submitted: 28.03.2024. *UDC : 625.732.4*
corrected: 25.04.2024. *Research scientific paper* *https://doi.org/10.62683/ZRGAF39.13-21*
accepted: 30.04.2024.

INFLUENCE OF VEHICLE SPEED IN FREE TRAFFIC FLOW ON DISTRIBUTION OF ROADWAY SUPERELEVATION

Dušan Cvetković[1]
Jelena Dimitrijević[2]
Nemanja Marinković[3]
Nikola Romić[4]

Abstract

In this paper, the theoretical concept of roadway superelevation based on speed in free traffic flow is derived. The influence of the radius of the horizontal curve on speed in free traffic flow as a basis of this analysis is taken from a more detailed experimental research for two-lane rural highways. This method is new and differs from others that use constant design speed value. However, this method gives similar results when compared to the empirical methods of computing roadway superelevation, where design speed is constant but it is assumed that when the curve radius is greater than the minimum, the driving speeds are greater than the design speed. Presented work defines and explains that assumption and takes it into account when computing roadway superelevation.

Key words: *Free Traffic Flow Speed, Roadway Superelevation, Roadway Cross Slope*

[1] Ph.D., Assistant, Faculty of Civil Engineering and Architecture, dusan.cvetkovic@gaf.ni.ac.rs
ORCID 0000-0001-7535-248X
[2] B.Sc., Assistant, Faculty of Civil Engineering and Architecture, jelena.dimitijevic@gaf.ni.ac.rs
ORCID 0009-0006-7158-0737
[3] M.Sc., Assistant, Faculty of Civil Engineering and Architecture, nemanja.marinkovic@gaf.ni.ac.rs
ORCID 0000-0001-5834-7910
[4] B.Sc., Assistant, Faculty of Civil Engineering and Architecture, nikola.romic@gaf.ni.ac.rs
ORCID 0000-0002-1075-2738

1. INTRODUCTION

In the road designing process, beside technical requirements dealing with the constructive problems, there is a need for further improvement of traffic safety, which can be achieved only if real circumstances that occur on the road are accounted in the process of road design. In many countries, the engineering praxis deals with a term called design speed (V_d), and all constructive elements of the road are dimensioned based on that speed. Design speed is a value that tends to be valid for the whole road or at least, for a large sections of it.

However, driving experience suggests that speed is a changeable value that depends on the changeable elements of the road, such as: radius of horizontal curve, sight distance, etc. Having this fact in mind and the requirements about traffic safety, a logical conclusion is that all constructive elements that depend on the speed of the vehicle must be adjusted to account a changeable velocity of the vehicle. That velocity is called the speed in free traffic flow (V_F) and $V_d<V_F<V_{max}$, where V_{max} represents the maximum speed that can be achieved. Among constructive elements of the road that depend on the vehicle's speed is most certainly the roadway superelevation rate (e) of the horizontal curve when $R>R_{min}$. (R) is the radius of the horizontal curve and R_{min} is the minimal value for the radius adopted based on V_d.

In this paper a new method for the derivation of the needed e is proposed. The derivation is based on the experimental data that has been collected on the Department of Road Construction at the Faculty of Civil Engineering and Architecture in Nis, Serbia, and deals with the influences of the road geometry on V_F [1]. Method gives one clear advantage in comparison with the other more complex methods [2,3,4,5,6,10,11] since the idea is to isolate a single construction element, such as the radius of the horizontal curve, and then observe how that isolated element affects V_F. The obtained expression for the required e is very simple, it can easily be programmed and yet the results are very close to the one obtained by methods given in [6].

2. EXPERIMENTAL RESEACH RESULTS

The influence of the radius of horizontal curve, on the speed in free traffic flow V_F is a part of a complex research that deals with influences of all road–geometric elements on V_F [1]. In this research, there were five experienced amateur drivers to whom instructions were given to drive the same way they usually drive, but with maximum safe speed that road elements allow. The experimental drives were done during the day on two-lane rural highways, where asphalt pavement had very good characteristics and when it was dry. The experimental vehicle had the following characteristics:

- Engine power, N=50 kW,
- Weight of the vehicle, G=12 kN,
- Maximum speed, V_{max} =150 km/h.

