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Determining Free-Flow Speed on Different Classes of Rural Two-Lane Highways

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ABSTRACT

Current analytical free-flow speed models consider all rural two-lane highways as the same road type despite their different functional significance in the network. The aim of this paper is to develop a prediction model for free-flow speed as a function of speed limit and road geometric characteristics for different classes of rural two-lane highways. The research was conducted on 50 representative sections of the two rural classes of two-lane highways equipped with automatic traffic counters in Serbia. In order to develop the appropriate models, it was necessary to determine the threshold values of vehicle time headway in the free-flow for both classes of rural two-lane highways, based on the total number of 191,720 vehicles. The obtained results show that there are differences in the threshold values of free-flow time headway for different road classes. Namely, it was determined that the values of free-flow time headway for Class I amounted to 6.3 s, and for Class II to 8.4 s. The free-flow speed prediction model for different road classes showed that speed limit had the highest impact on free-flow speed for Class I and II highways, followed by horizontal curve radius and shoulder width.

KEYWORDS

free-flow speed; two-lane rural highways; time headway; speed limit.

1. INTRODUCTION

Speed represents one of the main traffic flow parameters and is extremely significant for road design, level of service analysis, preparation of feasibility studies and traffic planning. Free-flow speed is particularly important since it is a direct indicator of the consistency of road design elements and the starting point when analysing capacity and level of service.

There is no unique definition of free-flow speed. Theoretically, free-flow speed can be defined as the space mean speed on the section when the density and volume tend to zero or when the speed of subject vehicle is not influenced by the vehicle in front, e.g. [1]. In addition, numerous studies consider free-flow speed to be the same as operating speed, which is frequently used in the papers and defined by AASHTO [2] as the speed selected by the majority of drivers under free-flow conditions. Operating speed is frequently calculated as the 85th percentile of the measured speed of vehicles driving under free-flow conditions, e.g. [3].

It is not easy to determine free-flow speed, particularly on rural two-lane highways with very diverse geometric characteristics. Highway capacity manual – HCM [4], as the most commonly used manual worldwide, recommends determining free-flow speed by direct measurements in the field as the average value of the measured speed of the minimum of 100 vehicles per direction, under low-demand conditions (two-way flow rate ≤ 200 veh/h). However, since measurements in the field are frequently impossible to conduct, particularly if a new road is being constructed, HCM [4] defined the possible analytical calculation of free-flow speed for two-lane rural highways using the following *Equation 1*:

$$FFS = BFFS - f_{LS} - f_A \quad (1)$$

where:

FFS – free-flow speed;

BFFS – base free-flow speed;

f_{LS} – adjustment for lane and shoulder width;

F_A – adjustment for access-point density.

The presented formula shows that free-flow speed mainly depends on base free-flow speed. HCM [4] recommends that BFFS should be obtained on the basis of the data on speeds and local knowledge about the operating conditions on similar facilities, using design speed or by roughly adding 10 mi/h to the posted speed limit value. These recommendations for determining BFFS clearly indicate problems and potential inaccuracies in the free-flow speed calculations, which can significantly affect the results of the level of service analysis later having in mind that average travel speed is directly calculated on the basis of free-flow speed.

Due to the lack of data on the design speed of numerous existing roads, studies frequently implement the recommendation related to adding 10 mi/h without too many additional analyses. Having in mind the different functions of two-lane rural highways in the traffic network, different geometric characteristics and terrain types they pass through, the use of a unique value might cause errors in subsequent analyses. Namely, HCM [4] methodology envisages the classification of roads into three classes, where the first two classes of two-lane highways address rural two-lane highways while Class III addresses two-lane highways in developed areas. More specifically, Class I highways represent major intercity routes and links in the state network, serving long-distance trips while Class II highways relate to access routes to Class I roads, roads serving as scenic or recreational routes or passing through rough terrain, used for short distance or the beginning and ending of longer trips. Class III highways may be portions of Class I or Class II highways that pass through small towns or developed recreational areas. Regardless of the mentioned differences, the model for free-flow speed calculation using the unique recommended value added to the speed limit value is universal or the same for all classes [4]. HCM [4] itself recognised the problem of the unique recommended value, but no thorough analyses per road class have been conducted up to now. Rough addition of a unique free-flow speed value for each two-lane highway class can result in insufficiently precise calculations of average travel speed. This leads to inaccurate calculation of the level of service, but also has an impact on making decisions about road network planning and design, transport system management, application of appropriate traffic management measures etc. One of the most common applications of the free-flow and average travel speed analysis is in the process of rural road network design, by means of conducting feasibility studies whose validity directly depends on the above-mentioned criteria. Namely, speed represents one of the key input values of various cost models in cost/benefit analyses. In addition, its precise definition directly affects the algorithm for finding rational solutions. Inaccurate calculation of free-flow speed, and in the process of average travel speed as well, might lead to serious errors in calculating the benefits of road infrastructure and making appropriate decisions regarding its development. Rural two-lane highways are the most represented road type in the road network and their functional classification is wide-ranging – form Class I highways with efficiency as the dominant function to the roads passing through rough terrain, recreational areas, small towns etc. Bearing this in mind, it is necessary to define precise analytical models for calculating free-flow speed for different classes of rural two-lane highways. All of the above-mentioned problems become aggravated if the posted speed limit is not suitable for the characteristics of the road and its environment, i.e. when the speed limits are not credible [5].

Having in mind the above-mentioned problems, the main aim of this paper is to develop a model for predicting free-flow speed as a function of speed limit and road geometric characteristics for different classes of rural two-lane highways – Class I and II. In order to develop suitable models, it was also necessary to determine the threshold values of time headway under free-flow conditions for different rural highway classes, which is one of the contributions of this paper. Therefore, the main contribution of this paper lies in the individual analysis of free-flow speed per rural two-lane highway class and in the sample size based on a greater number of sections. The developed models enable the precise analytical determination of the free-flow speed on different classes of rural two-lane highways without field measurements, which significantly reduces the time and costs of the analysis. This is especially important in the process of designing new roads, when field measurements are not possible. Precise determination of the free-flow speed value per different classes of rural two-lane highways is significant due to the greater accuracy of capacity and level of service analysis, adoption of proper traffic management measures, preparation of feasibility studies etc.

After the description of the problem and literature review of the studies conducted in the field, the paper presents the research methodology – for calculating the threshold values of time headway of vehicles in the free flow and for determining the predictors affecting free-flow speed. This part is followed by the obtained results, free-flow speed model validation and discussion within which the obtained results were compared with the results from previous studies. Finally, the paper contains concluding remarks and directions for future research.

2. LITERATURE REVIEW

This chapter first presents the threshold values of time headway under free-flow conditions determined in previous research and then it provides the predictors which were proven to have an impact on free-flow speed.

