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Original Article

THE IMPACT OF BASIC TRAFFIC FLOW CHARACTERISTICS ON TRAFFIC ACCIDENT OCCURRENCE ON 2-LANE RURAL ROADS IN SERBIA

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Highlights:
- analysis of the mutual impact of traffic volume, *%HV* and speed parameters on traffic accident occurrence on Class I 2-lane rural roads;
- data on traffic flow characteristics were collected from ATCs, which enables to avoid any changes in driving behaviour;
- development of the 3 accident prediction models referring to the AC_T, AC_{PDO} and $AC_{I\&F}$;
- rise of the *AADT*, σ_S^2 and ΔS_{ff-lim} results increase of the traffic accidents in all 3 final models;
- growth of the *%HV* increase the AC_T and $AC_{I\&F}$.

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Abstract. Basic traffic flow characteristics, such as volume and speed, represent the key criteria for estimating the level of service and traffic safety. Numerous studies have been conducted with the aim of determining the impact of the basic traffic flow characteristics on traffic accident occurrence. However, the mutual impact of traffic volume and speed characteristics has not been examined to a sufficient degree. Therefore, the authors of the article analysed the mutual impact of average annual daily traffic (*AADT*), share of heavy vehicles in the traffic flow (*%HV*) and speed parameters (such as speed variance (σ_S^2), average travel speed (*ATS*), speed limit credibility and percentage of exceeding the speed limit (*%ESL*) on traffic accident occurrence on Class I 2-lane rural roads in the Serbia. The article analysed spatial distribution and traffic accidents' severity on homogeneous segments equipped with automatic traffic counters, which provided data on speeds and other traffic flow characteristics during a 5-year period. The application of generalised linear models led to the development of 3 negative binomial models with an natural logarithm (ln) link function for the (1) total number of traffic accidents (AC_T), (2) property damage only accidents (AC_{PDO}) and (3) injury and fatality accidents ($AC_{I\&F}$). The obtained results show that 3 variables are statistically significant in all 3 final models: (1) *AADT*, (2) σ_S^2 and (3) difference between the free-flow speed and speed limit (ΔS_{ff-lim}). All variables included in the final models are positively associated with the dependent variable. In other words, the rise of the values of *AADT*, σ_S^2 and ΔS_{ff-lim} variables increases the expected number of traffic accidents. The variable related to the *%HV* is statistically significant in the models related to the AC_T and traffic accidents with injuries and fatalities, and it is positively associated with the expected traffic accident number.

Keywords: traffic flow, automatic traffic counter, average annual daily traffic, speed variance, 2-lane rural road, speed limit credibility.

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Notations

Abbreviations:

AADT – average annual daily traffic;
AIC – Akaike information criterion;
ANOVA – analysis of variance;
ATC – automatic traffic counter;
BIC – Bayesian information criterion.

Variables and functions:

$AC_{I\&F}$ – injury and fatality accidents;
AC_{PDO} – property damage only accidents;
AC_T – total number of traffic accidents;
ATS – average travel speed of the vehicles in the flow;
B – unstandardized regression coefficient;
ΔS_{ff-lim} – difference between the free-flow speed and speed limit;
σ_S^2 – speed variance;
%ESL – percentage of exceeding the speed limit;
%HV – share of heavy vehicles in the traffic flow.

1. Introduction

In the last few decades, numerous studies have been conducted with the aim of quantifying the impact of the basic traffic flow characteristics on the occurrence of traffic accidents. Vehicle volume, expressed by *AADT*, has been analysed in a large number of conducted studies, which determined that the increase in *AADT* led to the increase in traffic accidents (e.g., Hadi *et al.* 1995; Cafiso *et al.* 2010, etc.). Speed also represents one of the basic parameters for describing the conditions in the traffic flow, i.e., it is one of the main criteria for estimating the efficiency (level of service) of the rural road sections. It is of great significance in terms of traffic safety, since there are very strong correlations between speed and risk of traffic accidents, i.e., between speed and consequences of the accidents (Aarts, Van Schagen 2006; Elvik *et al.* 2004). One of the most frequently used models in traffic safety is Nilsson's power model, showing that the increase in the average speed by 5% leads to the rise of the number of traffic accidents with injuries by 10% and rise of the number of traffic accidents with fatalities by 20% (Nilsson 2004). The latest research shows that the U-shaped relationship between operating speed and crash occurrence has been identified (Yu *et al.* 2018). However, in previous crash–speed relationship models, negative and positive correlations between speeds and accidents were determined depending on the different crash data aggregation concepts (link-based or condition-based) (Imprialou *et al.* 2016).