During the experimental drive, specially constructed device was recording the following:

- Position on horizontal alignment,
- Speed of the vehicle,

- Bending of the trajectory,
- Heart rate of the driver.

It has been concluded in [1] that all drivers were driving with the changeable speed that depended on curve radius R. When they accelerated, the maximum capability of the vehicle was not used; when they wanted to slow down, most of the time they were easing the gas pedal, and only occasionally pressing the brakes pedal. Interesting is the reaction of all drivers when approaching the critical point as a reason for slowing down; they did not want to take any measures until seven seconds of driving distance before that point. If in that time frame they could not reduce the speed to the maximum safe speed by easing off on the gas pedal, they used the brake pedal. However, in both cases the drivers did not react until seven seconds of driving distance before that critical point. It has also been observed that the radius of the current horizontal curve does not exclusively impact V_F. The size of the radius of previous and next horizontal curves has impact on V_F as well. This is a limiting factor for achieving the expected speed in a specific horizontal curve and it is due to the limited vehicle acceleration capability and the usual driver's behavior. The impact of this phenomenon can be quantified through the use of bendiness of the road (B), which represents a sum of the deviation angles of all horizontal curves on the observed kilometer, and it is expressed in [°/km]. The results of speed in free traffic flow measurement on 5 road sections are shown in Fig.1.

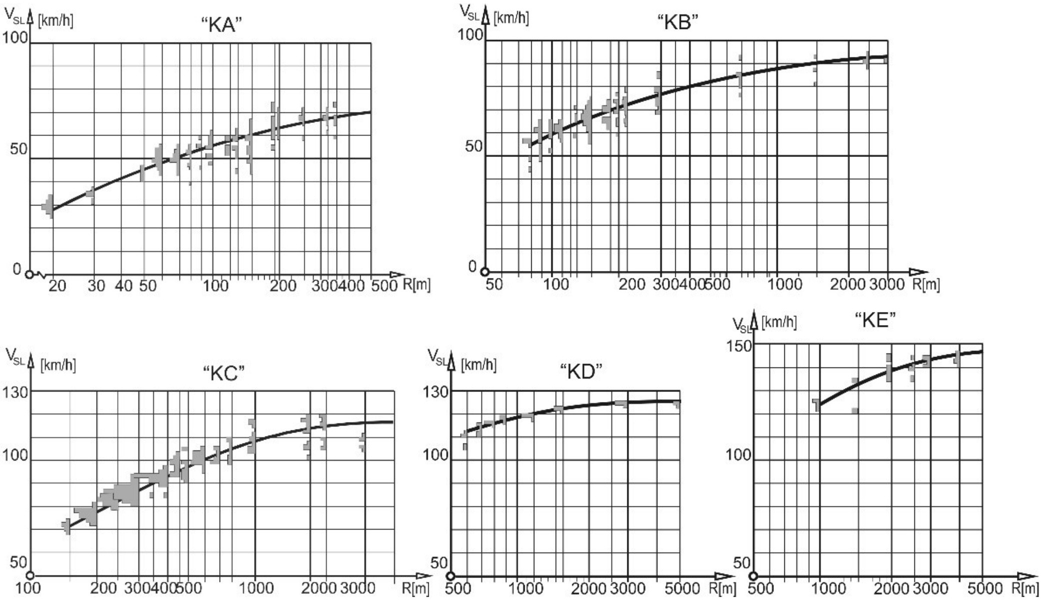

Figure 1: The measuring values of the radius of horizontal curve influence on speed in free traffic flow: road sections "KA", L=13.4 km and bendiness of the road B=457°/km, "KB", L=6.9 km and bendiness of the road B=178°/km,"KC", L=32.7 km and bendiness of the road B=86°/km, "KD", L=10.0 km and bendiness of the road B=37°/km,"KE", L=16.0 km and bendiness of the road B=18°/km,

After processing of the measured values, the diagram shown in Fig. 2 has been constructed [1].

