Application of the speed prediction model ($V_{85}$) ($V85$) in the design of freeway interchanges

R M Jafarov and V P Zaluga
Moscow Automobile and Road State Technical University (MADI), 64, Leningradsky ave., Moscow, 125319, Russia
E-mail: dzhafaroff89@gmail.com

Abstract. The design of freeway interchanges is performed on the basis of technical and economic comparison of options for a large number of indicators. Design decisions depend on a large number of factors: the class of intersecting streets and roads, the level of service, traffic intensity, the estimated speed at the ramps, terrain, urban development, hydrogeological conditions of construction, etc. An integral indicator of the quality of design decisions is the maximum safe speed. In most countries of the world, the speed of single passenger cars is 85% of the security ($V_{85}$), which may differ from the calculated speed at the maximum safe speed. In the article, on the basis of experimental data, empirical models for calculating speeds ($V_{85}$) are obtained at freeway interchanges with directional ramps. Experimental studies were performed at freeway interchanges in the city of Moscow using a car laboratory according to the method of following the leader, as well as by processing video from a quadrocopter. The results of the study make it possible to predict the speed of movement ($V_{85}$) at the ramps of freeway interchange and to compare the freeway interchanges schemes according to the criterion of speed, loss of time, relative safety and traffic capacity.

1. Introduction

The effectiveness of design solutions for freeway interchange depends on a large number of factors; the key ones are throughput, security, time loss, and capital costs. Mathematically, this position can be written in the form of the following expression:

$$\sum V_n (V_n; P_n; K_b) \rightarrow \max, \quad \sum T_n (T_n; E) \rightarrow \min \quad (1)$$

where $V_n$ is the speed at the exit section, km/h; $P_n$ – throughput of the exit section, vehicles/h; $K_b$ – accident rate at the ramp section; $T_n$ is the ramp time, s; $E$ – capital expenditures for the construction of the ramp section, million rubles; $n$ is the number of ramp sections, pieces.

Let us give a brief description of each variable presented in formula (1).

Travel time ($T_n$) – the travel time on the ramp depends on the path parameters ($S_n$) and speed ($V_n$).

The path ($S_n$) is the length of the ramp section, which depends on the layout of freeway interchange and the dimensions of the geometric elements in the plan and longitudinal profile, which are assigned depending on the category of intersecting streets and roads (read the estimated speed – $V_e$), and also local accommodation conditions. The path parameters ($S_n$) also determine capital investments ($K_n$).

Speed ($V_n$) – is a comprehensive indicator of the quality of the transport process when driving along ramps of a freeway interchange. The combination of geometric elements in plan and profile, the width of the carriageway, as well as the road situation (signs, markings, fences, etc.), form the initial data for the choice of speed by the participants in the movement.
Capital investments \((K_t)\) – the cost of construction, which also depends on the path length \((S_n)\), local accommodation conditions (land acquisition area, demolition of buildings, reconstruction of utilities, deforestation, etc.), type and size of artificial structures, additional costs for the organization of construction, etc.

Relative traffic safety \((K_b)\) – characterizes the degree of constancy in the behavior of the driver when passing adjacent sections at ramps. This parameter can be estimated by the method of traffic safety factors proposed by Professor V.F. Babkov [1]. The methodology is based on an assessment of the degree of reduction of the maximum safe speed of 85\% security in the study area \(V_{account}^{85}\) relative to the maximum safe speed on the approach to this site \(V_{ex}^{85}\).

The traffic freeway interchange capacity \((P)\) is determined by the capacity of its individual ramps. The main reason for the decrease in the traffic capacity and the formation of congestion at the ramps is the presence of sections of a sharp decrease in speed (this issue is not considered in detail in this article).

From the foregoing, it can be concluded that all key indicators \((P_n, K_b, T_n)\) can be estimated by knowing the maximum safe speed \(V_{85}\) in the appropriate road conditions.

2. Statement of the problem

It was found that drivers choose the high-speed mode in free conditions based on the balance between the minimum time and safety. In world practice, the speed of movement that characterizes a transport structure from the point of view of maintaining a balance between minimum time and maximum traffic safety is taken as the speed of movement of single passenger cars in free conditions of 85\% of security \(V_{85}\), i.e. a speed that exceeds only 15\% of observed cars.

The choice of speed at the exits of freeway interchanges in free conditions is affected by:

- the value of geometric elements (the radius of the curve in the plan is \(r\), the angle of rotation is \(\alpha\);
- the longitudinal slope is \(i\), the distance of visibility is \(L_{view}\), the width of the carriageway is \(B_{floor}\), etc.);
- arrangement of elements of arrangement (road signs, marking, fencing and much more);
- experience and psychophysiological characteristics of the driver; natural and climatic factors;
- the operational condition of the carriageway.