Traffic conditions and geometric characteristics of the road have a considerable impact on the vehicle's travelling speed in the traffic flow, and consequently on the traffic accident occurrence rate. Speed limits represent an important element of speed management policy. However, posting speed limits does not automatically lead to the compliance with the demanded speed. Exceeding the speed limit occurs very frequently on all road categories. In general, 40...50% of drivers drive faster than the posted speed limit (OECD 2006). Exceeding the speed limit is a common self-reported type of driver behaviour (Musselwhite *et al.* 2010). Speed limit can be exceeded both consciously and unconsciously, since the selection of speed and reasons for driving fast depend on numerous factors. The reasons for exceeding the speed limit can be diverse and can be related to temporary motives (for instance, being in a hurry), personal characteristics (for instance, risky driving) and characteristics of the vehicle, road and road environment (SWOV 2012). The perception of a safe travelling speed is very significant and it depends on the road geometry and its environment, the adjoining land use and weather conditions (Wilmot, Khanal 1999). Kanellaidis *et al.* (1995) concluded that the most important reason for not complying with the speed limits was the fact that drivers believed that the speed limits were not always realistic. One of the key factors affecting the driver's speed choice is the credibility of the posted speed limit (OECD 2006; Van Nes *et al.* 2008; Van Schagen *et al.* 2004). Goldenbeld & Van Schagen (2007) stated that it could be generally supposed that drivers would comply with the posted speed limit if they considered it reasonable or "credible". On the contrary, if the posted speed limit is not in line with the speed limit considered appropriate by drivers based on the corresponding road characteristics, the drivers may consequently disregard the posted speed limit. They also stated that if non-credible speed limits kept appearing frequently in the system, the complete speed management system might be compromised. Most drivers ignore the posted speed limits, which are set higher or lower than the ones dictated by traffic conditions (Parker *et al.* 2003).

Previous studies have determined that drivers whose speed considerably deviates from the posted speed limit have greater chances of participating in traffic accidents. Analysing the dependence between the vehicle speed and accident rate on rural roads in the US, Solomon (1964) found that the vehicles travelling by up to 10 km/h faster than the speed limit had the lowest accident rate, while the vehicles travelling significantly more slowly or quickly than the posted speed limit had a higher chance of participating in traffic accidents. Also, some articles determined that a large σ_S^2 in the flow led to the increased risk of traffic accident occurrence (Aarts, Van Schagen 2006; Montella, Imbriani 2015) and severity of traffic accident consequences (Yu, Abdel-Aty 2014a, 2014b). Hashim (2006) determined that the absolute difference between the speed limit and the 85th percentile speed of vehicles in the flow had the key role in traffic accidents with fatalities or serious injuries. Namely, it was determined that the increase in this difference resulted in the rising number of traffic accidents with fatalities and serious injuries. Milton & Mannering (1998) had previously reached a similar conclusion. Analysing the relationship between the σ_S^2 and traffic accident rate, Garber & Gadiraju (1989) found that the difference between the values of the posted speed limit and design speed had a great impact on the σ_S^2 in the flow. Namely, they determined that the σ_S^2 would be the lowest if the posted speed limit value were between 8 and 17 km/h lower than the design speed. Outside this range, σ_S^2 in the traffic flow increased with a growing difference between the mentioned speeds. It was also determined that drivers tended to increase their travelling speed if the road geometric characteristics were favourable (regardless of the posted speed limit) and that the rate of traffic accident occurrence did not necessarily increase with the increased speed, but that it did rise with the increase in σ_S^2 in the traffic flow (Garber, Gadiraju 1989). Quddus (2013) also determined that σ_S^2 was statistically and positively associated with accident rates, and that 1% increase in speed variation was associated with a 0.3% increase in accident rates.

Other authors (e.g., Yao *et al.* 2019a, 2019b, 2020a, 2020b) also studied the impact of road geometry and road environment on the speed limit credibility, using questionnaires and driving simulators, as well as monitoring the electrodermal response for risk assessment of respondents. Yao *et al.* (2019a, 2019b) determined that the speeds perceived as too low or too high did not provide a feeling of safety while driving, while the specific credible speed limit values varied depending on the road configuration. In similar research, they found that a higher risk factor contributed to a greater compliance with the speed limit; that a credible speed limit had a positive impact on greater compliance with speed limits, particularly with drivers considered to be more serious violators; and that the perception of a higher risk contributed to the negative estimation of the credible speed limit (Yao *et al.* 2019a, 2019b). Yao *et al.* (2020a) showed that a wide range of responses regarding the credible speed limit (20…80 mph) was recorded on rural roads, which resulted in the increased number of overtaking manoeuvres in the actual traffic flow. Yao *et al.* (2020b) also showed that the application of the boosting decision tree algorithm could help develop a model of driver behaviour based on the driver's perception of speed limit credibility and perception of risk.