2.1 Analysis of the free flow threshold value

Free traffic flow represents the flow where travel speed is primarily influenced by the geometric characteristics of the road, but also by the characteristics of vehicles, drivers and environment. In other words, vehicle movement in free flow is not affected by the interaction between vehicles. A number of previous studies have dealt with defining the free flow threshold value, i.e. the value which clearly defines when the interaction between vehicles has/does not have an impact on the vehicle movement. It was determined that the best parameter for defining this threshold was time headway of vehicles in the flow since it was relatively simple to define. However, previous studies have not determined the unique value of time headway. Consequently, there are numerous differences between studies. The threshold value of time headway was stated when explaining the criteria for defining level of service – percent time spent following, introduced in the 1985 HCM 3rd edition [6]. It amounted to 5 s at the time [6]. The later editions of HCM [1, 4, 7] define the threshold value of time headway as 3 s. It is stated that if this value is lower, vehicles move in a platoon, i.e. they are under the influence of their mutual interaction.

Homburger et al. recommended the value of 4 s as the minimum time headway for vehicles in free flow, but they underlined that higher values (above 7 s) would be desirable if traffic conditions allowed for it [8]. Mahmud et al. also used the value of 4 s, but the methodology for obtaining this value was not explained in their study [9].

The time headway threshold value under free flow conditions amounting to 5 s was defined in a significant number of studies, e.g. [10–13], although some of them do not provide the methodology for determining this value. Hashim [12] analysed the 85th percentile speed of vehicles in the flow on 20 sites equipped with automatic traffic counters on two-lane rural highways in Egypt, with approximately homogeneous geometric and traffic characteristics, in order to examine the correlation between time headway and free-flow speed. The author determined that the free flow threshold value of time headway was 5 s, i.e. that this value was the free flow threshold [12].

Lobo et al. suggested a five-step model for determining the minimum threshold value of gap interval between vehicles at which the speed of one vehicle is not affected by the speed of the vehicle ahead [3]. Recording by Doppler effect-based devices was carried out at four sites (2 in tangents and 2 in horizontal curves) of a two-lane rural highway section in Portugal. The obtained results, based on the total sample of 32,933 vehicles recorded during the 12 successive hours under uncongested traffic conditions, show that the speed of the following vehicle was not affected at the gap interval values between vehicles greater than 6 s [3]. The same gap interval value of 6 s was used by Lamm et al. [14] but without any detailed explanation. Vogel also obtained the time headway value of 6 s by analysing the traffic characteristics of more than 100,000 vehicles at an urban four-legged intersection in Sweden [15].

To provide the free flow conditions when measuring speeds on different road types, Fazio et al. used time headway values greater than 7 s [16]. They referred to the results of the studies conducted by Currin, Homburger and Robertson [8, 17, 18]. Silvano et al. analysed the impact of speed limit and geometric characteristics of urban roads on free-flow speed and determined that the critical value of time headway at which vehicles had a 50% probability to be under constrained conditions amounted to about 7 s [19]. The authors determined that the probability decreased drastically (<10%) at the time headway greater than 10 s, which is the threshold value obtained by Luttinen [20] for two-lane rural and urban highways.

In addition to the above-mentioned values, the literature contains the gap interval values greater than 8 s, at which speeds are stabilised and there is no impact of other vehicles [21].

2.2 Analysis of free-flow speed predictors

Several papers have dealt with the relationship between free-flow speed and speed limit on a section. If the definition of free-flow speed is taken into account, the extent of the speed limit's impact on the "driver-desired speed" is uncertain. Namely, it is debatable whether this impact is solely a consequence of geometric characteristics of the road which should be represented by speed limit or a consequence of potential fines that drivers must pay in case of exceeding the speed limit.

In practice, the most frequent methods for setting speed limits are design speed [22] and 85th percentile speed, e.g. [23, 24]. Numerous authors have analysed the impact of speed limits on free-flow speed, e.g. [16, 25]. Using the econometric model approach, Himes et al. showed that it was justified to use speed limits in the models for determining free-flow speed [26]. On the other hand, Wang et al. stated that speed limit should not be regarded as an independent variable in the free-flow speed prediction models together with design speed and geometric characteristics of the road, having in mind the high correlation between these variables [27]. Considering the above-mentioned, this paper provides a detailed description of the research methodology and obtained results of the previous studies in the field.

In the mentioned paper, Hashim analysed speed characteristics on 20 sections of rural two-lane highways with homogeneous characteristics and the general speed limit of 60 km/h [12]. The analyses showed that the 85th percentile speed varied from 51.1 km/h to 88.6 km/h. It was concluded that instead of a general speed limit, individual speed limits should be posted for each road section based on an engineering study. Hashim stated that these limits should be similar to the 85th percentile speed of vehicles in order to be observed by drivers, having in mind that the percentage of overspeeding ranged from 4% to 75% on the observed sections [12].

Fazio et al. [16] examined the association between speed limit and free-flow speed of vehicles on 10 sections with different speed limits (from 30 km/h to 120 km/h), out of which 5 were rural, 3 multi-lane and 2 freeway sections. Speeds, volume and headway were measured on 3 weekdays during daylight when the roadway was dry. In order to ensure free-flow conditions, the analysis considered passenger car speeds collected at the volume rates lower than 500 veh/h (HCM defines them as fewer than 1000 veh/h) and time headways greater than 7 s. The speeds were measured using a radar gun until the data were collected for the minimum of 100 passenger cars. The total of 1,668 speed observations was recorded on all sections, while space mean speed was determined on the basis of standard deviation. Simple linear regression models revealed the strong association between free-flow speed and posted speed limit, with the correlation coefficient of +0.99 [16].

Ye et al. [28] developed a model for determining free-flow speed of vehicles including speed limit, number of lanes, land use in the road environment (rural or urban) and road classification (freeway section or non-freeway sections). Considering different impacts, individual models were developed for passenger cars and heavy vehicles, as well as for daytime and nighttime driving conditions. Given the normal distribution of speeds in free flow, the study used a linear model with a least-square calibration method. The design sections of Indiana arterial roads with automatic traffic counters were selected, while the free-flow speeds were classified as the speeds at the volume of fewer than 1000 veh/h for two-lane sections and fewer than 1500 veh/h for three-lane sections. Among other things, the results showed that the increase in speed limit led to the increase in the free-flow speed of passenger cars and heavy vehicles. This was not the case under nighttime conditions when there was no significant impact of speed limit on passenger car speed [28].

Mahmud et al. [9] examined how the change of the general speed limit from 55 mph (88 km/h) to 65 mph (105 km/h) on rural two-lane highways in Michigan affected the change of traffic flow speed. The research involved recording of free-flow speeds – the minimum number of 100 passenger cars and 10 heavy vehicles per direction with the minimum time headway of 4 s, before and after the speed limit change. In addition, measurement was also conducted on control sections where the speed limit remained unchanged in order to examine possible spillover effects of the increased speed limit. Measurement of the speed of 46,162 free flowing vehicles was conducted using video cameras or radars based on LIDAR technology on the total number of 67 sections with the changed speed limit and 28 control sections. Most of the involved sections had ideal characteristics (straight road, lack of grade etc.), but the study also involved a group of sections with low values of horizontal curve radius and with the recommended speed lower than 55 mph. Quantile regression provided results stating that if speed limits were raised the average speeds increased by 3.8 mph to 4.5 mph, while the 85th percentile speeds increased by 4.0 to 5.0 mph along with the increase in the standard deviation of vehicle speeds. The speed on control sections remained unchanged, or lower values were recorded, which suggests that there was no spillover effect from neighbouring sections where the speed limit was increased [9].