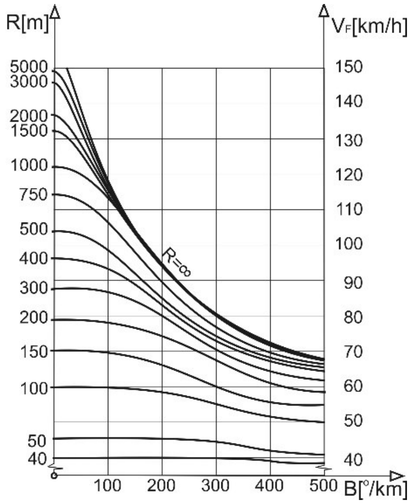

Figure 2: Speed in free traffic flow (V_F) *as a function of the bendiness of the road* (B) *with the radius of horizontal curve* (R) *as a parameter.*

The figure shows the average V_F as a function of B, where the radius of the current horizontal curve, R, is taken as a parameter. Since B depends on the number of applied horizontal curves, their radii and turning angles, it can be different for the same value of V_d. For a specific V_d, the average values for B are computed and used to transform the diagram presented in Fig.2, into the diagram presented in Fig. 3, which shows the influence of R on V_F for the specific V_d with average B [1]. The statistical indicators for Figure 3. show that the statistical error of regression is larger for $R>R_{min}$ than for $R=R_{min}$. This suggests that V_F has a smaller variance in the critical than in the non-critical curves.

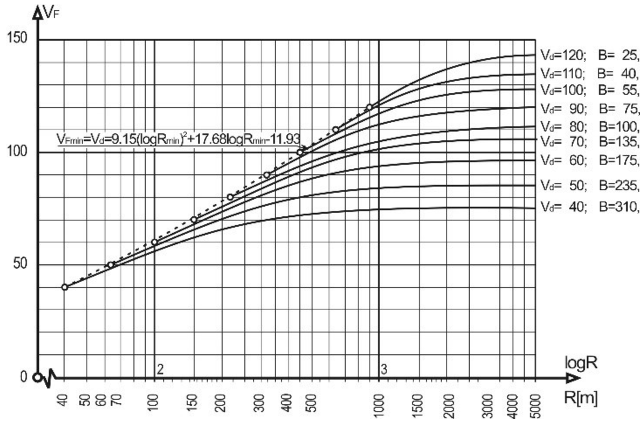

Figure 3: Speed in free traffic flow (V_F) *as a function of the radius of horizontal curve* (R) *with designed speed* (V_d) *and the average bendiness* (B) *of the road as a parameter*

Table 1. Statistical indicators for Fig. 3.

Statistical indicators	Label	$R=R_{min}$	$R>R_{min}$
Number of measurements	N	320	479
Coefficient of correlation	R	0.9953	0.9188
Standard error of regression	S	2.02 km/h	3.53 km/h
Percentage of mean value variation	P	2.87 %	4.17 %

3. REQUIRED RATE OF ROADWAY SUPERELEVATION IN HOROZONTAL CURVE

The roadway superelevation in the horizontal curve compensates a part of the centrifugal force. Before entering the curve, the driver can successfully predict only the curvature of the road, and based on that observation the he adjusts the speed. The driver cannot predict the rate of the roadway superelevation, but it is possible to feel effect of superelevation when driving through the curve.

Most of the engineers calculate the rate of the roadway superelevation, as proportional to the value of centrifugal force for the whole design section of the road, by using the following equation [1]:

$$\frac{e}{100} = k \cdot c \,, \tag{1}$$

where (k) is a reduction constant, and (c) is the coefficient value of the centrifugal force in the road curve. Roadway superelevation should give positive psychological effect on drivers [7,8,9], but because of the mistake in assumption that the drivers use V_d for the whole section of the road, this positive effect is missing. It is very obvious that neither are the drivers familiar with a term called design speed, nor they are driving with that speed. It has been determined experimentally in [1] that the drivers adjust the speed based on the radius of the horizontal curve and the capability of the vehicle. Having this fact in mind, in designing the rate of the roadway superelevation, real changeable speed should be used, instead of design speed. By doing this, the desired psychological effect for the driver's safety in any specific horizontal curve with arbitrary radius size is modeled.