The analysis of the previous results in the field has shown that a large number of studies have examined the impact of vehicle volume, expressed as *AADT*, and the vehicle speed in the traffic flow on the occurrence of traffic accidents. However, the mutual impact of *AADT* and specific speed parameters on the occurrence of traffic accidents has not been studied to a sufficient degree. Therefore, the aim of this article is to conduct a detailed examination of the mutual impact of traffic flow characteristics, such as *AADT*, percentage of heavy vehicles in traffic flow and basic speed parameters such as σ_S^2, speed limit credibility or ΔS_{ff-lim}, operating speed and %*ESL* on the occurrence of traffic accidents. The mutual impact of traffic flow characteristics was examined on homogeneous segments of the Class I 2-lane rural road sections in the Serbia, equipped with ATCs. The contribution of this article is reflected in the defined methodology – nature of the collected data and the sample size, as well as in the fact that, for the 1st time, the mutual impact of various speed parameters and traffic flow characteristics on traffic accident occurrence was analysed in detail.

Following the description of the problem and the results of the previous research in the field, the article provides the definition of the research methodology, which represents one of the main advantages of this study. Its advantage is reflected in the method of data collection and data processing. The chapter related to the research results presents the developed models related to the AC_T, AC_{PDO} and $AC_{I\&F}$ (accidents with injured and killed people). It is followed by the discussion, which explains the obtained results and compares them with the results of previous studies. Finally, the article offers concluding remarks and directions for future research.

2. Research methodology

2.1. Data collection

The literature review has shown that most previous studies have been based on the quantification of the speed impact based on measuring the average speeds on the section or measuring individual vehicles' speeds using a radar in the field on design days (Garber, Gadiraju 1989; Solomon 1964; Taylor *et al.* 2000), using software (Kloeden *et al.* 1997, 2001), a driving simulator (Van Nes *et al.* 2008), various types of questionnaires (Gardner, Rockwell 1983; Goldenbeld, Van Schagen 2007; Kanellaidis *et al.* 1995) or combining the mentioned methods (Fildes *et al.* 1991). The stated methods have numerous advantages but they also have shortcomings, which might affect the final results. Namely, the devices for speed measurement, although hidden in the best manner possible, can prompt drivers to reduce their speed (Fildes, Lee 1993; Teed *et al.* 1993). Fildes & Lee (1993) highlighted this fact in their research based on the results of a study conducted by the Institute for Highway Safety. In addition, software output depends on the precision of the input data, surveys can be incomplete and unclear and responses might be insincere and incorrect (Murgan 2015). Moreover, driving simulators frequently cannot consider numerous factors, which affect the driving process in the actual environment.

In order to eliminate the possible impact of the mentioned factors on the study results, this article used the data collected from ATCs posted on rural sections of Class I 2-lane state roads. These are modern automatic QLTC 10C counters operating on the principle of inductive loops. In addition to the data on volume, time headways, structure of the traffic flow, and temporal variations, the ATCs also register the travelling speed of each vehicle. Owing to the continuous measuring of data during 8760 h in a year, there are a large number of actual operating vehicle speeds measured at the sections' points. In comparison to the situation when speeds are measured by radars, here drivers are unaware of the measuring device's presence, i.e., they do not change their speed and driving style. The analysis encompassed the ATC impact zones of 1.6 km (1 mile) upstream and downstream of the ATC, in which the traffic flow speed representative for the ATC detection is stabilised. These zones have homogeneous road geometric characteristics, since the ATCs are posted on the segments having almost ideal rural conditions – the zones with proper pavement condition, without horizontal and vertical curve radius, critical grades, roadway width, shoulder width, etc. The speed limit on all analysed ATC zones is 80 km/h, which also represents the general statutory speed limits for the mentioned road classes. An overview of the range values of the basic characteristics for the analysed zones is presented in Table 1.

