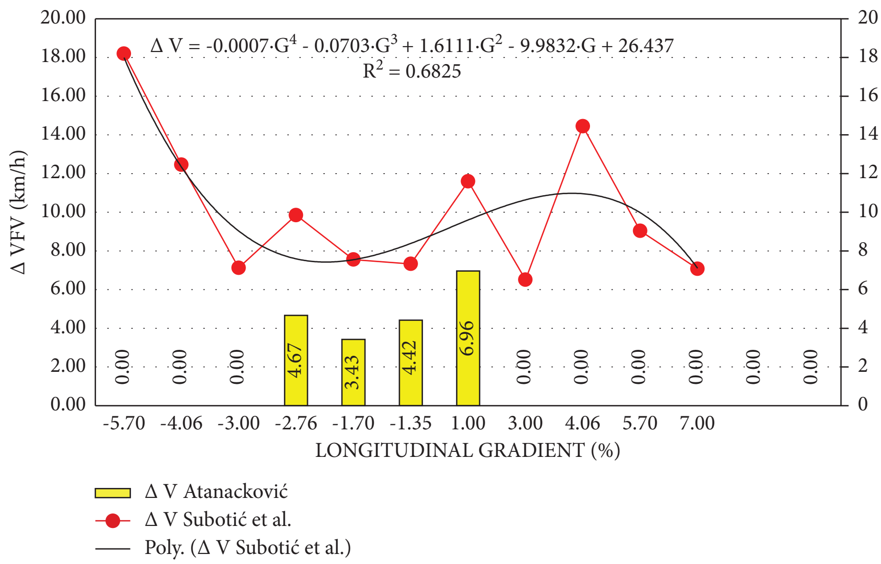

Figure 7: Comparative overview of ΔV for freight vehicles in Serbia (ΔV Atanacković) and BiH (ΔV Subotić et al.).

speed for the specified measuring sections was determined. Based on (1), the values of speed deviations from speed limits for the entire free traffic flow on two-lane roads in Serbia were determined. In this case, not only the speeds that deviated from the limited value were singled out, as is the case with this research, but also the focus of the observation refers to the entire flow. Considering that both surveys were conducted in the conditions of free traffic flow, it is possible to compare the obtained values and give an adequate conclusion in accordance with the speed limits provided.

Research studies with deviations from the speed limit in Serbia (ΔV Atanacković) were measured on cross sections of measuring sections Rudnik II–Ljig (±8.02%), Rudnik I–Gornji Milanovac (±6.34%), Borova Glava–Uvac (±5.14%), Rušanj III (±4.46%), Rušanj II (±3.56), Orlovača (±2.17), and Pančevo–Vršac (0.00%). Research studies with deviation from the speed limit in Bosnia and Herzegovina (ΔV Subotić et al.) were measured on cross sections of measuring sections Granica (RS/FBIH)–Donje Caparede (+7.00%), Klupe–Teslić (±5.70%, ±4.06%, ±3.00%), Maglaj –Ozimica (−2.76%, −1.70% *i* −1.35%), and Šepak–Karakaj 3 (+1.00%).

Figure 6 shows the values of AM speed deviations from the speed limit, towards the longitudinal gradients for PV for studies conducted in Serbia and Bosnia and Herzegovina. For PV, it is evident that the values of ΔV deviate significantly in Serbia, compared to BiH, if the values of $-5.0\% \geq G \geq 5.0\%$ are observed. These deviations would be significantly higher if only the speed values of vehicles that were speeding were taken into account in Serbia, which was the case with the research in BiH. Also, the largest deviation from the speed limit in Serbia for PV is given for a gradient of 0% and it is over 25 km/h. Also, for the research conducted in BiH, there is a large scattering of ΔV values, which shows a low correlation coefficient, $R^2 = 0.34$.

However, Figure 7 shows the values of speed deviation from the speed limit, for the conditions of free flow in Serbia and BiH for all freight vehicles in a function of gradient. In this case, based on the research conducted in Serbia on the sample of measured speeds, it can be concluded that freight vehicles exceed the speed only on flat terrain and a slight descent. If we compare speeding in Serbia and BiH, for all measuring sections of the longitudinal gradient, ΔV is significantly higher in Bosnia and Herzegovina than in the survey conducted in Serbia. Also, on greater ascents and descents, in Serbia, no speeding was recorded in the category of freight vehicles, which is not the case in BiH. In this case, with the development of the fourth-grade model for freight vehicles in Bosnia and Herzegovina, there is a good correlation, $R^2 = 0.6825$, which is not the case with PV.

The deviations recorded in this way in Serbia, which do not exceed 7 km/h, deviate a lot from the results in BiH, but the fact that a small percentage of vehicles on the ascent and descent that exceed the speed limit must be taken into account. For the research conducted in Serbia, freight vehicles that do not exceed the speed limit were not eliminated from the sample, which is a significant limitation compared to this research.

5. Research Results and Discussion

A large number of studies of speed credibility refer to the analysis of meritorious influencing factors that contribute to the increase/decrease of exceeding the speed limit in real road and environmental conditions. In the previous literature review, it was noticed that one part of them is mainly based on the influential factors of road geometry, which includes the longitudinal gradient, and radii of curves. In order to determine the credible value of speed deviation from the speed limit, it is necessary to observe each measuring section separately because there are a large number of road factors, psychophysical abilities of drivers, and driving dynamics characteristics of vehicles that can be representatively influential.