Since c_{max} is determined by V_d and R_{min} and V_F=V_d at R_{min}, it should to be computed k first as:

$$k = \frac{\frac{e_{\max}}{100}}{c_{\max}} = \frac{\frac{e_{\max}}{100}}{\frac{V_d^2}{127 \cdot R_{\min}}} = \frac{127 \cdot e_{\max} \cdot R_{\min}}{100 \cdot V_d^2} \,, \tag{2}$$

where e_{max} is determined based on the climate conditions (in Serbia regulations e_{max}=7%). Since it follows from (1) and (2) that:

$$\frac{e}{100} = k \cdot c_F = \frac{127 \cdot e_{\max} \cdot R_{\min}}{100 \cdot V_d^{\,2}} \cdot \frac{V_F^{\,2}}{127 \cdot R} \,, \tag{3}$$

finally e can be expressed as:

$$e = e_{\max} \cdot \frac{R_{\min}}{R} \cdot \left(\frac{V_F}{V_d} \right)^2 \,, \tag{4}$$

which gives the general formula. Fig. 4. shows superelevation rate as given by equation (1) by using the values of the design speed, V_d, and the values of the speed in free traffic flow, V_F, where c_d and c_F are the corresponding coefficients of centrifugal force. R_n is a radius where e reaches its minimum value (in Serbian regulations e_{min}=2.5 %), which is determined by the efficient side pavement drainage, and f_{max} is the maximum side friction factor. The figure illustrates different values for R_n when V_F is considered instead of V_d.

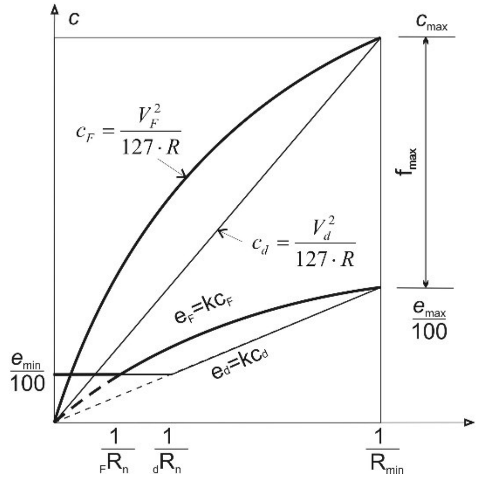

Figure 4: Distribution of the centrifugal coefficient on superelevation and side friction factor.

For the adopted maximum and minimum values of e, e_{max}=7% and e_{min}=2.5%, it can be constructed a curve, e=F(R), where the design speed is taken as a parameter, as shown in Fig. 4.

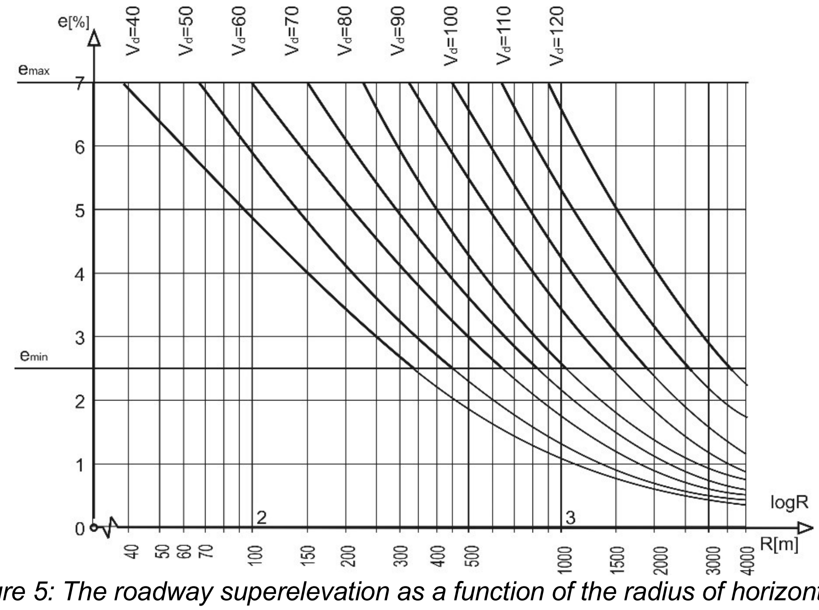

Figure 5: The roadway superelevation as a function of the radius of horizontal curve with design speed as a parameter.