Silvano et al. [19] examined the impact of speed limit changes and characteristics of urban roads on free-flow speed of vehicles in the flow using the parametric probabilistic latent approach. The data were obtained by measuring speeds and time headway, using the total sample of 67,000, before and after changing the speed limit from 50 km/h to 40 km/h. The analysis included 32 urban sections in Sweden. Measurements were conducted on the locations with the right of way, situated far away from signalised intersections, roundabouts and pedestrian crossings. The results showed that the probability of a saturated traffic flow was greatly dependent on time headway and on the differences between vehicle speeds, but only when the distance headway is smaller than 60 m. In addition, the results showed that the model described well how the change of road characteristics affected free-flow speed. It also showed that adjacent land use, car parks and sidewalks had the greatest impact on it. The speed limit change affected the distribution of free-flow speeds, and it also influenced the speeds in the saturated traffic flow. A more pronounced impact was determined in suburban areas than on the roads in the central city areas [19].

Numerous studies examined the impact of geometric characteristics of the road on free-flow speed, e.g. [11, 13, 29]. Medina and Tarko [11] conducted a study taking into account not only speed limits but also the impact of mean speed, speed dispersion and geometric characteristics on free-flow speed on rural two-lane highways. In this manner they enabled the prediction of any percentile speed, particularly considering the impact of geometric characteristics on mean speed and the impact on speed dispersion. Sekhar et al. [13] conducted a study on two-lane highways in India which had different pavement conditions. They showed that the deterioration of the pavement led to the linear reduction of free-flow speed, particularly for different categories of passenger cars. Lovrić and Breški [29] developed an adequate model for calculating free-flow speed on rural two-lane highways in Bosnia and Herzegovina and determined that the following variables had a statistically significant impact on free-flow speed: degree of horizontal curvature, traffic lane width and average longitudinal grade. The first two variables had the greatest impact on free-flow speed.

The most commonly used manuals in engineering practice also use the geometric characteristics of the road as influential factors for the calculation of the free-flow speed of two-lane highways. Thus, the already mentioned HCM [1, 4, 7], in addition to the base free-flow speed determined on the basis of design speed/speed limit, takes into account the roadway width, lateral clearance and number of access points. In the German manual HBS [30], the speed calculation procedure is based on the longitudinal grade and the degree of horizontal curvature of the section. HBS is applied much less frequently and it is limited by its guidelines and design standards which are valid primarily in Germany. Namely, its starting hypothesis is the precise classification of roads per category according to RIN (Richtlinien für integrierte Netzgestaltung – Guidelines for Integrated Network Design), which limits its use in other countries [30]. Consequently, the limitations regarding the use of this manual are also evident in the Republic of Serbia. While some of the tested sections might be classified in accordance with RIN since they have the same design standards, this would not be possible for most other sections. Unlike HBS which is dominantly limited by design standards, the HCM classification defines roads according to their functions in the network. Thus, it can be applied in various countries/regions, including Serbia. This is the reason why the validation of the obtained models in this paper was conducted based on comparison with the HCM model.

2.3 Summary

Based on the current literature review, it was concluded that there was a problem of defining the free-flow threshold value accurately, which is necessary for various examinations. Namely, according to the traffic flow theory, the main approach to determining free flow threshold values is based on defining the threshold value of time headway. Over time, researchers have attempted to apply more practical methods, such as using volume, to define this threshold. However, time headway has been confirmed to be the most adequate parameter for this, [3, 9]. Numerous researchers to date have used a particular time headway value as the threshold free-flow value without giving precise explanations for this, e.g. [9, 14]. On the other hand, some researchers have conducted very exact and precise measurements of this parameter, e.g. [3, 15], but they obtained large differences in its values, ranging mostly from 3 s to 10 s. Due to the wide range of the time headway threshold values in the previous studies and in order to develop a model for calculating free-flow speed for separate classes of two-lane highways, it was necessary to precisely determine the time headway values for each class separately in this paper. In the process, appropriate methodology was applied.

Among analytical models for calculating free-flow speed which are mainly applied when it is not possible to measure speed in the field (for example, if a new road is being constructed), the most commonly used model has been the HCM model based on rough addition of BFFS (adding 16 km/h to the posted speed limit value) for all classes of two-lane roads [4]. HCM itself highlighted the inaccuracy of rough addition [4], but no thorough examination has been conducted. In addition to different impacts of geometric characteristics of the road on free-flow speed, numerous authors have analysed the impact of speed limits on free-flow speed in their studies, e.g. [9, 16]. It was determined that a lot of papers used the rule of simply adding the fixed speed value to the speed limit, which was not defined exactly and did not involve other factors of the roads with different functions in the network [16]. Opinions differ regarding the justification of including the speed limit into the models, e.g. [26, 27]. Up to now, current manuals and studies have developed a unique model for calculating free-flow speed for two-lane highways despite the stated difference between the functions of different classes of two-lane highways. In order to improve accuracy, this study has developed separate models for determining free-flow speed on both classes of rural two-lane highways. In this manner, we avoided rough addition of the unique speed value to the posted speed limit value recommended by HCM [4].

3. METHODOLOGY

3.1 Data collection

In order to determine the impact of speed limit and other geometric characteristics of the road on free-flow speed for different classes of rural two-lane highways, it was necessary to select the representative sections of the Serbian road network which correlate to the HCM [4] functional classification of rural two-lane highways, equipped with automatic traffic counters (ATC). According to the HCM [4] classification, 50 sections in total were selected, 30 of which were Class I highways and 20 were Class II highways. All of the sections are equipped with modern ATC (QLTC 10C) operating on the principle of inductive loops. It is worth noting that inductive loops are still predominantly used in rural but also in urban networks and advanced traffic control systems [31]. In addition to the data on traffic volume, traffic flow structure, temporal variations and alike, these counters also register the travelling speed of each vehicle, as well as time headways. All analyses conducted in this paper refer to the zones 0.75 km upstream and downstream of the ATCs, so that the traffic flow parameters read from the ATCs can be representative for the segment of the observed section *(Figure 1)*. According to the database of the public enterprise “Roads of Serbia”, geometric characteristics of the road were determined for all mentioned ATC impact zones: minimal horizontal curve radius R_{min} (m), grade G (%), minimal roadway width RW (m), minimal shoulder width SW (m) and number of access points AP (-). All selected ATC impact zones have good pavement condition. An overview of the range values of the basic characteristics for the analysed sections are presented in *Table 1*. In addition, using the database of the Ministry of Internal Affairs of the Republic of Serbia, the data on speed limits – SL (km/h) – in each ATC impact zone were collected. The speed limits on the sections varied from 40 km/h and 80 km/h. The most frequently recorded speed values were 80 km/h on both rural two-lane highways, which represent general statutory speed limits for the mentioned road classes.