The data were collected for the sample of 235 sections during the 5-year period. In addition to the data on *AADT*, %*HV*, %*ESL* and *ATS*, the ATCs provided the free-flow vehicle speeds, which were calculated for each separate section. The free-flow speeds were calculated as the 85th percentile speed of the vehicles in the traffic flow. Reviewing the literature, it was determined that there were no precisely determined vehicle headway values, which described the conditions in the free flow. The following values were obtained in the studies: 4 s (Homburger *et al.* 2007), 5 s (Fitzpatrick *et al.* 2005; Hashim 2011; Poe *et al.* 1996), 6 s (Lamm *et al.* 1990; Lobo *et al.* 2011) and 8 s (Lin *et al.* 1996). The largest number of studies identified the headways greater than 5 s and 6 s for the free-flow conditions.

Table 1. Range values of the basic geometric characteristics for the analysed ATC impact zones

2-lane road sections of ATC impact zones	Minimal horizontal curve radius [m]	Maximal longitudinal grade [%]	Minimal roadway width [m]	Minimal shoulder width [m]	Speed limit [km/h]
Range values	346...6500	0...1.6	7.0....8.5	1.5...2.0	80
Average values	1792	0.5	7.9	1.7	80

In other words, there is no impact on the vehicle speed at these or greater headway values. Since the threshold value of 8 s had also been recorded in the literature and since there were no problems regarding the sample due to the large number of registered vehicles, this article used the threshold value ≥8 s for the free-flow conditions.

On the basis of the stated ATC data (Figure 1) obtained from the database of the public enterprise "Roads of Serbia" (*https://www.putevi-srbije.rs/index.php/en*), it was possible to calculate *AADT*, *%HV*, *%ESL*, *ATS*, free-flow speeds and σ_S^2 for each ATC zone.

In order to examine the impact of the mentioned traffic flow characteristics on the occurrence of traffic accidents, the authors conducted a detailed analysis of the spatial distribution and consequences of traffic accidents (AC_T, AC_{PDO} and $AC_{I\&F}$) in the ATC zones. The mentioned analysis was conducted using the Integrated Database on Traffic Safety Characteristics by the Road Traffic Safety Agency of the of Serbia (GDi LOCALIS Visios 2025). Applying the ANOVA test, it was determined that the COVID-19 pandemic did not affect the traffic accident number in the observed ATC zones. In other words, the null hypothesis of equality of variances in traffic accidents (p = 0.993) as well as the null hypothesis of equality of means of traffic accidents from the year 2016 to 2020 (F = 1.247, p = 0.06) were accepted. Consequently, due to the larger sample number, the analysis involved the data for 5 available years: 2016–2020. The analysis included the total of 802 accidents – 387 with property damage only and 415 with injuries and fatalities. Figure 2 shows a graphic representation of the spatial distribution of traffic accidents in the ATC zones.

```
00377 02.02.19 06:32:17  0  0 C1  75 1503
00460 02.02.19 06:32:44  3  1 A1  84  483
00461 02.02.19 06:32:48  3  1 A1  86  450
00462 02.02.19 06:32:59  3  1 A1  78  459
00378 02.02.19 06:33:03  0  0 B2  56  727
00379 02.02.19 06:33:04  0  0 B2  56  877
00380 02.02.19 06:33:06  0  0 B2  54  871
00463 02.02.19 06:33:20  3  1 A1  92  547
00464 02.02.19 06:33:32  3  1 A1  90  491
00465 02.02.19 06:33:34  3  1 B1  86  717
00466 02.02.19 06:33:39  3  1 A2  86  659
00467 02.02.19 06:34:06  3  1 A1  75  435
00468 02.02.19 06:34:09  3  1 A2  77  677
00469 02.02.19 06:34:15  3  1 A1  82  505
00470 02.02.19 06:34:18  3  1 A1 113  537
00471 02.02.19 06:34:45  3  1 A1  84  529
00381 02.02.19 06:35:01  0  0 A1  55  486
00472 02.02.19 06:35:36  3  1 A1  77  438
00473 02.02.19 06:35:59  3  1 B5  78 1806
```

Figure 1. An example of the ATC data showing: the ordinal number of the vehicle per direction, date [dd:mm:yy], arrival time [h:min:s], travelling direction, vehicle category, speed [km/h] and vehicle length [cm]

Figure 2. Spatial distribution of traffic accidents (red points) in the ATC zone – ATC 1122 (green point) on state road IB 02211

2.2. Statistical analysis

The analysis of the impact of traffic flow characteristics on the occurrence of traffic accidents was conducted using methods of descriptive and analytical statistics, while the data were processed using the software package IBM *SPSS Statistics 21.0* (*https://www.ibm.com/spss*).

