Mathematical models to determine the influence of road parameters and conditions on vehicular speed

V G Kozlov\textsuperscript{1,5}, A V Skrypnikov\textsuperscript{2}, V V Samcov\textsuperscript{2}, D M Levushkin\textsuperscript{2}, A A Nikitin\textsuperscript{3}, A N Zaikin\textsuperscript{4}

\textsuperscript{1} Voronezh State Agrarian University named after Emperor Peter the Great, 1 Michurina Ave, Voronezh, 394087, Russia
\textsuperscript{2} Voronezh State University of Engineering Technologies, 19, Revolution ave, Voronezh, 394036, Russia
\textsuperscript{3} Mytischi branch, Bauman Moscow State Technical University, 1 1st Institutskaya Str., Mytischi, Moscow region, 141005, Russia
\textsuperscript{4} Bryansk State Engineering and Technological University, 3 Stanke Dimitrova Ave., Bryansk, 241037, Russia
\textsuperscript{5} Corresponding author’s e-mail: vya-kozlov@yandex.ru

Abstract. The study of vehicular movement modes in adverse weather conditions allowed defining the dependence of traffic modes at certain road segments on weather conditions. It is found that the average vehicle speed changes within a year over a wide range depending on road conditions even on its straight horizontal sections. There is a considerable difference in the maximum speed of traffic movement. Complex road sections significantly influence the traffic mode during any period of the year, especially in adverse weather conditions. The road surface condition exerts the greatest impact on the traffic speed. If the adhesion coefficient equals 0.2-0.3 the average traffic speed is 20-25% lower than if that adhesion coefficient equals 0.5-0.6, and in ice conditions the average traffic speed decreases by 40-50%. The proposed calculation formula allows defining the influence of weather conditions on the traffic mode of free-moving cars or cars in a joint traffic flow. It provides for the feasibility study regarding measures aimed to increase the traffic speed in adverse weather conditions of the year. Based on the observations and calculations the correlation dependences of average and maximum traffic speeds on the adhesion coefficient within a 7.0 m-wide road without the hard shoulder were obtained.

1. Introduction
The purpose of experimental observations over the traffic speeds was to test the theory on the influence of changes in road conditions under the influence of weather and climatic factors on the speed of single cars, on the average speed of free movement and movement within a traffic flow, as well as on the correlations between the design speed and the specified characteristics of the traffic mode during various periods of the year.

The study of traffic modes in adverse weather conditions allowed defining the dependence of traffic modes at particular road sections on weather conditions.
2. Materials and methods

It is found that the average vehicle speed changes within a year over a wide range depending on road conditions even on its straight horizontal sections.

The distribution of traffic speeds within a flow is also changing depending on road and weather conditions in various year seasons. For example, the difference in average speeds of motor cars and trucks along dry coating makes 8-11.3 km/h in summer, along wet coating – 8.1 km/h in autumn, along a snow-covered road – 5.4-7.3 km/h in winter, and 5.3-8 km/h on an ice-slick. In fact, the speed spread becomes even more noticeable [9-12].

There is a considerable difference in the maximum speed of the traffic flow. Complex road sections significantly influence the traffic mode during any period of the year, especially in adverse weather conditions. There is a certain dependence of traffic speeds on road and weather conditions. It is also possible to link the change of road conditions with traffic modes not only for the road in general but also for its separate elements.

The observations showed that the average traffic speed under good weather and sufficient road maintenance (fully cleaned road and roadsides) does not differ much in winter from the traffic speed in summer. The considerable change is observed under adverse weather conditions and the relevant decrease in road service quality and change of road geometry (Figure 1).

![Figure 1. Distribution of traffic speeds in winter and summer under various road conditions in the Komi Republic: 1 – dry in winter; 2 – wet coating; 3 – snow-covered road; 4 – wet in summer on a dual road; 5 – ice-covered in winter on the same dual road.](image)

The range between the maximum and minimum speed is reduced on a traffic-bound snowy and ice-covered coating compared to the range of speed on dry and wet coatings.

In winter the number of areas with side obstacles for moving cars, which cause local speed reduction within the traffic flow, is higher. In these road sections the drivers sharply cut the speed down, which, at low adhesion coefficient typical for winter, leads to road accidents.

Roads with low traffic intensity (up to 1000 vehicles/day) and during a long winter period are characterized by a considerable narrowing of a clean coating (up to 4-3.5 m), where its other part is covered with a layer of compacted snow or ice. The traffic speed on a clean coating makes 75-80 km/h while in case of oncoming vehicles it decreases to 40-45 km/h caused by the need to move to a snow-covered or ice-covered surface.