The design day in the design month was selected for the analysis – Thursday, 18 April 2019. This year was selected to avoid the COVID-19 impact and its temporary measures (limited mobility and alike) on traffic flow variations. Having in mind that the paper analyses free-flow speed, the research day and period were selected

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

Two-lane highways class	R_{min} [m]	G [%]	RW [m]	SW [m]	AP [-]
I	120 – 4584	0 – 4.2	6.5 – 9	0.5 – 2	2 – 34
II	85 – 2450	0 – 6.1	5.5 – 8.6	0.5 – 2	3 – 41

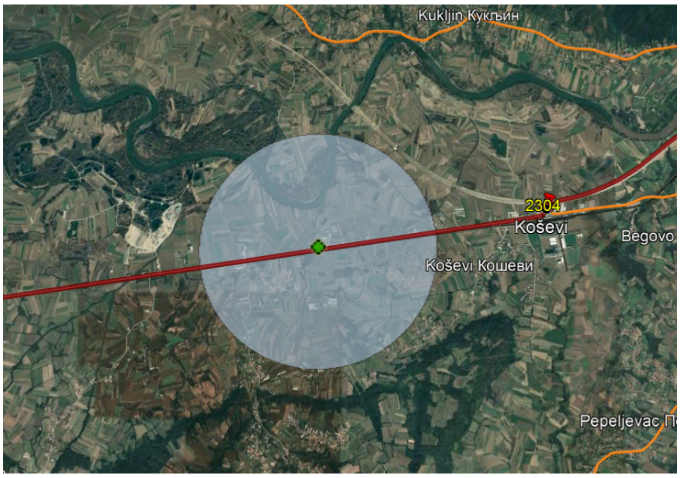


Figure 1 – Example of an ATC zone: ATC 1222 (green point) on the state road IB 02305
Source: Google Earth

so to obtain approximately ideal conditions – it was a sunny day on all the selected sections, with no precipitation (dry pavement) and the data were collected during daytime periods from 06:00 a.m. to 08:00 p.m. The total valid sample on all 50 sections equipped with ATCs amounted to 191,720 vehicles. Distribution of all vehicles' speeds measured by ATCs per two-lane rural highway class has a tendency toward normal, which is expected having in mind the sample size (*Figure 2*). Higher traffic load can be noticed on Class I highways – on average 4,450 vehicles during the research day, compared to 2,911 vehicles detected on Class II highways. In addition, greater speeds can be perceived on Class I highways, so the following can be highlighted: there are 9.6% vehicles having the speed lower than 60 km/h on Class I highways, compared to 14.1% on Class II highways; there are 21.4% vehicles having the speed greater than or equal to 90 km/h on Class I highways, compared to 15.3% on Class II highways etc. The mean speed on Class I highways amounts to 77.8 km/h while the median is 77.0 km/h, whereas on Class II highways these values amount to 74.31 km/h and 73.0 km/h, respectively.

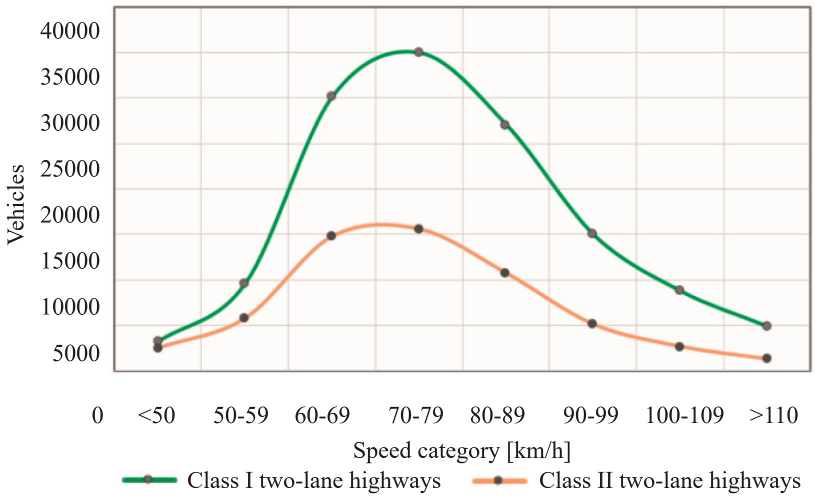


Figure 2 – Distribution of raw speed from ATCs for Class I and Class II two-lane highways

3.2 Determining the free flow threshold value

In order to determine free-flow speed on the observed sections of rural two-lane highways, it was primarily required to examine when the travelling of a vehicle n had no impact on the speed of the following vehicle n-1, i.e. to find the free flow threshold value with no impact of the interaction between vehicles. As mentioned above, the most used parameter for determining this threshold is the time headway of vehicles in the flow, e.g. [3, 9]. However, free flow threshold values have significantly varied in studies so far – from 3 seconds to over 10 seconds. In order to determine differences in threshold values of time headway that occurs on different classes of rural two-lane highways, it was necessary to conduct analysis on both classes separately.

Time headway or headway is the time between successive vehicles as they pass a point on a lane or roadway, measured from the same point on the vehicles [4]. When calculating time headway based on detectors, the passing time of two same axes of the vehicles *n* and *n*-1 is observed, as it was the case in this paper. It is known that the vehicle *n* has a great impact on the following vehicle (*n*-1) when time headway values are small, while under free flow conditions this impact is minimal since the travelling of the vehicle is in this case primarily affected by the characteristics of the road, vehicles and drivers. Therefore, speeds between the vehicles *n* and *n*-1 should not correlate under free flow conditions. In other words, under free flow conditions, their correlations are expected to decrease with the increase in time headway until they reach stable values close to zero [15]. Bearing this in mind, we should define the threshold value up to which the relationship between the vehicles' speeds is dependent on time headway, i.e. after which this relationship is weak. Values up to 0.4 are regarded as a weak correlation [32]. Then, it is possible to classify vehicles according to the obtained threshold value of time headway and find the regression that predicts the correlation value for the following vehicles for groups with strong and weak correlations. Thus, it is possible to obtain an additional criterion for determining the accurate threshold value. This criterion is related to the time headway value read at the point where two curves meet. The obtained value should be close to the value used for the division into two groups. If this is not the case, the procedure should be repeated [15].

Since the ATCs on the studied sections measure time headways and round them up to the values of 1 s, 15 groups in total were created according to the time headway values between successive vehicles. Consequently, the speeds of all vehicles whose time headway was 1 s belonged to Group 1, while the last group involved the speeds of all vehicles with time headways ≥15 s. Time headways lower than 1 s (lower than 0.5 s) were not analysed since these were mainly the vehicles abruptly starting or ending their overtaking manoeuvres. Correlations between the distributed speeds of each vehicle (*n*) and the following vehicle (*n*-1) within each of the 15 groups were examined for all the studied sections with ATCs. Database forming and data processing were performed using the software package IBM SPSS Statistics v. 21.

