IVAN LOVRIĆ, Ph.D.
E-mail: ilovric@sve-mo.ba
Faculty of Civil Engineering, University of Mostar
Matice hrvatske bb, 88000 Mostar,
Bosnia and Herzegovina
DRAŽEN CVITANIĆ, Ph.D.
E-mail: drazen.cvitanic@gradst.hr
DEANA BREŠKI, Ph.D.
E-mail: deana.breski@gradst.hr
Faculty of Civil Engineering, Architecture and Geodesy,
University of Split
Ulica Matice hrvatske 15, 21000 Split, Croatia

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MODELLING FREE FLOW SPEED ON TWO-LANE RURAL HIGHWAYS IN BOSNIA AND HERZEGOVINA

ABSTRACT

Free flow speed is used as a parameter in transportation planning and capacity analysis models, as well as speed-flow diagrams. Many of these models suggest estimating free flow speed according to measurements from similar highways, which is not a practical method for use in B&H. This paper first discusses problems with using these methodologies in conditions prevailing in B&H and then presents a free flow speed evaluation model developed from a comprehensive field survey conducted on nine homogeneous sections of state and regional roads.

KEY WORDS

free flow speed; rural roads; curvature characteristics; space mean speed; gradient

1. INTRODUCTION

Analysis of continuous traffic flow is based on the basic relation of traffic flow that involves three basic parameters: flow = speed * density. Considering the difficulties in measuring flow density in the field, flow rate and speed are the most influential variables both in transportation planning methods (when allocating traffic to a network) and methods of capacity analysis on roads with continuous flow.

Proper evaluation of the average travel speed in prevailing road and traffic conditions requires an accurately estimated free flow speed. However, free flow speed estimates based on present methodologies of transportation planning and capacity analysis are not sufficiently accurate or clear. Incorrect estimations of free flow speed may eventually result in inadequate planning and design of road networks.

For example, the key step in assessing the level of service (LOS) of a two-lane highway in traffic capacity models is to determine free flow speed (FFS). FFS is the measured mean speed of traffic in low traffic flow conditions.

According to Highway Capacity Manual (HCM) [1], we can use two general methods to determine FFS for a two-lane highway: field measurements and estimates.

Since field measurements are often not feasible, HCM gives the following procedure for estimating free flow speed: *Estimation of free flow speed on two-lane highways is a great challenge because the FFS of a two-lane highway can range from 70 to 110 km/h. To estimate FFS the analyst must determine the operating conditions of the facility in terms of a base free flow speed (BFFS) that reflects the character of traffic and the alignment of the facility. Because of the broad range of speed conditions on two-lane highways and the importance of local and regional factors that influence the driver-desired speeds, no guidance on estimating the BFFS is provided. Estimates of BFFS can be developed based on speed data and local knowledge of operating conditions on similar facilities. Once BFFS is estimated, adjustments can be made for the influence of lane width, shoulder width, and access-point density. The FFS is estimated using the equation:*

$$FFS = BFFS - fLS - fA$$

where

FFS = *estimated FFS (km/h),*

BFFS = *base FFS (km/h),*

fLS = *adjustment for lane width and shoulder width, and*

fA = *adjustment for access points.*

Hence, the estimation of free flow speed (FFS) requires an estimated value of base free flow speed (BFFS), which makes the HCM method difficult for use, especially in Bosnia and Herzegovina.

A particular problem in practical application of the capacity analysis using the HCM method in B&H is the maximum allowable speed of 80 km/h on two-lane roads. This practically means that, if this methodology is to be applied (which is mandatory according to B&H road design guidelines), it is necessary to classify all two-lane roads as Class II according to HCM and determine the level of service using PTSF (Percent Time Spent Following) only, without considering the average travel speed.

As for the German method HBS 2001 [2], one of the problems with using it is the missing effect of traffic lane width on the travel speed. Namely, the actual widths of traffic lanes of state and regional roads in B&H range from 2.5 m to 3.5 m although the required minimum lane width on public roads is 2.75 m.

The aim of this paper is to define a model of free flow speed on sections of two-lane rural roads in B&H and determine the variables that influence the speed by using field measurements and data collection results.