However, there are key factors that are laid at the stage of development of the project and which have the greatest impact on the value of the speed chosen by the driver in free conditions:

- the radius of the curve in the plan \((r)\);
- longitudinal slope \((i)\);
- the angle of rotation \((\alpha)\).

At the moment, there are a large number of empirical dependencies for calculating the speed of movement \(V_{85}\) [2–8]. Most of the dependencies were obtained between 1980 and 2008 in the conditions of country two-way roads.

For traffic conditions at the ramp sections of freeway interchange, the work of scientists from China is known today [9], who in 2014 proposed empirical models for calculating the speed \(V_{85}\) depending on the parameters of the curvature of the route (rad / km) and the amount of slope of the turn (%) for sections of deceleration, uniform movement and acceleration at the ramp. However, it is not clear from the work to which type of ramp sections these dependencies (flyover or tunnel) are applicable and how to determine the speed in a straight section in a plan with zero curvature.

The analysis shows that all existing models for calculating the speed of movement have little convergence with the results obtained in Russia. The reason is the difference in road conditions, the difference in approaches to the designation of the geometric parameters of the ramps, the composition of the traffic flow, climatic conditions and driving style.

3. Materials and Methods

To obtain reliable empirical models for calculating the velocities \(V_{85}\) in the period of 2015-2019, field studies were carried out for 10 freeway interchanges, including 18 ramps with a different combination of geometric elements in Moscow and the Moscow region.
Figure 1. Planning schemes for freeway interchanges’ ramps: 1–3 – semi-directional ramp; 4 – loop ramp

All the ramps were of a flyover type, with 2 lanes, the total width of the carriageway: $10.4 \leq b \leq 11.2$ m, the radius of the curve in the plan: $30 \leq r \leq 270$ m, longitudinal slope: $-55 \leq I \leq +50$ ‰, the angle of turn of the track $40^\circ \leq \alpha \leq 180^\circ$, the transverse slope of the turn: 20 ‰.

Velocity measurements were performed using a laboratory car, which was equipped with a high-frequency (10 Hz/s) GPS logger with 2 cameras of the English company Racelogic. This equipment made it possible to continuously record diagrams of speeds, accelerations (longitudinal and transverse) and trajectories of movement of single cars in free conditions along the entire route along the ramp. Using specialized software, Circuit Tools and Vbox Tools, velocity plots and other motion characteristics were analyzed (Fig. 2).

Figure 2. The dialog box of the Circuit Tools program with the results of 6 rides at the freeway interchange at the intersection of Dmitrovskoye Highway and Moscow Ring Road in Moscow
From the diagrams of motion velocities (Fig. 1), characteristic points of variation of the motion velocities (extrema in the velocity diagram) were revealed, including the midpoints of the curves in the plan (minimum speeds of motion), the points of the beginning of braking in front of the curves in the plane, and the points of the beginning of acceleration at the exit from curves, as well as sections of maximum speed on straight sections of ramps.

To increase the objectivity of the experimental data, additional studies using a quadrocopter were also conducted. The video recording from the quadrocopter was processed using the Sony Vegas Pro 13 program, which allowed frame-by-frame scrolling of the video (25–30 frames per second) and with high accuracy to determine the travel time between the characteristic points recorded on the video.

By regression analysis of the experimental data, cumulative curves of the distribution of movement speeds at the characteristic points of the ramps were obtained (Fig. 3).

**Figure 3.** Schedule of the distribution of free movement speeds of cars at a directional ramp at the intersection of the Moscow Ring Road and Leninsky Prospekt in the city of Moscow at a characteristic ramp point with geometric parameters: 1 angle, $\alpha_1 = 44^\circ$, $R_1 = 100$ m, $i = +30\%$.

Based on the results of processing the experimental data, graphs of the dependence of the velocity $V_{85}$ were constructed for various curve radii in the $(r)$ plane (Fig. 4).

**Figure 4.** The graph of the dependence of the speed of movement ($V_{85}$) on the radius of the curve in terms of the radius $(r)$, $V_p$ – calculated speed.
4. Discussion of the results
The data shown on the graph (Fig. 3) can be described in the form of mathematical formulas:

\[ V_{85} = 20.162 \ln (r) - 30.163 \quad R^2 = 0.995 \]  

\[ V_p = (127r (\mu \pm in))^{1/2} \]

where \( r \) is the radius of the curve in the plan; \( in \) – a bias of a turn, \( \% \); \( \mu \) is the shear force coefficient adopted according to table 1; \( R^2 \) – the accuracy of the approximation, characterizing the convergence of the proposed model with experimental data.