It can be seen from the Fig.5. that coefficient η is the ratio of R_n determined by e_{min}, and R_{min} determined by e_{max}. Ratio $\eta=R_n/R_{min}$ is decreasing as V_d is increasing. Using parabolic regression η is expressed as a function of V_d as it is shown in Fig. 6. The figure emphasizes the importance of the considering V_F instead of V_d, especially for small values of V_d. Moreover, in the same figure this new method with much more complex procedure from [6] is compared. Method 5 [6] is chosen because it represents a superelevation and side friction distribution reasonably retaining the advantages of both methods 1 and 4, and represents a practical distribution for superelevation over the range of curvature.

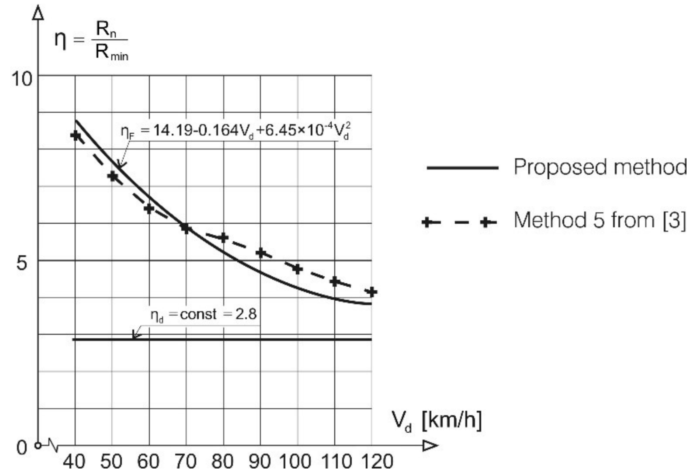

Figure 6: Ratio η as a function of design speed.

The results obtained using when e_{max}=7% and e_{min}=2.5% are shown and close agreement between two methods is obvious.

If a general formula given by equation (4) is used in the variation range of the mean speed value in the free traffic flow when R>R_{min} for the amount of P=4.17 %, we come up with the wide range for the roadway superelevation ${}_{15\%}e$ - ${}_{85\%}e$, where:

$$ {}_{15\%}e = \left(1 - \frac{P}{100}\right)^2 = (1.0417)^2 e = 1.085e \,, \tag{5} $$

and

$$ {}_{85\%}e = \left(1 - \frac{P}{100}\right)^2 = (0.9583)^2 e = 0.918e \,, \tag{6} $$

Equations (5) and (6) represent the range of e variation, when considering variation of V_F for the amount of mean value variation P=4.17 %, taken from the statistical indicators for Fig. 3. The values of speed variation, 1.0417 and 0.9583 are squared since V_F effects c_F as square and that finally effects e as square.

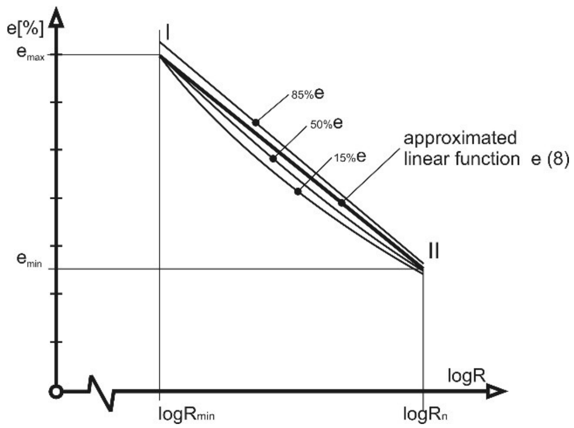

Figure 7: Logarithmic form of the roadway superelevation (e) for R>Rmin.