As stated earlier in this paper, there is virtually no reliable way of determining free flow speed on two-lane sections except measurements. In practice, this almost always poses a problem in financial and organizational terms, especially when dealing with multiple sections of inhomogeneous roads affected by the mountainous and hilly terrain across B&H.

Difficulties in describing the existing road network by using a mathematical model of transportation planning (for example the most commonly used link cost function, the Bureau of Public Roads BPR function [3]) and difficulties in conducting capacity analysis of two-lane rural roads in B&H by using HCM or HBS methodology necessitate further research aimed at establishing principles that would realistically describe dependency of traffic flow on geometric characteristics of two-lane rural road sections in conditions prevailing in B&H. Two-lane roads constitute over 80% of total rural road networks both worldwide and in B&H, which further justifies the need for research. The necessary comprehensive studies and analyses should provide grounds for proper decision-making in planning and managing road transportation systems.

It should be noted here that many researchers have investigated speeds on rural roads in the last few decades, but most of them investigated the 85th percentile operating speeds on individual alignment elements (curves, tangents) for the purpose of evaluating alignment consistency. The most recent review of the operating free flow speed models in various parts of the world is given in *Modeling Operating Speed* [4]. The operating speed represents 85th percentile speed of all drivers and is used for evaluation of highway alignment consistency.

Researchers find many factors affecting the operating free flow speed of vehicles, among which the most investigated are: physical characteristics of the road, weather conditions and speed limit. It is found that the radii of the horizontal curves have the greatest impact on the passenger car free flow speed. Vertical alignment and the cross slope have a much smaller influence.

Models developed in North America (Lamm & Choueiri [5], Moral & Tallarico [6], Gibreel et al. [7], Krammes [8], Fitzpatrick et al. [9], Figueroa, Medina, and Tarko [10] Misachi & Hassan [11]) deal with operating speeds on individual elements.

In Europe, some countries (Germany, Greece, France) officially use operating speed models in their guidelines. Some of them use models to estimate operating speed on individual alignment elements, while others use models to estimate the operating speed on homogeneous road sections. In Italy, many researchers (e.g. Cafiso et al. [12], Marchionna and Perco [13], Esposito and Mauro [14], De Luca and Dell'Acqua [15]) treated this problem, but official guidelines have not been changed in accordance with the findings of these investigations. In the neighbouring Republic of Croatia only a few authors have treated this problem [16], but the difference between the operating speed and the project speed is not taken into account in official practice.

The developed operating speed models deal with 85th percentile vehicle speed and they are used to draw speed profiles and evaluate alignment consistency.

Consequently, there are many operating speed models intended for use in road alignment design. There are also many speed-flow models designed for use in capacity analysis and transportation planning problems. The latter use free flow speed as the input parameter, but there are no road section free flow speed models developed for use in capacity analysis and transportation planning models.

In this paper, an empirical model for determining the mean free flow speed on rural roads in B&H is derived on the basis of geometric characteristics of homogeneous sections. The model of free flow speed is based on measurements of travel time in a sample of homogeneous sections that contains all extreme values of defined elements of horizontal and vertical road alignment and cross section. It is intended to be used as the input parameter in capacity analysis (HCM, HBS) and transportation planning methods (BPR or other link cost functions).

2. METHODOLOGY

2.1 Free flow speed

Theoretically, free flow speed represents the speed at traffic flow density close to zero or the speed of the first coming passenger car. Practically, free flow speed is determined as the average speed of passenger cars in conditions of low traffic flow rates (<200 pc/h in both directions). From the driver's point of view, that would mean driving at a desired speed that is not limited by the presence of other vehicles, but limited by physical conditions of the road and environment.

To use the analytical speed-flow models, it is necessary to know the free flow speed as the input parameter. From the definition of free flow speed, it can be concluded that it depends mostly on the variables related to road geometry.

Therefore, the aim of the methodology applied in this study is to clearly define the free flow speed as function of road geometry characteristics. The existing methodologies require the input values of free flow speed, without offering sufficiently clear methods to determine them, except the measurements in the field. In everyday engineering practice, this most often proves to be unfeasible.