3.3 Determining free-flow speed predictors

After determining the threshold value of the free-flow time headway for each rural highway class, the average speed was determined per direction on the basis of data from ATCs. Thus obtained speed data can be classified into indirect spot speed data measurements, i.e. they represent the time mean speed due to the small distance between the inductive loop detectors [33]. However, taking into account the negligible speed variance, it can be concluded that the values of time mean speed are similar to the values of space mean speed [34], and that it represents the free-flow speed of the observed ATC impact zones. Thus determined free-flow speed on the observed sections per direction represented the dependent variable in the developed model. The following variables were selected to be independent variables: speed limit SL (km/h), minimal horizontal curve radius R_{min} (m), grade G (%), roadway width RW (m), shoulder width SW (m) and number of access points AP (-). All variables in the paper are continuous.

Linear regression (stepwise method) was used to analyse the association between mentioned predictors and free-flow speed for different highway classes. Two independent models for the sections of Class I and II two-lane highways were tested. First, collinearity of the independent variables was examined, given that these were multiple regression models. The hypothesis regarding the non-existence of multicollinearity was not compromised since the Tolerance Value was considerably higher than the threshold value. Namely, the obtained minimal Tolerance Value greater than 0.4 is higher than the threshold value of 0.10 [35]. Similarly, VIF as the reciprocal of the Tolerance Value had no worrying values, since the maximum obtained value of 2.5 is lower than 10 [35].

4. RESULTS

4.1 Determining the free flow threshold value

Examination of the correlations (*r*) between the speed of the vehicle *n* and the following vehicle (*n*-1) for each of the defined 15 groups of time headways (t_h) and both rural two-lane highway classes provided the following results (*Table 2* and *Figure 3*).

Table 2 – Correlation coefficients of successive vehicles' speeds per defined group of time headway on rural two-lane highways

t_h [s]	Class I two-lane highways			Class II two-lane highways		
	Correlation	Sig.	Valid cases	Correlation	Sig.	Valid cases
1	0.892	<0.001	17048	0.895	<0.001	5082
2	0.817	<0.001	17397	0.824	<0.001	6851
3	0.682	<0.001	9433	0.700	<0.001	4153
4	0.600	<0.001	6223	0.586	<0.001	2642
5	0.479	<0.001	4730	0.512	<0.001	1800
6	0.439	<0.001	3899	0.405	<0.001	1452
7	0.365	<0.001	3380	0.387	<0.001	1263
8	0.350	<0.001	3113	0.415	<0.001	1101
9	0.360	<0.001	2827	0.264	<0.001	1073
10	0.326	<0.001	2605	0.269	<0.001	985
11	0.325	<0.001	2465	0.264	<0.001	897
12	0.316	<0.001	2276	0.232	<0.001	864
13	0.278	<0.001	2183	0.279	<0.001	817
14	0.250	<0.001	1995	0.254	<0.001	765
15	0.236	<0.001	50566	0.176	<0.001	28175

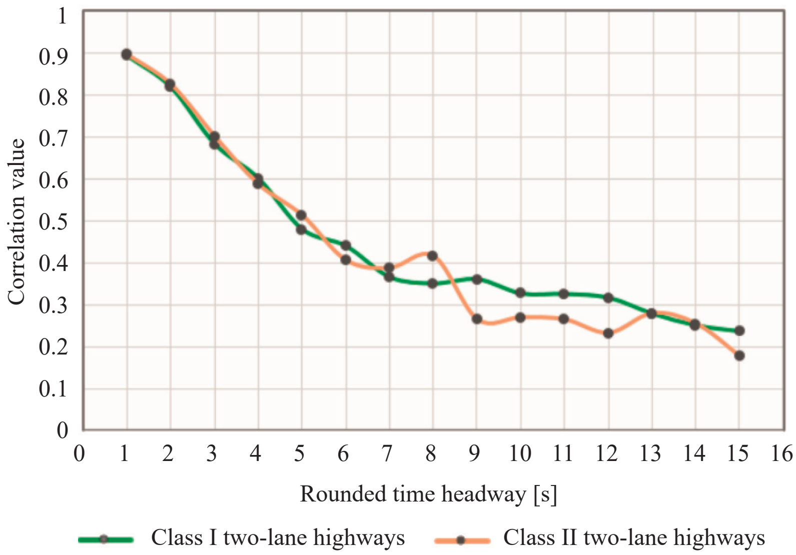
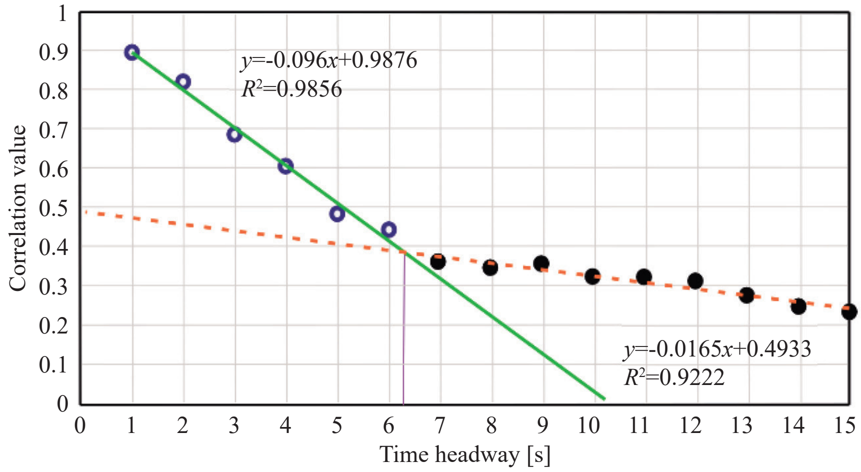


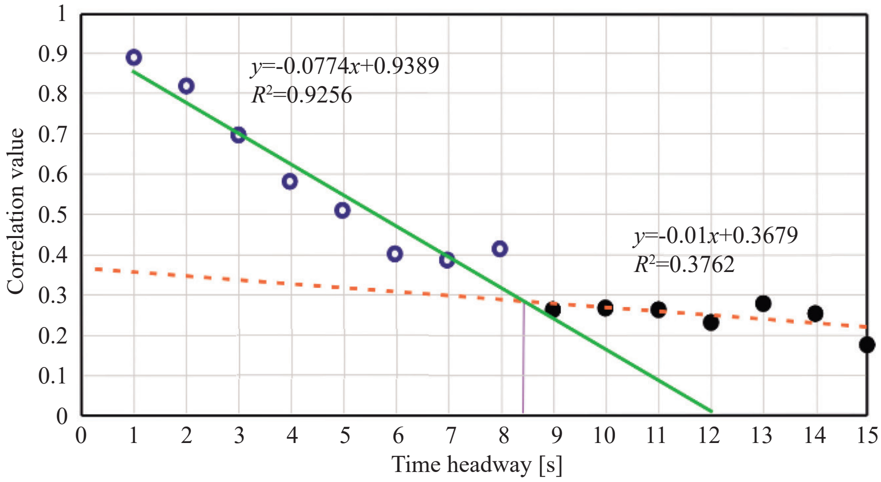
Figure 3 – Correlation values for each defined group of time headway

The obtained data show that there is a statistically significant correlation between the speeds of successive vehicles for all studied groups of time headway. As expected, there is a general decrease of the correlation coefficient, i.e. decrease of the relationship between the speeds of successive vehicles *n* and *n*-1 with the increase in time headway, as well as lowering of decrease (curve flattening) after a specific value of time headway. The obtained results clearly indicate that there is a difference between the threshold values of free-flow time headway per highway class. Namely, if the values up to 0.4 are regarded as a weak correlation [32], it can be concluded on the basis of *Table 2* and *Figure 3* that stable conditions for Class I highways begin at the 7th second and for Class II at the 9th second.