**Table 1.** The values of the shear force coefficient (\( \mu \)) in the Russian Federation for roads outside settlements, depending on the estimated speed

| Estimated speed (\( V_r \), km/h) | 150 | 120 | 100 | 80 | 60 | 50 | 40 | 30 |
|----------------------------------|-----|-----|-----|----|----|----|----|----|
| Shear coefficient (\( \mu \))    | 0.08| 0.09| 0.12| 0.14| 0.17| 0.19| 0.23| 0.28|

The graphs show that the speed (V85) at the ramps is 9–20 \% higher than the calculated speed (VR). Formula (2) is true for the parts of the curves in terms of radius 30m < \( r \) < 270 m with transitions normative long, with an angle 40° < \( \alpha \) < 60°, the longitudinal slope of 30 \( \%e \) < \( I \) < +30 \( \%e \) for two-lane roadway cross-slope (super elevation) 20 \( \%e \) < IB < 30 \( \%e \).

The influence of the longitudinal slope (\( i \)) can be taken into account by introducing the following correction factors:

- when the angle of rotation \( \alpha \) < 60° and the slope on the approach to the curve (\( r \)) on the rise up to +30 \( \%e \) < \( I \) ≤ +50 \( \%e \) and the curve position on a slope in the range of +30 \( \%e \) < \( I \) ≤ +40 \( \%e \) coefficient equal \( K_{prod} = 1.03 \);
- when the rotation angle \( \alpha \) < 60° and the slopes after the curve (\( r \)) on the descent are within −50 \( \%e \) ≤ \( i \) < −30 \( \%e \) and the curve is located on the slope within −40 \( \%e \) ≤ \( i \) < −30 \( \%e \), the coefficient is \( K_{prod} = 0.97 \).

The influence of the rotation angle (\( \alpha \)) in combination with the longitudinal slope (\( i \)) can be taken into account by introducing the following correction factors:

- when the rotation angle \( \alpha \) > 60° in the middle of a circular curve located on longitudinal slopes −30 \( \%e \) ≤ \( i \) ≤ +30 \( \%e \), the coefficient is \( K_{\alpha} = 0.97 \);
- at an angle of rotation \( \alpha \) > 60° at the beginning of a circular curve in the lifting section with a slope of +30 \( \%e \) < \( I \) < +55 \( \%e \) the coefficient is \( K_{\alpha} = 0.94 \);
- when the rotation angle \( \alpha \) > 60° at the end of the circular curve in the descent section with a slope of −30 \( \%e \) < \( i \) < −50 \( \%e \), the coefficient is \( K_{\alpha} = 1.06 \).

Due to the fact that the plan of the freeway interchange ramps consists not only of curves of different radius (\( r \)), but also sections of lines, the empirical equations for determining the speed (V85) depending on the value of the longitudinal slope (\( i \)) and the radius of the curve in plan (\( r \)) at the end of the line were also obtained (3–5).

With a longitudinal slope of rise +40 \( \%e \) < \( I \) < + 55 \( \%e \) the speed on the straight section is:

\[ V_{85} = 0.0786r + 72.571 \quad R^2 = 0.9912 \]

With a longitudinal slope of rise +40 \( \%e \) < \( I \) < + 55 \( \%e \) the speed on the straight section is:

\[ V_{85} = 0.111r + 64.167 \quad R^2 = 0.9973 \]

With a longitudinal slope of rise +40 \( \%e \) < \( I \) <+55 \( \%e \) the speed on the straight section is:

\[ V_{85} = 0.0688r + 79.533 \quad R^2 = 0.9888 \]

To determine the position of the extremum point (maximum speed) and the section with constant speed at the ramp, it is necessary to know the magnitude of the longitudinal accelerations (\( a_{ij} \), m/s\(^2\)), which depends on the degree of change of speed (\( \Delta V_{ij} = V_j - V_i \)) and the values of the longitudinal slope.

Deceleration or acceleration on a straight section with a longitudinal slope of +30\( \%e \) < \( i \) < +55 \( \%e \) after leaving the main road, depending on the speed difference (\( \Delta V_{ij} \)) is equal to:

\[ a_{ij} = 0.0697 \Delta V_{ij} + 0.0696 \text{ at } V_i < V_j \quad R^2 = 0.6524 \]
\[ a_{ij} = -0.079 \Delta V_{ij} - 0.0208 \text{ at } V_i > V_j \quad R^2 = 0.8591 \quad (7) \]

The deceleration in a straight section with a longitudinal slope of \(+30\% < I < +55\%\) before the curve of any radius (r) depending on the speed difference \((\Delta V_{ij})\) is equal to:

\[ a_{ij} = -0.0342 \Delta V_{ij} + 0.1049 \quad R^2 = 0.7849 \quad (8) \]