The idea presented in this paper is as follows:

- First, selecting homogenous road sections that considerably differ in geometric characteristics, covering the entire range from the best to the worst in order to clearly define their influence on FFS.
- Then measuring the travel times in the sections and inquiring the same drivers outside of the sections in order to obtain data on driver and vehicle characteristics.
- In this way we can obtain the dependence between space mean free flow speed of passenger cars and variables associated with road geometry and driver and vehicle characteristics in homogenous sections of two-lane rural roads.

2.2 Methodological approach

Almost all the mathematical speed-flow models are in the form $v = f(v_0)$, hence they assume free flow speed as the initial parameter. The methodology applied here for estimating the free flow speed on state and regional roads is based on the following:

- The definition of free flow speed indicates its functional dependence on the prevailing road conditions. The idea implemented in this paper is to use the multiple linear regression for estimating the free flow speed in homogenous sections of two-lane rural roads.
- When preparing a sample in multiple regressions, one of the key requirements apart from the sample size is to make sure that all the limit values (minimum and maximum) of individual variables are included in the sample. Based on that, we selected nine sections that were homogeneous in terms of geometry characteristics. The selected sections have distinctly different geometric characteristics, covering the range of prevailing geometric elements on the state and regional roads in B&H. This allows us to evaluate the dependence of free flow speed on values varying throughout the range of applicable road elements.
- For each section, field measurements of speed (space mean speed) of individual vehicles were carried out in both directions in conditions of low flow rate. Practically, we measured the travel times of individual vehicles in segments of defined lengths. The measurements were carried out using video camera recordings of section endpoints and establishing times of vehicles passing the determined cross sections at entry and exit points of segments using simple computer software.
- Drivers were interviewed outside of the sections in order to examine the potential influence of variables such as vehicle age and driver experience. Based on conducted investigations, data matrix with values of speed as dependent variables and a range of values of independent variables was created. Using multiple regressions, an empirical model was obtained for free flow speed as a function of variables that demonstrated significant influence.

2.3 Influence of independent variables

For this research, two-lane rural road sections that constitute homogeneous entities in terms of horizontal and vertical alignment and cross section elements were selected. In the following, only the variables that demonstrated significant influence on the speed are presented. They are defined as follows:

(i) The curvature characteristic CC of a section calculated as

$$CC = \frac{\sum_i \alpha_i}{L} (^\circ/km) \tag{1}$$

where:

α_i (°) – *deflection angles of curves, and*

L (km) – section length.

(ii) Average longitudinal gradient LG of a section is calculated as

$$LG = \frac{\sum_i \left| LG_i \right| * L_i}{L} (\%) \tag{2}$$

where:

$\left| LG_i \right|$ – absolute values of individual longitudinal gradients within the observed section,

L_i (m) – lengths over which individual longitudinal gradients extend, and

L (m) – total length of the section.

(iii) Traffic lane width LW. As already stated, these are homogeneous sections of constant widths. In the sample, they range from 2.5 to 3.5 m. Although the B&H rules define the minimum width of traffic lanes as 2.75 m for public roads, there is a significant number of regional roads with lane widths of 2.5 m.

In the first step of the regression model, also some other influence factors related to road elements were examined.

These are the average number of curves per kilometre, the average value of radii of curves in a section, shoulder width and condition of road surface (expressed in International Roughness Index IRI which was measured and defined using the Highway Development and Management System HDM 4 methodology). From the interviewed drivers, the data on vehicle type, vehicle age, driver's age and driver's experience were collected. For all these variables, the results did not show any significant effect on free flow speed, so they are not described in detail here.

3. FIELD INVESTIGATIONS AND OBTAINED DATA

When applying the multiple regression, one of the recommendations is to collect extreme values of independent variables. The sections with different geometric characteristics presented in *Table 1* were accordingly selected for measurements of travel time or free flow speed.

The measurements were performed using two video cameras placed at the start and the end point of each section. Several recordings were conducted in one-hour intervals and at the same time drivers were interviewed outside the sections. The recording interval was one hour in order to verify that the traffic volume was low. Essentially, we took into consideration only the individual speeds of passenger cars unobstructed by heavy vehicles. The weather conditions were good, without rainfall. The main purpose of interviews was to obtain data on vehicle type and age, and driver age and experience. The data were acquired during low traffic volumes (less than 200 veh/h in both directions) and for passenger cars only. Times of vehicles passing start and end points of sections were subsequently determined by analyzing the video recordings. Individual vehicles were identified by travel direction, vehicle type and last three digits of the registration plates, which were simultaneously spoken to camera microphone each time a vehicle passed a recorded endpoint. In this way, it was possible to assign vehicles their respective passing times at both endpoints. The result of the field survey is travel time, which, when divided by section length, represents the average travel speed or space mean speed.