Independent variables were the variables related to the traffic flow characteristics in the analysed ATC zones, such as *AADT*, *%HV*, *ATS*, σ_S^2, ΔS_{ff-lim} and *%ESL*.

3 models were developed. In the 1st model, the dependent variable was the variable referring to the AC_T, including all accidents with property damage only, injuries and fatalities. In the 2nd and 3rd model, the dependent variables involved AC_{PDO} and $AC_{I\&F}$, respectively. The descriptive statistics of the dependent variables are shown in Table 2.

Table 2. Descriptive statistics of the dependent variables

	N	Minimum	Maximum	Mean	Variance
AC_{PDO}	235	0.00	11.00	1.6511	3.681
$AC_{I\&F}$	235	0.00	8.00	1.7660	3.240
A_CT	235	0.00	15.00	3.4128	8.004
Valid *N* (listwise)	235	–	–	–	–

When analysing these models, the review of the dependent variable histogram and the fact that they are count data led to the conclusion that generalised linear models would be a good choice. The authors used the Kolmogorov–Smirnov test to confirm that the dependent variables did not fit the Poisson distribution well. Using this conclusion and the fact that the assumption of equidispersion is violated for each dependent variable, the negative binomial models with an ln link function were proposed. After checking the assumptions and excluding the independent variables that did not contribute significantly to the quality of the fit, the final models were obtained.

3. Results

3.1. Total number of traffic accidents

The Kolmogorov–Smirnov test determined that the distribution of the AC_T did not fit the Poisson distribution well (p < 0.001). After checking the assumption about the presence of overdispersion (*mean* = 3.41, *variance* = 8.01), the negative binomial regression model was used. The ratio of Pearson's χ^2 value and df (1.05) leads to the conclusion that the problem of overdispersion might be overcome using this model. Another way to confirm that the negative binomial model is appropriate is to check its residual plot. It can be seen that the residuals are less spread out than for the Poisson regression model, where some residuals extend beyond 3. Following this, the authors performed a likelihood ratio test to determine if there was a statistically significant difference in the fit of the 2 regression models. The p-value of the test was very close to zero (p < 0.001), so it was concluded that the negative binomial regression model offered a significantly better fit to the data compared to the Poisson regression model. The initial negative binomial model can be improved by excluding the variable ATS (p = 0.511) from the model due to its high p-value.

When it comes to the final model, the ratio of Pearson's χ^2 value and degrees of freedom df changes to 1.04. Observing the AIC and BIC criteria, it can be noticed that their values have decreased, which indicates that the final model has been improved in comparison with the preliminary model. The dispersion parameter was estimated using the maximum likelihood method. All independent variables included in the final model are positively associated with the dependent variable. In other words, the rise of independent variables' values increases the expected number of total traffic accidents (Table 3). For every one-unit increase in the difference between the free-flow speed and the speed limit, the expected value of total traffic accidents increases by 4.2%, provided other predictor variables are constant. The expected value of total traffic accidents increases by 0.4% and 2.8% for every one-unit increase in the σ_S^2 and the $\%HV$, respectively. There is only a minor increase (0.001%) in the expected value of the total accident number for every one-unit increase in $AADT$, owing to the big difference between the scales of measurement of these variables and the fact that this variable has a small contribution to the final model.

The final model has the following form – Equations (1) and (2):

$$\ln(\mu) = -0.956 + 0.041 \cdot \Delta S_{ff-lim} + 0.004 \cdot \sigma_S^2 + 0.028 \cdot \%HV + 0.000097 \cdot AADT, \quad (1)$$

that is:

$$\mu = \exp\left(-0.956 + 0.041 \cdot \Delta S_{ff-lim} + 0.004 \cdot \sigma_S^2 + 0.028 \cdot \%HV + 0.000097 \cdot AADT\right), \quad (2)$$

where: μ represents the mathematical expectation of the dependent variable of the AC_T.

3.2. Property damage only accidents

The distribution of property damage only traffic accidents did not fit the Poisson distribution well, according to the Kolmogorov–Smirnov test (p < 0.001). The negative binomial regression model was used (Pearson's χ^2/df = 1.037) based on the presence of overdispersion, which was verified in several ways. The mean and variance of property damage only traffic accidents are 1.65 and 3.69, respectively. Due to their high p-values, the variables ATS (p = 0.664) and the share of heavy vehicles (p = 0.056) can be removed from the model in order to improve it.