In this paper, 11 measuring sections of main two-lane roads (S1-11) were analyzed, with the aim of determining a credible speed deviation of vehicles that exceed the speed limit as a function of longitudinal gradient. At the given measuring sections, it was determined that the speed limit is exceeded by over 65% of vehicles, and at certain sections ≈95%. By analyzing the speeding, on the basis of empirical measurements, it was determined that the highest speeding occurs for PV, where the average value of AM for ΔV in all measuring sections is 14.898 km/h (≈15 km/h). The lowest value of AM for ΔV on all measuring sections was measured for HDV and is 8.585 km/h (≈9 km/h), while this value for BUS (9.785 km/h) and LDV (10.201 km/h) is ≈10 km/*h*.

Since a credible limit is also an eligible speed limit, it can be represented by the perception of drivers according to road and traffic conditions prevailing on homogeneous road sections, which allow drivers to move at higher speeds. It is the reason why it would be necessary to reconsider the set speed limit on certain measuring sections. By analyzing the previous values of speed deviations from the speed limit on 11 measuring sections (S1-11), it is obtained the values that can be recommended for a credible speed deviation of 10 km/h on two-lane roads in BiH, regardless of the longitudinal gradient.

Based on the synthesis of the obtained data, multistep deterministic mathematical models of the functional dependence on the longitudinal gradient have been developed. Furthermore, in order to generalize the model, a general model was developed for all vehicles, where deviations of ΔV values are shown as two extremes, which occur at the value of $G = \pm 5\%$. Based on the general multistep model calibrated by the fourth-degree polynomial, ΔV 15%, 50%, and 85% models were developed. The deviations between these three models for ΔV are greater than 10 km/h for all measuring sections, and with increasing a percentile value, the scattering of deviations for ΔV increases. Also, at 85% of the percentile value ΔV, the largest scattering of the deviation value was obtained.

Studies [15, 16] have concluded that the credible deviation of real from limited speeds is 10%. Comparing these conclusions with the obtained research results, which determined a deviation of 10 km/h, it can be seen that the threshold of credible deviation obtained in this paper is much more tolerant.

Also, based on the research [5], where it was found that 40% of drivers exceed the speed limit; in this study, this percentage is significantly higher (>65%), but both studies have in common that the percentage of speeding varies on measuring sections. However, it is not possible to have equal limits of deviation, comparing both studies because the exploitation characteristics of sections in the conducted research are specific in relation to the mentioned research [5]. Also, the applied methodology in the research includes sections with ideal characteristics, and with a speed limit of 60 km/h. This is a significant methodological deviation in comparison with the research conducted in this paper.

By comparative analysis of the results obtained in this research and in Serbia [32], the deviation values of PV for ΔV in the Republic of Serbia are higher than in BiH. In Serbia, the analysis also includes PVs that do not exceed the limited speed. These deviations would be even bigger, if only speeding vehicles were singled out in Serbia. Contrary to the deviation for PV, significantly higher values of exceeding ΔV are obtained in BiH than in Serbia.

There are some other factors that influence the deviation from the speed limit. Shoulder width has a larger effect on speed when lanes are narrow, but the effect of shoulder width decreases as lane width increases. A plausible explanation is that a wider lane could be expected to allow a higher traveling speed. It is known that with the increase in the number of access points and no-passing zones, the speed of free flow decreases. However, these parameters were not investigated in this study.

6. Conclusion

The paper presents a detailed analysis of operating speed deviation of different vehicle classes from the speed limit, in a function of longitudinal gradient on two-lane roads of Bosnia and Herzegovina. Based on empirical research conducted on 11 cross sections of representative sections, it has been shown that the deviation depends on a number of factors. In most of the sections, a great compliance of all analyzed speeds has been determined, which indicates that these are measuring sections where the geometric characteristics and the environment of the road correspond to the class of the road.

The conducted research confirmed the hypothetical assumption that with an increase of the longitudinal gradient in real conditions, there is an increase in the deviation of the values of traffic flow speeds from the speed limit. Certainly, if it is taken into account the analysis of individual classes of vehicles in real traffic flow, it can be concluded that the increase in speed deviation increases with increasing the longitudinal descent, while the value of speed varies continuously with increasing the ascent.

Based on the developed models for the prediction of the deviation of operating speeds from the limited speeds as a function of longitudinal gradient, the values of credible deviation by 10 km/h from set limit values were obtained. The obtained values of exceeding the speed limit are closer to the values of the 85th percentile of deviations on the measuring sections, which confirms the validity of using the 85th percentile of measured speeds when determining speed limits in many countries [36] (TRB, 1998). Given the high deviations of speeds from set speed limits, the need for their review was detected. Namely, the highest deviations were recorded on sections with a limit of 50 km/h, where by increasing the speed limit by determined 10 km/h, the percentage of exceeding the speed limit would decrease significantly. This provided a greater degree of harmonization of vehicle speeds of different classes in traffic flow, which would increase efficiency and safety. The obtained results are in accordance with the results of a study [37] conducted by Solomon (1964), which has shown that exceeding the speed limit of 10 km/h leads to the lowest rate of traffic accidents.

Since the focus of the analysis in this paper was on longitudinal gradients, in future research, it is necessary to examine additional factors that have not been considered, such as the influence of transverse profile characteristics, horizontal curvature, vehicle characteristics, meteorological influences, and driver characteristics. Additionally, in order to obtain the most accurate data, in the coming period, it is necessary to conduct a detailed analysis of an even larger number of measuring sections. Continuous research of the values of speed deviations from the speed limit will provide representative criteria for project procedures for determining credible speed limits, with the aim of improving traffic conditions.

Data Availability

All data used to support the findings of the study are included within the paper..

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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