Figure 1 shows the data on measured speeds S from the sample (N = 578) for nine sections in both directions in the same order and with the same marks as the sections were listed in *Table 1*. *Table 2* presents

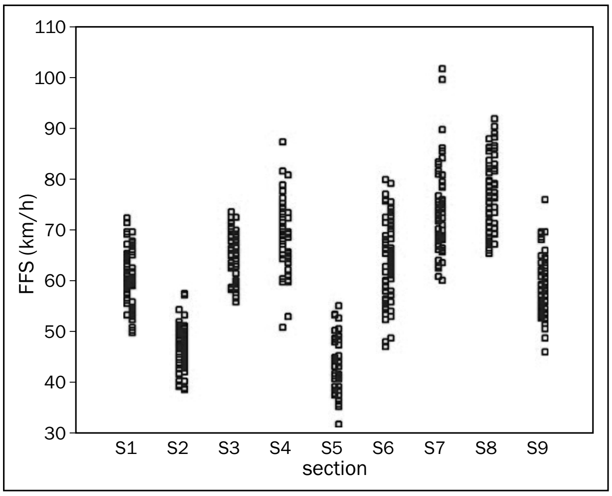

Figure 1 - Sample data graph of free flow speeds by sections

Table 1 - Geometric characteristics of FFS measurement sections

Section Mark	Road No.	Section name	L [m]	CC [°/km]	LG [%]	nR/km	LW [m]
S1	R424	Varda – Kruševo	3,100	183.87	1.50	6.13	2.50
S2	R424	Mostar – Miljkovići	4,675	506.524	4.86	11.34	2.50
S3	M6	Tasovčići – Domanovići	3,900	171.03	1.32	4.87	3.00
S4	M6	Domanovići – Masline	3,400	99.706	2.45	4.12	3.00
S5	R425	Žitomislići – Čitluk	3,450	566.38	5.28	12.17	2.50
S6	M17.3	Buna – Hodbina	4,100	248.05	5.10	13.66	3.50
S7	M17.3	Hodbina – Hodovo	4,700	192.13	2.98	13.83	3.50
S8	M17	Buna – Žitomislići	5,100	61.386	0.55	1.37	3.50
S9	M6.1	Medjine – Zovnica	3,800	194.47	4.22	8.42	2.85

CC – curvature characteristic, LG – average longitudinal grade, nR/km – number of curves per kilometer, LW – lane width, L – length the basic statistical data on the sample of free flow speeds. Resulting deviations are large due to extreme values of road elements in selected sections. As stated earlier, when preparing a sample in multiple regression, one of the key requirements is to make sure that all the limit values (minimum and maximum) of individual variables are included in the sample. However, for $\sigma = 11.7528$, $z = 1.96$ (95%) and $d = 1$ km/h the sample size is $530.63 < 578$.

Table 2 - Basic statistical data of the sample of free flow speeds

	N	Min.	Max.	Mean	Std. Dev.
S (km/h)	578	35.18	101.83	61.9193	11.7528

4. ANALYSIS OF INFLUENCES

The dependence of free flow speed on road and vehicle characteristics was estimated using multiple linear regression. The speed obtained from section travel time measurements is the space mean speed and it is a dependent variable. Curvature characteristic (CC), average longitudinal gradient (LG) and section lane width (LW) are independent variables. *Table 3* presents the results of multidimensional regression analysis.