In order to check the obtained values and confirm the exact threshold values of time headway, the authors defined regression lines for the correlation values below (group with weak correlation) and above (group with moderate and strong correlation) the stated threshold values (*Figures 4a and 4b*). It can be noticed that for both examined highway classes the intersection point of two regression lines is close to the assumed values of 6.3 s for Class I two-lane highways and 8.4 s for Class II highways. Therefore, it can be concluded that these values represent free-flow threshold values.



a) Class I highways



b) Class II highways

Figure 4 – Regression lines for the correlation values for groups of vehicles below and above the time headway threshold value

4.2 Determining free-flow speed predictors

The defined time headway threshold values in the free flow were rounded up to the first greater whole digit, so the speeds of vehicles having time headways greater or equal to the following threshold values were used for the free-flow speed prediction: 7 s for Class I highways and 9 s for Class II highways. The average values of vehicle speeds in the free flow, the analysed geometric characteristics and speed limits were determined per direction. *Table 3* presents the results of the two separately developed models for the rural two-lane highways sections of Class I and II.

The first regression model tested the hypothesis that the free-flow speed on Class I two-lane highways was defined by the variables: speed limit, minimal horizontal curve radius, average grade, roadway width, shoulder width and number of access points. The stepwise regression model isolated three models. The first step isolated the variable: speed limit (β=0.620; 95% CI: 0.336–0.672; p<0.001), which on its own explained 37% of the variability of the dependent variable. The second step identified the variables: speed limit (β=0.494; 95% CI: 0.231-0.573; p<0.001) and minimal horizontal curve radius (β=0.319; 95% CI: 0.001-0.003; p=0.004), explaining 45% of the variability of the dependent variable. The final model explained 49% of the variability of free-flow speed on rural highways. This variability was explained by the variables: speed limit (β=0.421; 95% CI: 0.170–0.515; p<0.001), minimal horizontal curve radius (β=0.262; 95% CI: 0.000–0.003; p=0.015) and shoulder width (β=0.241; 95% CI: 0.660–9.312; p=0.025). All regression models explain a significant percent-

Table 3 – Linear regression models of the association between free-flow speed and road characteristics

Models	Beta (95% CI), p value
Class I two-lane highways	
Step 1: ($\Delta R^2 = 0.37$; $F(1.58) = 36.17$; $p < 0.001$) SL [km/h]	 0.620 (0.336 - 0.672), p < 0.001
Step 2: ($\Delta R^2 = 0.45$; $F(2.57) = 25.28$; $p < 0.001$) SL [km/h] R_{min} [m]	 0.494 (0.231-0.573), p < 0.001 0.319 (0.001-0.003), p = 0.004
Step 3: ($\Delta R^2 = 0.49$; $F(3.56) = 19.91$; $p < 0.001$) SL [km/h] R_{min} [m] SW [m]	 0.421 (0.170 - 0.515), p < 0.001 0.262 (0.000 - 0.003), p = 0.015 0.241 (0.660 - 9.312), p = 0.025
Class II two-lane highways	
Step 1: ($\Delta R^2 = 0.27$; $F(1.38) = 15.76$; $p < 0.001$) R_{min} [m]	 0.541 (0.001 - 0.003), p < 0.001
Step 2: ($\Delta R^2 = 0.37$; $F(2.37) = 12.67$; $p < 0.001$) R_{min} [m] SL [km/h]	 0.520 (0.001 - 0.003), p < 0.001 0.337 (0.072 - 0.532), p = 0.012
Step 3: ($\Delta R^2 = 0.45$; $F(3.36) = 11.84$; $p < 0.001$) R_{min} [m] SL [km/h] SW [m]	 0.392 (0.000 - 0.002), p = 0.004 0.377 (0.121 - 0.554), p = 0.003 0.328 (1.289 - 11.496), p = 0.016

age of variability of the dependent variable. Also, the change of the coefficient of determination is statistically significant. The final model has the following form as *Equation 2*:

$$y = 46.038 + 0.343\ SL + 0.002\ R_{min} + 4.986\ SW \tag{2}$$

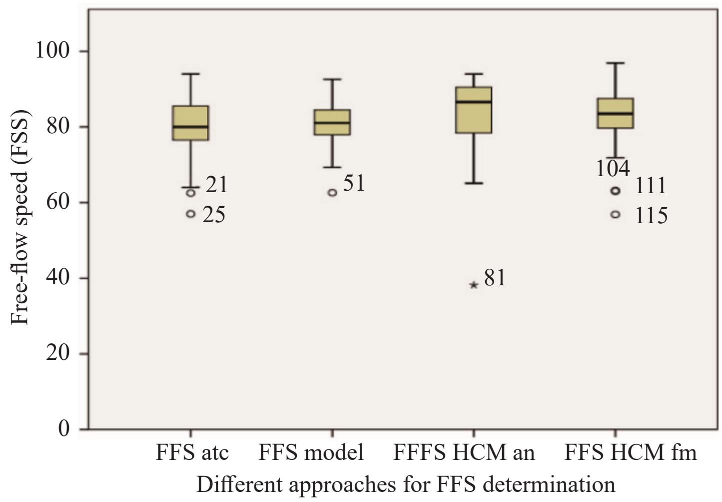
The explanation of vehicle free-flow speeds on Class II two-lane highways has three steps. The F statistic is statistically significant for all three models, which indicates that models predict the dependent variable significantly well. In the first step, one predictor explained 27% of the variability of the dependent variable. In the second step, two predictors explained 37% of the variability, while the last third step isolated three statistically significant predictors explaining 45% of the variability of the dependent variable. Having in mind the results of the last third step of the stepwise regression, the greatest contribution to the explanation of free-flow speed on Class II two-lane highways was shown by the variable: minimal horizontal curve radius (β=0.392; 95% CI: 0.000–0.002; p=0.004). It was followed by the variable: speed limit (β=0.377; 95% CI: 0.121–0.554; p=0.003), and then by shoulder width (β=0.328; 95% CI: 1.289–11.496; p=0.016). The final model has the following form as *Equation 3*:

$$y = 41.508 + 0.338\ SL + 0.001\ R_{min} + 6.392\ SW \tag{3}$$

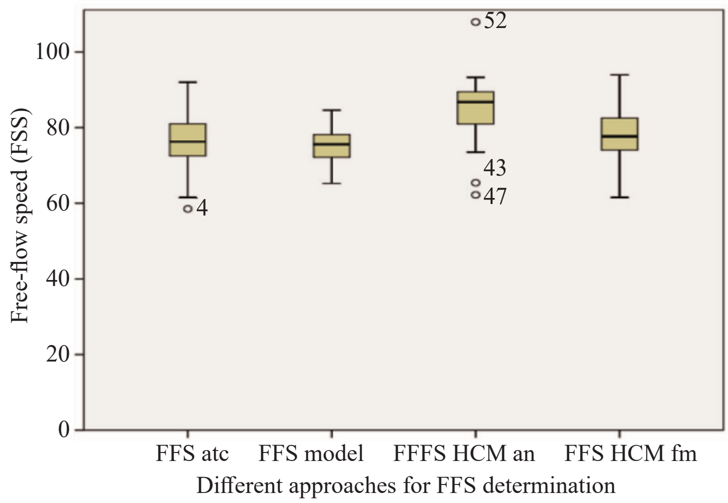
4.3 Free-flow speed model validation

In order to compare the results obtained by the developed free-flow speed models for both rural two-lane highways classes and HCM's models with the free-flow speed values obtained from automatic traffic counters, the boxplots and the One-Sample T Test were used. The results comparison was carried out on the same number of ATC impact zones of the I and II two-lane highway classes, on the road sections which were not used in the model development.

Bearing in mind that boxplots are useful for displaying the distribution of speed data, *Figures 5a and 5b* show boxplots with the values of free-flow speeds obtained by different methods – two analytical methods including the developed models (FFS model) and HCM analytical equation (FFS HCM an) – *Equation 1*, and two methods obtained by automatic traffic counters (ATCs). The methods obtained by ATCs involve the free-flow speeds calculated based on the time headway threshold values in the free flow (FFS atc) and HCM model for field measurements based on volume (FFS HCM fm). The application of the latter model (FFS HCM fm) implied calculation of free-flow speeds by using one of the two possible approaches depending on the volume (greater then or less then 200 veh/h) and speed data obtained from ATCs. As stated above, it was determined that that the most adequate parameter for defining free-flow threshold was time headway of vehicles in the flow, e.g. [3,9]. What is more, in case of larger volumes (>200 veh/h) the HCM method of field measurements requires adjustment of the ATC measured speed values using an analytical pattern. The free-flow speed values obtained by the HCM method in this manner also depend on commercial vehicles, whose application requires calibration to local conditions. Bearing this in mind, as well as the fact that the HCM model does not observe the difference occurring on different two-lane highway classes, the representative values used in further comparisons were the free-flow speed values obtained by ATCs (FFS atc). Based on the presented boxplots, it can be seen that in comparison to the HCM model (FFS HCM an), the speed data distribution acquired by the developed free-flow speed models (FFS model) is more similar to the speed data distribution obtained by ATCs (FFS atc), for both classes of rural two-lane highways.



a) Class I highways



b) Class II highways

Figure 5 – Boxplots for free-flow speed determination using different approaches

Observing the results of the One-Sample T Test conducted on Class I highways, it can be noticed that there is no statistically significant difference between the values obtained by ATCs (FFS atc) and the values obtained by the model (FFS model) – t=0.792; p=0.435. Also, there is no statistically significant difference when comparing the values obtained by the HCM model (FFS HCM an) and the field measured values – t=1.344; p=0.189, but the obtained p value is somewhat lower.

The results of the One-Sample T Test conducted on sections of Class II highways show that there is no statistically significant difference between the values obtained by ATCs (FFS atc) and the values obtained by the model (FFS model) – t=-0.660; p=0.517). On the contrary, when comparing the values obtained by the HCM model (FFS HCM an) and the values obtained by ATCs (FFS atc), it was shown that the difference is statistically significant (t=3.955; p=0.01).

Based on the presented boxplots and conducted One-Sample T Test, it can be seen that the values obtained using the developed models (FFS model) fit better to the values obtained by ATCs (FFS atc) compared to the HCM model (FFS HCM an), for both road classes.

5. DISCUSSION

5.1 Determining the free flow threshold value

The obtained differences in the threshold values of free-flow time headway can be explained by the different conditions in the traffic flow on different classes of rural two-lane highways. Class I highways represent the roads with the highest traffic load (on average 4,450 vehicles during the period from 6 a.m. to 8 p.m. on the studied day). Consequently, here drivers perceive lack of the impact of the vehicle travelling ahead at lower values of time headway than it is the case on Class II highways. Class II highways have significantly lower traffic load (on average 2,911 vehicles during the period from 6 a.m. to 8 p.m. on the studied day), so drivers are accustomed to free flow conditions. In other words, the impact of the interaction with the vehicle ahead starts at higher time headway values. Although no studies have examined different classes of two-lane highways so far, the obtained results – 6.3 s for Class I and 8.4 s for Class II highways – are in accordance with the values obtained in similar research on rural two-lane roads. These values are slightly higher than the value (5 s) obtained by Hashim [12] but very similar to the values (6 s) reached by Lobo et al. [3], and to the value (7 s) recommended by Homburger et al. [8] if the conditions allow for it.

5.2 Determining free-flow speed predictors

The analysis of speed limit as an independent variable in the models for calculating free-flow speed proved justified, which corresponds to the findings of some other studies, e.g. [25, 26]. However, this conclusion is contrary to the conclusions of Wang et al. [27], who highlighted the problem of the mutual impact of geometric characteristics of the road and speed limit. Still, in this paper the hypothesis regarding multicollinearity in the mentioned models was not compromised (tolerance higher than 0.10, VIF lower than 10), which means that the correlation between the variables related to geometric characteristics of the route and speed limit was not confirmed. This can be explained by the fact that most of the sections contain general statutory speed limits for the subject road category (80 km/h), while a large number of sections have the characteristics which allow for greater vehicle speeds. This indicates that the posted speed limits are not credible [5], as Hashim concluded as well [12], and that more attention should be paid to setting speed limits in accordance with geometric characteristics of the road. The research by Mahmud et al. [9] showed that the increase in speed limits on two-lane highway sections led to a slight increase in free-flow speeds in the flow (by approximately 4 mi/h) and contributed to greater speed limit observance.

Considering the individual impact of speed limit on free-flow speed, it can be noticed that this variable has the strongest impact on Class I two-lane highways when compared to all other studied variables, while it is the second strongest on Class II highways. This is in accordance with the results of Medina and Tarko [11]. It was shown that the increase in speed limit resulted in the rise of free-flow speed, and that speed limit explained 37% of the variability of the dependent variable on Class I highways and 27% on Class II highways. The impact of speed limit on free-flow speed can be the result of legal penalties prescribed for exceeding the speed limit. In other words, speeding fines have an impact on driver behaviour in the free flow even in numerous situations when road geometric features or dynamic characteristics of vehicles enable driving at much faster speeds than the posted speed limits allow on certain sections. This corresponds to the findings of other studies [36].