The ratio between Pearson's χ^2 value and degree of freedom df changed to 1.004 in the final model. The AIC and BIC criteria's values decreased, which suggests that the final model was improved in comparison with the preliminary model. The dependent variable is positively associated with the independent variables that were used to create the final model (Table 4). For every one-unit increase in the difference between the free-flow speed and the speed limit, the expected value of AC_{PDO} increases by

Table 3. Evaluation of parameters of the total accident model for the analysed time period

Parameter	B	Standard error	95% Wald confidence interval		Hypothesis test			exp(B)	95% Wald confidence interval for exp(B)	
			lower	upper	Wald χ^2	df	σ		lower	upper
Intercept	–0.956	0.2304	–1.408	–0.505	17.224	1	0.000	0.384	0.245	0.604
ΔS_{ff-lim}	0.041	0.0091	0.023	0.059	20.063	1	0.000	1.042	1.023	1.060
σ_S^2	0.004	0.0007	0.003	0.005	38.840	1	0.000	1.004	1.003	1.005
$\%HV$	0.028	0.0085	0.011	0.045	11.010	1	0.001	1.028	1.012	1.046
AADT	$9.698 \cdot 10^{-5}$	$1.0925 \cdot 10^{-5}$	$7.557 \cdot 10^{-5}$	0.000	78.794	1	0.000	1.00001	1.000	1.000
Negative binomial	0.094	0.0342	0.046	0.191	–	–	–	–	–	–

4% provided that other predictors are constant. The expected value of AC_{PDO} increases by 0.4% for every one-unit increase in the σ_S^2. There is only a minor increase (0.008%) in the expected value of the property damage only traffic accidents for every one-unit increase in *AADT*.

The final model has the following form – Equations (3) and (4):

$$\ln(\mu) = -1.119 + 0.04 \cdot \Delta S_{ff-lim} + 0.004 \cdot \sigma_S^2 + 0.000083 \cdot AADT, \quad (3)$$

that is:

$$\mu = \exp\left(-1.119 + 0.04 \cdot \Delta S_{ff-lim} + 0.004 \cdot \sigma_S^2 + 0.000083 \cdot AADT\right), \quad (4)$$

where: μ represents the mathematical expectation of the dependent variable of the AC_{PDO}.

3.3. Traffic accidents with injuries and fatalities

The Kolmogorov–Smirnov test determined that the distribution of traffic accidents with injuries and fatalities did not fit the Poisson distribution well (p < 0.001). The mean and variance of the number of traffic accidents with injuries and fatalities are 1.77 and 3.24, respectively. The overdispersion is present, like in the previous models. After checking the residual plots and performing the likelihood ratio test, we can conclude that the negative binomial regression model offers a significantly better fit to the data compared to the Poisson regression model. The initial negative binomial model can be improved by excluding the variables with high p-values because they did not contribute significantly to the quality of the fit.

4 independent variables were included in the final model: *AADT* (p < 0.001), %*HV* (p = 0.004), σ_S^2 (p < 0.001) and the difference between the free-flow speed and the speed limit (p < 0.001). The ratio of Pearson's χ^2 value and degree of freedom *df* is 1.03, which shows that the problem of overdispersion has been overcome. Observing the AIC and BIC criteria, it can be noticed that their values have decreased, which indicates that the final model has been improved in comparison with the preliminary negative binomial model. All variables presented in the final model are positively associated with the dependent variable (Table 5). For every one-unit increase in the %*HV*, the expected value of traffic accidents with injuries and fatalities increases by 3.3%, provided the other independent variables are fixed. The expected value of traffic accidents with injuries and fatalities increases by 4.3% for every one-unit increase in the difference between the free-flow speed and the speed limit. There is only a minor increase (0.4% and 0.01%) in the expected value of the accident number for every one-unit increase in σ_S^2 and *AADT*, respectively, which is the consequence of the great difference between the scales of measurement of these variables.