The results presented in *Table 3* yield the following equation for estimating free flow speed - FFS.

$$FFS = 38.182 - 0.034CC - 1.64LG + 12.21LW \quad (3)$$

Analyzing the above results obtained by multiple regression, the following can be concluded:

- Signs associated with coefficients of independent variables are as expected. Thus, higher values of curvature characteristics CC and average longitudinal gradients LG decrease the free flow speeds, while wider lane LW allows higher free flow speeds.
- Results of F and t tests indicate that the model and the previously described independent variables (influence parameters) have significant effects on free flow speed. Their individual influences are shown in *Figure 2*.
- The values of the coefficient of determination and the corrected coefficient of determination are close to each other and demonstrate a high percentage of mathematical description of free flow speed with the used independent variables.
- From the standardized coefficient, it is evident that CC and LW have the largest influence on FFS, while the influence of LG is somewhat lower but still significant.

Table 4 - Speed ranges for extreme values of influence parameters

	CC (°/km)	LG (%)	LW (m)	FFS (km/h)
Case 1	61.37	0.55	3.5	78.11
Case 2	566.38	5.28	2.5	42.27

Ranges of free flow speeds for extreme values of influence parameters from the sample are shown in *Table 4*. From the values of free flow speed obtained using Equation 3, it is evident that the free flow speed is 78.11 km/h for the best road conditions in the sample (Case 1). By the same analogy, the minimum value of FFS is 42.27 km/h for the worst road conditions in the sample (Case 2).

4.1 Individual influences

The following describes the individual influences by equations and graphs of all influence quantities used for determining the free flow speed (*Figure 2*). Individual influence equations are obtained by averaging other influence quantities obtained in the sample, multiplying them with their respective coefficients from Equation 3 and adding them to the free term.

*Figure 2*a shows the graph and equation of the influence of curvature characteristic CC on free flow speed. As expected, the influence is significant and its range between the best and the worst horizontal geometry is 20 km/h.

Table 3 - Results of the regression analysis

R	R^2	adj R^2	Std. Error of the Estimate	Sum of Squares	Df	Mean square	F	Sig.
0.836	0.700	0.698	6.458	REG 55,757.8 RES 23,942.2 TOT 79,700.0	3 574 577	18,585.94 41.71	445.59	0.000

Model	Unstandard coefficients		Standard coefficients	t	Sign.	95% confidence interval	
	B	Std. err.		T	Sign.	lower bound	upper bound
Const.	38.182	2.608		14.642	0.000	33.060	43.303
CC	-3.14 E-02	0.003	-0.418	-10.394	0.000	-0.037	-0.025
LG	-1.640	0.256	-0.324	-6.404	0.000	-2.143	-1.137
LW	12.210	0.811	0.410	15.064	0.000	10.618	13.803

Considering the influence of average longitudinal gradient LG, it is worth noting that section lengths in the sample range from 3,100 to 5,100 m, while average longitudinal gradients of sections range from 0.55% to 5.28%. For average values of other independent variables, the value of free flow speed varies from 66.64 km/h in level sections to 57.88 km/h in the section with the average longitudinal gradient of 6%. The resulting reduction in free flow speed is 8.76 km/h (*Figure 2*b). Comparison of these results with flow speed diagrams from HBS 2001, where the influence of longitudinal gradient on FFS was not taken into account, confirms the possible difficulties in applying the existing methodologies for analyses of speed, flow and capacity in B&H prevailing conditions.

The individual influence of lane width on free flow speed is shown in *Figure 2*c. The German methodology did not take into account the effect of lane width. The HBS 2001 methodology only applies to the domain of traffic lane widths between 3 and 3.5 m in the case of two-lane rural roads.

In HCM methodology, the maximum influence of lane and shoulder width is 10.3 km/h. Lane widths range from 2.7 to 3.6 m, and shoulder widths from less than 0.6 m up to 1.8 m. According to the research conducted here, the maximum influence of the lane width (ranging from 2.5 to 3.5 m) on free flow speed is 12.172 km/h.