In addition to the impact of speed limit, it was determined that geometric characteristics of the road were associated with free-flow speed. Along with speed limit, minimal horizontal curve radius represents the most influential variable among the tested variables for Class I and II two-lane highways. Horizontal curve radius explains 8% of the variability of the dependent variable on Class I highways, while it explains 27% on Class II highways. The greater impact of horizontal curve radius on Class II highways can be explained by the fact that this class involves sections of two-lane highways passing through rugged terrain. Therefore, the tested section sample included more sections with critical horizontal curve radii which belonged to this highway class than to Class I. This road feature was determined to have a positive impact, i.e. the increase in the minimal value of horizontal curve radius led to the increase in free-flow speed. The conclusion regarding the significance of the impact of horizontal curves on flow speed is in accordance with the results obtained in the majority of studies, e.g. [9, 11, 29] etc. It can be explained by the acting of centripetal force on the vehicle and by poorer sight distance, which makes drivers slow down at low radius values. Free-flow speed on Class I two-lane highways is also affected by shoulder width, which corresponds to the studies by Medina and Tarko [11]. The positive impact of shoulder width was also noticed on Class II two-lane highways, so it can be concluded that the same variables have an impact on both classes of rural two-lane highways.

6. CONCLUSION

The paper presents the models for determining free-flow speed on rural two-lane highways as a function of speed limit and geometric characteristics of the road section. In contrast to some models which do not consider speed limit to be an influential factor [27], the results of this paper confirm the significance of using speed limit for determining free-flow speed. A special contribution of this paper is an individual analysis per rural two-lane highway class – I and II classes according to HCM [4], which underlined the necessity for individual models for free-flow speed prediction. Nevertheless, in order to develop suitable models, it was first necessary to determine accurate threshold values of free flow for both highway class. Free-flow conditions envisage lack of mutual interaction between vehicles. Therefore, the paper defined the free flow threshold on the basis of the weak correlation between vehicles *n* and *n*-1 and time headway. To this end, the parameter of time headway was selected. The obtained results showed that there were differences between the threshold values of free-flow time headway of different rural two-lane highway classes. These findings correspond to the results of previous research – 6.3 s for Class I highways and 8.4 s for Class II highways. The obtained difference in the threshold values of free-flow time headway can be explained by the different conditions in the traffic flow due to different functions of roads in the network. The defined threshold values were then used for determining free-flow speeds on the analysed sections of the observed two-lane highway classes. Linear regression and the stepwise method were used to develop the appropriate models of the dependence of free-flow speed on speed limit and geometric characteristics of the road. In order to compare results of different approaches the boxplots and One-Sample T Test were conducted. It can be seen that the values obtained using the proposed models fit better to the values obtained from ATCs compared to the most commonly used HCM [4] analytical model, for both rural two-lane highway classes. The obtained results showed that, in addition to the already mentioned speed limit, horizontal curve radius and shoulder width also affected the free-flow speed on Class I and II highways. The obtained models quantify the different impact of the posted speed limit in accordance with the road's function in the network. In this manner, rough addition of the unique speed value to the posted speed limit value recommended by HCM was avoided [4].

On the basis of all the above mentioned, several main contributions of this paper can be highlighted:

- definition of the separate time headway threshold values of the free flow for both two-lane rural highways classes – 6.3 s for Class I highways and 8.4 s for Class II highways,
- development of the free-flow speed prediction model for both classes of two-lane rural highways as a function of speed limit, horizontal curve radius and shoulder width,
- boxplots and One-Sample T Test showed that the values obtained using the developed models fit better to the values obtained by field measurements compared to the HCM analytical model, for both road classes of rural two-lane highways,
- possibility of applying the mentioned methodologies in different countries/areas, bearing in mind the possibility of determining the functional classification of two-lane roads in accordance with the classification in HCM [4].

One of the recommendations regarding future research refers to the necessity of conducting separate analysis of Class III two-lane highways due to specific characteristics of the roads belonging to this class. Namely, the abrupt change of rural into urban road environment and mixing of long-distance and local traffic requires a more thorough division of time headway groups for the free-flow time headway threshold value analysis. Also, having in mind the specific characteristics of Class III two-lane highways, it would be significant for future studies for adequate free-flow speed models to include the impact of the road environment in addition to the analysed variables in this paper. The road environment includes examining the impact of pedestrians, cyclists, attractive facilities in the vicinity of the road, degree of development (urbanisation) of settlements, and all the characteristics having a significant impact on the travelling of vehicles in urban areas.

Furthermore, future studies should examine the impact of additional road geometric and operational features of all classes of rural two-lane highways on free-flow speed, such as pavement condition, sight distance, percentage of no-passing zones, degree of horizontal curvature etc.

One of the most significant recommendations for future research is related to a more detailed examination of the speed limit impact on base free-flow speed [4]. Having in mind that this paper confirmed that there was a different impact of speed limit on free-flow speed on different classes of rural two-lane highways, it is requisite to research the possibility of a thorough analysis of base free-flow speed and its more accurate definition per road class. This would enable a more precise quantification of free-flow speed in the situation when analytical methods must be applied. It would result in numerous positive effects in the field of civil and transportation engineering, such as improving the accuracy of level of service calculation, road design process, preparation of feasibility studies and traffic planning.

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Nemanja Stepanović, Vladan Tubić, Stefan Zdravković

Utvrđivanje slobodne brzine na vangradskim dvotračnim putevima različitih klasa

Abstrakt

Postojeći modeli za proračun slobodne brzine jedinstveno tretiraju sve vangradske dvotračne puteve bez obzira na njihovu različitu funkcionalnu klasifikaciju u mreži. Glavni cilj ovog rada ogleda se u razvoju modela predikcije slobodne brzine u funkciji ograničenja brzine i geometrijskih karakteristika puta za različite klase vangradskih dvotračnih puteva. Istraživanje je sprovedeno na 50 reprezentativnih deonica prve i druge klase dvotračnih puteva opremljenih automatskim brojačima saobraćaja u Srbiji. Kako bi se razvili odgovarajući modeli, bilo je neophodno utvrditi granične vrednosti intervala sleđenja vozila u slobodnom toku za obe klase vangradskih dvotračnih puteva, na osnovu uzorka od 191720 vozila. Dobijeni rezultati pokazuju da postoje razlike u graničnoj vrednosti intervala sleđenja slobodnog toka na putevima različitih klasa. Naime, utvrđeno je da vrednosti intervala sleđenja slobodnog toka za puteve I klase iznose 6,3 s, a za puteve II klase 8,4 s. Razvijeni modeli predikcije slobodne brzine za dvotračne puteve različitih klasa pokazali su da ograničenje brzine ima najjači uticaj kod vangradskih dvotračnih puteva obe klase, zatim radijus horizontalne krivine i širina bankine.

Ključne riječi

slobodna brzina; vangradski dvotračni putevi; interval sleđenja; ograničenje brzine.