The acceleration in a straight section with a longitudinal slope of \(-20\% < i < +20\%\) after a curve of any radius (r) depending on the speed difference \((\Delta V_{ij})\) is equal to:

\[ a_{ij} = 0.0231 \Delta V_{ij} + 0.1776 \quad R^2 = 0.6589 \quad (9) \]

The deceleration in a straight section with a longitudinal slope of \(+30\% < i < +55\%\) before the curve of any radius (r) depending on the speed difference \((\Delta V_{ij})\) is equal to:

\[ a_{ij} = -0.0315 \Delta V_{ij} - 0.1096 \quad R^2 = 0.6068 \quad (10) \]

The acceleration in a straight section with a longitudinal slope of \(-20\% < i < +20\%\) after a curve of any radius (r) depending on the speed difference \((\Delta V_{ij})\) is equal to:

\[ a_{ij} = 0.0315 \Delta V_{ij} + 0.1664 \quad R^2 = 0.7482 \quad (11) \]

To determine the length of the section of uniform movement with constant speed, it is necessary to calculate the linear position of the point at the ramp at which the extreme (maximum) speed value \(V_{85}\) is reached:

\[ S_{ij} = (V_j^2 - V_i^2) (26a_{ij})^{-1}. \quad (12) \]

Let us give an example of plotting the motion velocities \(V_{85}\) for a directed ramp at the intersection of Leninsky Prospekt and the Moscow Ring Road in Moscow. The design scheme is shown in Fig. 5.

**Figure 5.** The design scheme for plotting traffic speeds at a directional ramp at the intersection of Leninsky Prospekt and the Moscow Ring Road in Moscow

The methodology includes the following steps:

- Step 1. Determine the characteristic points of change in speed at a directional ramp.
- Step 2. Calculate the \(V_{85}\) speeds at characteristic points at the ramp using formulas (2–5).
• Step 3. Calculate the lengths of the characteristic sections (S) using formula (12) using formulas (6–11).
• Step 4. Plotting in MS Excel, as shown in Fig. 6.

Figure 6. Let us give an example of plotting the motion velocities $V_{85}$ for a directed ramp at the intersection of Leninsky Prospekt and the Moscow Ring Road in Moscow

5. Conclusion
It has been established that an integral indicator of the quality of the transport process is the maximum safe speed equal to the speed of 85% of security ($V_{85}$). The choice of speed of movement is influenced by many factors, but the greatest influence during free movement is exerted by the radius of the curve in the plan ($r$), the longitudinal slope ($i$), the angle of rotation ($\alpha$) and, as a result, the distance of visibility in the plan ($L_{\text{view}}$).

It is proved that the developed methodology for predicting the speed of movement ($V_{85}$) is effective in the techno-economic comparison of planning schemes of freeway interchanges by the criterion of travel time, relative traffic safety and relative traffic capacity (this issue was not considered in this article), as well as in solving a wide range of tasks of transport planning and traffic management.

References
[1] Babkov V F 1993 Road conditions and traffic safety (Moscow: Transport)
[2] Liapis ED, Psarianos B and Kasapi E 2001 Speed Behavior Analysis at Curved Ramp Sections of Minor Interchanges Transportation Research Record 1751 35–43
[3] Abdul-Mawjoud Ayman A and Sofia Gandhi G 2008 Development of models for predicting speed on horizontal curves for two-lane rural highways The Arabian J. for Sci. and Engineer. 33(2B)
[4] Cantisania G and Di Vitoa Michele 2012 CCV: A New Model for $S85$ SIIV – 5th Int. Congr. – Sustainability of Road Infrastructures (Rome, Italy: University of Roma La Sapienza Department of Civil & Environmental Engineering)
[5] Castro M 2010 Speed models for highway consistency analysis A Colombian case study. 4th Int. Symp. on Highway Geometric Design (Valencia: Universidad Politécnica de Madrid)
[6] Collins K M and Krammes R A 1996 Preliminary Validation of a Speed-Profile Model for...
Design Consistency Evaluation *Transport. Res. Record* **1523** 11–21

[7] Fitzpatrick K and Collins J 2000 Speed profile model for two lane rural highways *Transport. Res. Record* **1737** 42–9

[8] Syed Khairi Syed Abbas, Muhammad Akram Adnana and Intan Rohani Endut 2011 Exploration of 85th Percentile Operating Speed Model on Horizontal Curve: A Case Study for Two-Lane Rural Highways *Procedia Social and Behavioral Sci.* **16** 352–63

[9] Zhi-yong Zhang, Xiao-yun Hao and Wen-bin Wu 2014 Research on the Running Speed Prediction Model of Interchange *Procedia Social and Behavioral Sci.* **138** 340–9