The final model has the following form – Equations (5) and (6):

$$\ln(\mu) = -1.855 + 0.00011 \cdot AADT + 0.042 \cdot \Delta S_{ff-lim} + 0.004 \cdot \sigma_S^2 + 0.032 \cdot \%HV, \quad (5)$$

Table 4. Evaluation of parameters of the property damage only model for the analysed time period

Parameter	*B*	Standard error	95% Wald confidence interval		Hypothesis test			exp(*B*)	95% Wald confidence interval for exp(*B*)	
			lower	upper	Wald χ^2	*df*	σ		lower	upper
Intercept	–1.119	0.2931	–1.694	–0.545	14.590	1	0.000	0.326	0.184	0.580
ΔS_{ff-lim}	0.040	0.0163	0.008	0.071	5.910	1	0.015	1.040	1.008	1.074
σ_S^2	0.004	0.0011	0.002	0.006	13.643	1	0.000	1.004	1.002	1.006
AADT	$8.354 \cdot 10^{-5}$	$1.7937 \cdot 10^{-5}$	$4.839 \cdot 10^{-5}$	0.000	21.692	1	0.000	1.00008	1.000	1.000
Negative binomial	0.094	0.0342	0.046	0.191	–	–	–	–	–	–

Table 5. Evaluation of parameters of the injuries and fatalities accident model in the analysed period

Parameter	*B*	Standard error	95% Wald confidence interval		Hypothesis test			exp(*B*)	95% Wald confidence interval for exp(*B*)	
			lower	upper	Wald χ^2	*df*	σ		lower	upper
Intercept	–1.855	0.3135	–2.469	–1.240	34.998	1	0.000	0.157	0.085	0.289
AADT	0.00011	$1.4457 \cdot 10^{-5}$	$8.582 \cdot 10^{-5}$	0.000	62.348	1	0.000	1.00001	1.000	1.000
ΔS_{ff-lim}	0.042	0.0115	0.020	0.065	13.400	1	0.000	1.043	1.020	1.067
σ_S^2	0.004	0.0009	0.003	0.006	23.726	1	0.000	1.004	1.003	1.006
%*HV*	0.032	0.0113	0.010	0.055	8.209	1	0.004	1.033	1.010	1.056
Negative binomial	0.109	0.0632	0.035	0.340	–	–	–	–	–	–

that is:

$$\mu = \exp\left(-1.855 + 0.00011 \cdot AADT + 0.042 \cdot \Delta S_{ff-lim} + 0.004 \cdot \sigma_S^2 + 0.032 \cdot \%HV\right), \quad (6)$$

where: μ represents the mathematical expectation of the dependent variable of the $AC_{I\&F}$.

The estimated dispersion parameter of the negative binomial model does not affect the mathematical expectation of the dependent variable of traffic accidents with injuries and fatalities.

4. Discussion

The obtained results of the 3 negative binomial models for the AC_T, accidents with injuries and fatalities and AC_{PDO} show that 3 variables are statistically significant in each of them: *AADT*, σ_S^2 and ΔS_{ff-lim}. All independent variables included in the final models are positively associated with the dependent variable. In other words, the rise of the values of *AADT*, σ_S^2 and ΔS_{ff-lim} variables increases the expected number of traffic accidents. The variable *AADT* is among the strongest predictors of the traffic accident number. This result is in accordance with previous research on the impact of *AADT* on traffic accident occurrence (e.g., Cafiso *et al.* 2010; Hadi *et al.* 1995, etc.). The result is logical considering the fact that the increase in the vehicle number leads to the greater interaction between vehicles in the flow, and consequently results in a greater risk of traffic accident occurrence. The results related to the positive impact of σ_S^2 on the occurrence of traffic accidents are similar to the results of several previous studies, which determined that the increase in variance led to the increase in traffic accidents (e.g., Aarts, Van Schagen 2006; Garber, Gadiraju 1989; Quddus 2013, etc.). The obtained results are logical because when the σ_S^2 increases, or the speed harmonization in the traffic flow decreases, there is a growth in the overtaking demand and potential conflicts. Also, the ΔS_{ff-lim} is positively associated with the dependent variable, which confirms the findings of previous studies, which state that (non)-credibility of speed limits is a significant factor for traffic accident occurrence, i.e., that a greater difference between these speeds results in a greater number of accidents (e.g., Hashim 2006; Montella, Imbriani 2015, etc.). Therefore, there is a necessity of re-examining the speed limit credibility on the segments characterised by large differences between the free-flow speed and speed limits.

In addition to the 3 previously mentioned variables, the variable related to the %*HV* also has a statistical significance in the models related to the AC_T and traffic accidents with injuries and fatalities. The positive impact of %*HV* on traffic accident occurrence was determined in both models, which is in accordance with the results of previous research (e.g., Chen *et al.* 2021, etc.). The obtained result is logical since the increase in %*HV* (i.e., vehicles that have poor dynamic characteristics) in the traffic flow negatively affects the speed of the traffic flow, the increase in the overtaking demand, etc. In the AC_{PDO} model, no statistical significance of this variable was shown. Considering the dynamic characteristics of heavy vehicles, and above all their large mass, it is clear that accidents involving vehicles of this category involve greater forces and, therefore, more serious consequences for other participants in the accident. This is why multiple vehicle accidents involving heavy vehicles usually result in injuries or fatalities suffered by the accident participants, and not only in property damage (Zhu, Srinivasan 2011).