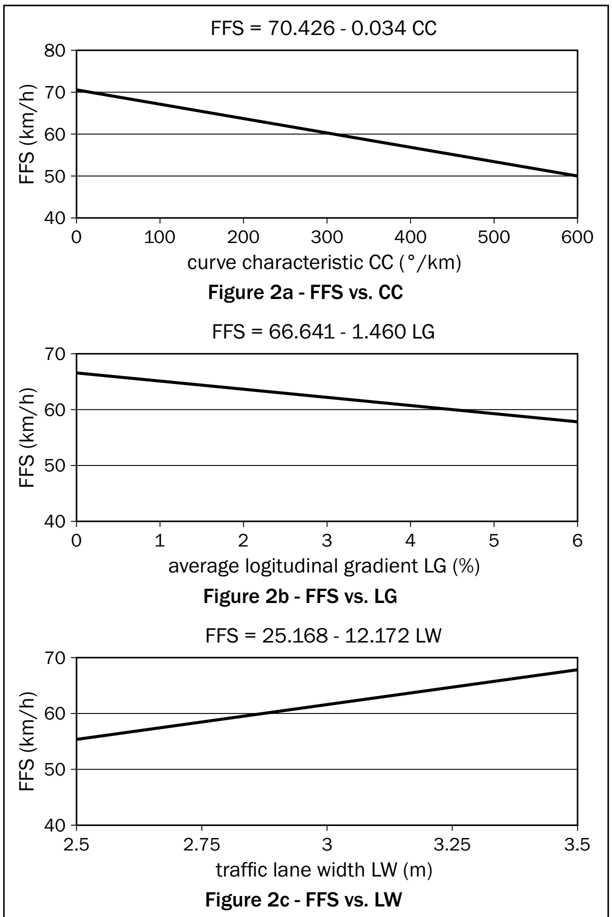

Figure 2 - Influence of individual parameters on free flow speed

5. CONCLUSION

The introduction describes the shortcomings and limitations in applying the existing methodologies for estimating FFS in road and traffic conditions prevailing in B&H. The equation of free flow speed was obtained on the basis of a representative sample in which speeds of passenger cars were measured in sections with geometry elements ranging from the worst to the best.

The results obtained by the regression equation, which describes the combined effects of these parameters and determines values of individual influences, confirm the hypothesis that practical application of the HCM and HBS methodologies is difficult in B&H prevailing conditions. Specifically, while free flow speeds range from 70 to 110 km/h in HCM and from 60(65) to 100 km/h in HBS, the results of these studies indicate the ranges from approximately 40 km/h for the worst to 80 km/h for the best prevailing road conditions. The maximum speed limit on roads in B&H is 80 km/h, which is consistent with these results.

Unlike in the HBS 2001 approach, the longitudinal gradient was found to have a significant effect on FFS. Combined with the problem of cross section widths, this indicates the need for comprehensive studies of local prevailing road and traffic conditions.

The entire research was conducted taking into account the applicability of results both in capacity analysis and transportation planning.

Dr. sc. **IVAN LOVRIĆ**
E-mail: ilovric@sve-mo.ba
Građevinski fakultet, Sveučilište u Mostaru
Matice hrvatske bb, 88000 Mostar, Bosna i Hercegovina
Dr. sc. **DRAŽEN CVITANIĆ**
E-mail: drazen.cvitanic@gradst.hr
Dr. sc. **DEANA BREŠKI**
E-mail: deana.breski@gradst.hr
Fakultet građevinarstva, arhitekture i geodezije,
Sveučilište u Splitu
Ulica Matice hrvatske 15, 21000 Split, Hrvatska

SAŽETAK

MODEL BRZINE SLOBODNOG TOKA NA DVOTRAČNIM CESTAMA U BiH

Brzina slobodnog toka koristi se kao parametar u modelima transportnog planiranja, modelima analize kapaciteta cestovnih prometnica kao i u izradi dijagrama brzina-tok. Značajan broj razvijenih modela ne koristi procedure za procjenu brzine slobodnog toka već predlaže da se brzina slobodnog toka procijeni usporedbom sa zabilježenim brzinama slobodnog toka na sličnim već izgrađenim promet-

nicama što predstavlja značajan problem, a naročito na području Bosne i Hercegovine. U ovom se radu u prvom dijelu analiziraju problemi upotrebe postojećih modela u uvjetima prometa i prometnica u BiH, a u drugom se prikazuje model za procjenu brzine slobodnog toka razvijen na temelju opsežnog terenskog istraživanja provedenog na devet homogenih dionica državnih i regionalnih cesta.

KLJUČNE RIJEČI

brzina slobodnog toka; vangradske ceste; krivinska karakteristika; prostorna brzina; nagib

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