Comparison between ${}_{15\%}e$, ${}_{50\%}e$ and ${}_{85\%}e$ is given in Fig. 7. It is obvious that there is a little difference among them and that there is approximately linear relationship between e and logR. Therefore, in order to simplify the calculation, the linear function e=F(logR) is constructed. In that aim, two known points, point I ($\log R_{min}$, e_{max}), and point II ($\log R_n$, e_{min}) have been taken, and the following linear relation between e and logR is obtained:

$$e = e_{\max} - (\log R - \log R_{\min}) \frac{e_{\max} - e_{\min}}{\log R_n - \log R_{\min}}, \tag{7}$$

which can be reduced to:

$$e = e_{\max} - (e_{\max} - e_{\min}) \frac{\log\left(\dfrac{R}{R_{\min}}\right)}{\log\left(\dfrac{R_n}{R_{\min}}\right)}, \tag{8}$$

Finally, when $\eta = R_n/R_{min}$ which was obtained earlier is included in the equation (8), it is obtained:

$$e = e_{\max} - (e_{\max} - e_{\min}) \frac{\log\left(\dfrac{R}{R_{\min}}\right)}{\log(14.19 - 0.164 \cdot V_d + 6.45 \cdot 10^{-4} V_d)}, \tag{9}$$

which represents the final equation for roadway superelevation.

4. CONCLUSION

In this paper it is proposed a method that determinates the required rate of the roadway superelevation in the horizontal curves. The method is based on the real changeable speed – speed in free traffic flow, V_F. For values of $R>R_{min}$, it gives almost the same results as Method 5 [6]. The final equation is a mathematical model for distribution of the roadway superelevation in the horizontal curve for $R>R_{min}$. Value of e can be calculated by just knowing design speed, V_d, and the minimal radius, R_{min}, or by knowing just design speed since the minimal radius also depends on in V_d. The results are in compliance with real conditions in traffic, and expected effects of roadway superelevation in the horizontal curve.

Considering that the research that led to the results presented in this paper was based on measurements with vehicles from the end of the 20th century, it would be good to make new measurements, with vehicles that are in use today, because the dynamic characteristics of modern vehicles are significantly different from those of that time. This procedure would thus be modernized, which would lead to the designing of safer roads in the future.

REFERENCES

[1] Damnjanović Dragorad: **Uticaj elemenata puta na brzinu u slobodnom saobraćajnom toku / Influence of Road Elements on Speed in Free Traffic Flow**. Nis, Yugoslavia: Ph.D. Thesis, University of Nis, 1980, in Serbian.

[2] Katanić Jovan, Anđus Vojo, Maletin Mihajlo: **Projektovanje puteva**. Beograd, Jugoslavija: IRO Građevinska knjiga, 1983,

[3] Neumann Erwin: **Der neuzeitliche Straßenbau**. Spinger-Verlag, Berlin/Gottingen/Heidelberg, 1959., the Serbian translation, Beograd, Građevinska knjiga, 1963,

[4] Cvetanović Aleksandar: **Osnovi puteva**. Beograd, Jugoslavija: IRO Naučna knjiga, 1989,

[5] Lorenz E.H. Hans: **Trassierung und Gestaltung von Straßen und Autobahnen**. Bauverlag GMBH, Wiesbaden und Berlin,1970,

[6] **A Policy on Geometric Design of Highways and Streets**. Washington, D.C., USA: AASHTO, 2011,

[7] Yanna Yin, Huiying Wen, Lu Sun, Wei Hou: **Study on the Influence of Road Geometry on Vehicle Lateral Instability**. Journal of Advanced Transportation, 2020, https://doi.org/10.1155/2020/7943739

[8] Debela Jima, Sipos Tibor: **Empirical model and side friction factor effect on desired operating speed at horizontal curved road**. Journal of Engineering Research, https://doi.org/10.1016/j.jer.2024.01.026, 2024.

[9] Bonneson J.A.: **NCHRP Report 439, Superelevation distribution methods and transition designs**. TRB, National Research Council, Washington, D.C., 2000.

[10] Pratt, M.P., Geedipally, S.R., Pike, A.M.: **Analysis of vehicle speeds and speed differentials in curves**. Transportation Research Record Volume 2486, Pages 28-36, 2015.

[11] Bonneson, J.A., Pratt, M.P.: **Model for predicting speed along horizontal curves on two-lane highways**. Transportation Research Record, Issue 2092, 2009.