5. Conclusions

In the last few decades numerous studies have been conducted with the aim of determining the impact of basic traffic flow characteristics on traffic accident occurrence but the mutual impact of traffic volume and speed characteristics has not been examined to a sufficient degree. Therefore, the aim of this article and one of its main advantages was to analyse the mutual impact of *AADT*, %*HV* and basic speed parameters such as σ_S^2, speed limit credibility or ΔS_{ff-lim}, *ATS* and %*ESL*, on the of traffic accident occurrence.

One of the crucial advantages of this article is the nature of the collected data and the sample size. In this article, the basic traffic flow parameters such as volume and speeds of all vehicles in the analysed 5-year period were obtained from ATCs posted along the sections of Class I 2-lane rural roads in the Serbia. This enables avoiding any changes of driving parameters (speed, headway, etc.) that might occur when using other types of equipment, such as radars. The analysis encompassed 802 accidents, which had occurred during a 5-year period on the sample of 235 sections of the homogeneous ATC impact zones – 1.6 km upstream and downstream of the ATC. In order to examine the impact of the mentioned traffic flow parameters on the occurrence of traffic accidents with different consequences, 3 models were developed referring to the AC_T, AC_{PDO} and $AC_{I\&F}$.

One of the greatest practical benefits based on the obtained results is the confirmation of the necessity for analysing the posted speed limit credibility. The need for the stated measure is reflected in the results, which show that the differences between the free-flow speed and speed limit, as well as σ_S^2, are positively associated with the number of traffic accidents. Namely, in Serbia, as well as in the other countries worldwide, there are speed limits, which do not correspond to road and road environment characteristics, and which, consequently, some drivers do not comply with. Frequent occurrence of non-credible speed limits threatens the complete speed management system since drivers' trust decreases, which in turn increases the traffic accident number (Goldenbeld, Van Schagen 2007). Therefore, when creating road design guidelines, it would be desirable to consider the possibility of introducing an obligation of sending a design for correction in case of identifying non-credible speed limits. This should be the basis for making a decision whether to revise (increase or decrease) the speed limit or change road geometric characteristics to correspond to the posted speed limit, since such inconsistencies have been determined to directly increase the total number of accidents and accidents with injuries and fatalities. Only the speed limits that drivers perceived as credible, or adequate for the road and road environment characteristics, could lead to the reduction of traffic accidents. Obtained results highlight the need for speed harmonization in the traffic flow, which reduces σ_S^2 and increases safety and efficiency (level of service).

The obtained results represent a significant basis for future research, which should be aimed at improving traffic flow conditions from the point of view of efficiency and traffic safety. 1st, a similar analysis should be conducted on other types of rural roads, such as motorways and multi-lane roads or 2-lane roads of lower classes, since they have different traffic flow conditions. Furthermore, additional ATC equipment on road sections would increase the sample, which would consequently improve the model. Future studies should continue to develop the model for predicting traffic accidents, since the focus of this article was solely on examining the mutual impact of traffic flow characteristics (*AADT*, *%HV* and speed characteristics) on traffic accident occurrence. Namely, future studies should thoroughly examine the impact of other traffic flow characteristics (such as time headways, traffic flow variations per direction), the impact of road geometric characteristics (such as the percentage of no-passing zones, lateral clearance distances), as well as the impact of weather conditions based on the data from the road weather information systems in the ATC impact zones, which have not been sufficiently examined so far. Incorporation of the traffic flow parameters, which were identified to have an impact on traffic accident occurrence into future accident prediction models would present another important practical significance of this article. In this manner, the findings of the article would represent a good basis for traffic accident cost models used in the feasibility studies of road infrastructure.

Author contributions

The authors confirm contribution to the article as follows:

- study conception and design: *Nemanja Stepanović*, *Vladan Tubić*;
- data collection: *Nemanja Stepanović*;
- analysis and interpretation of results: *Nemanja Stepanović*, *Vladan Tubić*, *Marina Milenković*, *Katarina Halaj*;
- draft manuscript preparation: *Nemanja Stepanović*.

All authors reviewed the results and approved the final version of the manuscript.

Disclosure statement

The authors report there are no competing financial, professional, or personal interests to declare.

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