On completely snow-covered road at the adhesion coefficient of 0.15-0.35 the speed capacity of vehicles may reach 70 km/h and above. However, such speed is only possible in the absence of obstacles, which may cause braking or overtaking.
The study carried out in winter on roads located in various regions shows that on a snow-covered coating the average speed does not usually exceed 60 km/h, on congested areas and in case of road humps and ruts it decrease to 40-50 km/h.

**Figure 2.** Speed of motor cars (left) and trucks (right) along different roads (a, b – straight horizontal road segment, shoulder-to-shoulder width is 6.5 m; c, d – traffic-bound road with a 600 m radius, shoulder-to-shoulder width is 6.5 m; e, f – traffic-bound road with a 500 m radius, 30% downhill, shoulder-to-shoulder width is 6.5 m; g, h – traffic-bound road with a 330 m radius, 40% downhill, shoulder-to-shoulder width is 6.5 m
The road condition impacts the traffic speed the most. At adhesion coefficient of 0.2-0.3 the average traffic speed is 20-25% lower than at 0.5-0.6, and during ice it decreases by 40-50%. The speed distribution curves are characteristic in this case [6-8]. The reduction demonstrates the speed alignment within a traffic flow. Considerable speed range is observed on a snow traffic-bound coating – there are cars moving with high speed. The distribution curve on a wet coating is close to normal with similar percentage of quickly and slowly moving cars. The traffic speed and scope of its fluctuation increase on a dry coating.

On ice-covered road, the traffic speed sharply decreases and approaches the traffic speed of trucks: in general, the traffic speed is aligned and becomes uniform.

The traffic modes also change on wet roads with dirty roadsides in spring and autumn, especially during heavy rainfalls.

Figure 2 shows the distribution and cumulative curves of traffic speed for motor cars and trucks in spring, summer and autumn moving along a straight horizontal road section of one of the exits from Ukhta with the shoulder-to-shoulder width of 11.5 m divided by marking into three lanes and having hard shoulders. In summer, the study was carried out on a dry coating, in fine and warm weather, in spring – in fine weather, but on a wet coating in certain sites, and in autumn – in cloudy weather and on a wet coating. In general, these conditions are typical for the considered periods. The study shows that despite high service performance of a road and quite high level of its composition, the vehicular speed fluctuates over a wide range. Thus, the average speed of motor cars was 11-28% higher in summer than in spring and in autumn. It is obvious that if the traffic intensity is considerably smaller than the road capacity, such low speed can be explained by the influence of weather conditions. The marked difference was also observed regarding the speed of trucks, which during transition periods decreased by 15-21%.

By comparing the data concerning the change of speed on roads in summer, autumn and spring it is fair to state that the decrease in speed during adverse weather conditions in many respects depends on technical conditions of the road, its geometrical parameters and, first of all, the type of coating and condition of roadsides (Figure 2).

Different authors obtained data indicating that under dirty road conditions the effective width is reduced thus forcing a driver to reduce the speed when facing other oncoming cars. The higher the traffic intensity, the more often the cars meet and thus the more noticeable the speed decrease. To verify this assumption the traffic speed along roads with different actual width was studied. The study was carried out on straight horizontal road sections with a width of 6.7 and 7.5 m with earth and hard shoulders, at traffic intensity ranging from 70 to 520 vehicles/hour. It is found that the traffic speed depends on actually used, but not on the design width of the road. Similar results are obtained during measurements of the traffic speed on roads with various design width in winter with similar clearing width. Based on the study the dependence of traffic speed on the actual road width was found (Figure 3).

The analysis of data on the traffic speed when vehicles meet on roads with various width shows that the safety margin between the road curb Y almost equals the half of the safety margin between the bodies of two oncoming cars X. By taking $Y = \frac{2X}{2}$, it was suggested to use the formula to determine the necessary width of the dual road.

Thus, it was possible to confirm the dependence of the traffic speed of cars on road parameters and its condition D, traffic intensity and the traffic flow structure, weather conditions C, i.e. $V = f(D, TV, C)$. 

3. Results and Discussion

The analysis of materials results in the following empirical dependence of the specified parameters:

\[ \bar{V} = V_{CB} - \alpha \beta N \]  \hspace{1cm} (1)
\[ \bar{V} = K_{RS} V_a - 3 \sigma_{vp} - \alpha \beta N \]  \hspace{1cm} (2)

where

- \( \bar{V} \) – average traffic flow speed, km/h at traffic intensity \( N \);
- \( V_{CB} \) – average traffic speed of vehicles in a free traffic flow (at intensity up to 100-150 vehicles/h) along the dual road;
- \( K_{RS} \) – reduction coefficient of design speed considering the change of weather conditions or the maximum possible speed (95%) of a vehicle under reference conditions;
- \( \sigma_{vp} \) – mean square deviation of the traffic speed within a free traffic flow, km/h, is accepted according to diagram (Figure 4) for

\[ V_p = K_{pc} \cdot V_a \]  \hspace{1cm} (3)

- \( \alpha \) – coefficient considering the influence of traffic intensity (Figure 5);
- \( \beta \) – coefficient considering the traffic flow structure (equal to the percentage of trucks in a flow).

The formula is valid under the traffic intensity along dual roads equal to 700 vehicles/h and in the presence of over 45-50% log trucks, trucks and buses in a traffic flow \( \beta \geq 0.45 \), i.e. is applicable to determine the traffic speed on roads of the II-IV technical category (Figure 5). The difference in the average speed calculated according to the formula and measured on roads varied from 5% to 12%, since the average speed is mainly affected by the range of speed fluctuations, which is defined as \( \sigma = R/\sigma \), where \( R \) – difference between the maximum and minimum speed, km/h.

The observations show that \( \sigma \) significantly depends on the maximum possible traffic speed at a given road segment and on the structure of traffic flow. The more uniform the traffic structure, the less the range of fluctuations.
Figure 4. Dependence of the mean square deviation on the maximum traffic speed.

Figure 5. Dependence of intensity coefficients and the traffic flow structure on a dual road.

Figure 6. Influence of road conditions, weather conditions, traffic structure and intensity on the traffic speed.
The observations show that $\sigma$ significantly depends on the maximum possible traffic speed at a given road segment and on the structure of traffic flow. The more uniform the traffic structure, the less the range of fluctuations.

It is found that in real conditions the influence of the traffic intensity is essential when the intensity is more than 100-180 vehicles/h on a dual road (Figure 6).

The proposed formula allows defining the influence of weather conditions on the traffic mode of free-moving cars or cars in a joint traffic flow. It provides for the feasibility study regarding measures aimed to increase the traffic speed in adverse weather conditions of the year.

The reliability of the suggested formula is checked through the comparison of average and maximum traffic speeds obtained by a design formula with the corresponding speeds obtained during observations at various road conditions (with a road width of 7.0 m without hard shoulders) and the traffic intensity from 900 to 2000 vehicles/day (Figure 7).

To check the hypothesis on the agreement of calculated values $T_i$ with experimental values $x_i$, the so-called $F$-statistics is calculated [1-5].

Other values are calculated as follows:

$$
\bar{x} = \frac{1}{n} \sum x_i; \quad T = \frac{1}{n} \sum T_i
$$

$$
\|T - \bar{T}\|^2 = \sum (T_i - \bar{T})^2; \quad \|x - \bar{x}\|^2 = \sum (x_i - \bar{x})^2
$$

$$
(x - \bar{x}, T - \bar{T}) = \sum (x_i - \bar{x})(T_i - \bar{T})
$$

$$
\beta_1 = \frac{(x - \bar{x}, T - \bar{T})}{\|T - \bar{T}\|^2}
$$

$$
\Delta^2 = \|x - \bar{x}\|^2 - \frac{(x - \bar{x}, T - \bar{T})^2}{\|T - \bar{T}\|^2}
$$

The obtained values of $F$-statistics are compared with the tabulated values of the Fisher distribution $F_\alpha, n = e$.

Let us assume that $T_i = \bar{v}_{pi}$ – average traffic speed obtained through a design formula for a given adhesion coefficient and the traffic intensity, and $x_i = \bar{v}_{pi}$ – average speed (50% coverage) obtained through observations under the same conditions.

Table 1 and Figure 7 show the initial data to determine the $F$-statistics.

| $i$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $T_i$ | 38.5 | 38.5 | 45 | 45 | 49.5 | 49.5 | 5.5 | 5.5 | 50.9 | 50.9 | 56 | 56 | 58 | 58 | 58 | 58 | 58 | 58 |
| $x_i$ | 37 | 43.5 | 42.5 | 48 | 55 | 48 | 47 | 50 | 56 | 58 | 57 | 52 | 58 | 60 | 60.5 | 62 | 59.5 | 58 |

Auxiliary characteristics

$$
\bar{x} = 52,889, \quad \bar{T} = 51,517, \quad \|x - \bar{x}\|^2 = 884,778; \quad \|T - \bar{T}\|^2 = 689,465;
$$

$$
(x - \bar{x}, T - \bar{T}) = 676,386; \quad \beta = 0.981; \quad \Delta^2 = 221,223.
$$

The $F$-statistics will equal

$$
F_{2,16} = \frac{1}{\frac{1}{18} - \frac{\Delta^2}{\|T - \bar{T}\|^2}} = 0.419
$$

The $F$-statistics is defined in a similar manner by comparing the maximum traffic speed calculated by the suggested formula and the speed of 95% coverage obtained through observations. The $F$ statistics resulted in $F_{2,16} = 3.546$.

The tabulated values of the Fisher distribution for 0.95 quantile equal $F_{2,16} = 6.01$, and for 0.99 quantile $F_{2,16} = 3.55$. By comparing the calculated and tabulated values of $F$-statistics it is possible
to conclude that the speeds $\bar{V}$ and $V_{\text{max}}$ calculated by the formulas are in good agreement with the speeds received through experiments.

The observations and calculations resulted in the correlation dependences of the average and maximum traffic speed on adhesion coefficient on a road width of 7.0 m without hard shoulders:

$$\bar{V} = 33.2 + 61.14\phi - 19.54\phi^2 \text{km/h}$$

Correlation ratio $r = 0.908$;

$$V_{\text{max}} = 37.8 + 96.44\phi - 20.44\phi^2 \text{km/h}$$

Correlation ratio $r = 0.969$.

Adverse weather conditions influence the traffic mode through the ‘driver-road-car’ system and directly through the driver. During the initial influence of adverse meteorological factors, the driver chooses the traffic mode by assessing the interaction of a ‘car-road’ mechanical system. This factor is key on roads with poor technical conditions. However, sharp increase in the influence of weather conditions also affects the psychophysiological status of a driver. For example, during autumn rains the traffic speed decreases mainly due to the decrease in the grip of wheels and the danger of moving onto dirty earth shoulders. During summer heavy rains the speed decreases due to poor visibility and loss of orientation. The influence of certain factors is so high that the movement stops (during heavy rains, snowstorms and fogs). The role of weather conditions on psychophysiological status is especially critical on well-developed roads where the ‘car-road’ mechanical system is quite reliable. This may be illustrated by observations on well-developed roads with rough coating and hard shoulders during heavy rains. The average traffic speed in rainy weather decreased from 86 km/h to 57 km/h, i.e. by 33.7%, and the speed of 85% coverage decreased from 110 km/h to 70 km/h, i.e. by 36.4%.

4. Conclusion

Similar results were obtained through the study of the influence of rough parameters on the traffic speed within a traffic flow. The study covered the traffic modes of road sections with a smooth asphalt concrete coating and with a rough coating along Irayel-Izhma, Syktyvkar-Kotlas, Mikun-Usogorsk, Saratov-Balashov roads with the traffic intensity of 2-2.5 thousand vehicles/day. The road width on a section with a rough coating equals 7.0 m, and on the section with a smooth coating – 7.5 m. Figure 8 shows that the coating roughness has significant effect on the traffic speed of a traffic flow and certain vehicles, especially under wet conditions. Hence, the task of increasing the speed in adverse weather conditions shall be solved differently and in different sequence. On roads with low technical condition, the main task is to increase adhesion, flatness, roadside soil stabilization, improve crossings, etc. Alongside with the above-stated, there is a need to ensure visual and psychological orientation of a driver (road marking, guiding system, signals, etc.) on roads with higher technological condition. Such measures shall be arranged on any road; however, their efficiency will not be the same.

References

[1] Berestnev O, Soliterman Y, and Goman A 2000 In proc. of International symposium on history of machines and mechanisms proceedings (Springer) pp. 325-332.
[2] Bially T, Mc Laughlin A and Weinstein C 1980 Voice IEEE Trans. on Commun. 9 1478-1490.
[3] Brion W 2015 Transportation research record. Res 2483 57-65.
[4] Kopriva P 1990 Vybrane problemy teorie apedehlvesty (Lausch-mann: Praha Academia)
[5] Kozlov V G, Gulevsky V A, Skrypnikov A V, Logoya V S and Menzhulova A S 2018 IOP Conference Series: Materials Science and Engineering 327(4) 042-056.
[6] Kozlov V G, Skrypnikov A V, Chernyshova E V, Mogutnov R V and Levushkin D M 2018 Journal of Physics: Conference Series 1015(3) 032069.
[7] Oliver R M 1962 Operat. Res. 2 197-217.
[8] Park K, Hwang Y, Seo S, Asce M and Seo H 2003 *Journal of Construction Engineering and Management* **129**(1) 25-31.
[9] Pestigay S 1961 *Annales des Fonts et Chaussees* **2** 145-225.
[10] Phillips W S 1979 *Transportation Planning and Technology* **3** 131-158.
[11] Dorokhin S V, Chernyshova E V 2017 *Journal of Engineering and Applied Sciences* **2** 511-515.