

ENGINEER



international scientific journal

ISSUE 3, 2026 Vol. 4

E-ISSN

3030-3893

ISSN

3060-5172



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ENGINEER

A bridge between science and innovation

E-ISSN: 3030-3893

ISSN: 3060-5172

VOLUME 4, ISSUE 3

SEPTEMBER, 2026



engineer.tstu.uz

TASHKENT STATE TRANSPORT UNIVERSITY

ENGINEER

INTERNATIONAL SCIENTIFIC JOURNAL
VOLUME 4, ISSUE 3 SEPTEMBER, 2026

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The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

The journal is published 4 times a year and contains publications in the following main areas:

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Tashkent State Transport University had the opportunity to publish the international scientific journal “Engineer” based on the **Certificate No. 1183** of the Information and Mass Communications Agency under the Administration of the President of the Republic of Uzbekistan. **E-ISSN: 3030-3893, ISSN: 3060-5172.** Articles in the journal are published in English language.

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Scientific and practical justification of safe vehicle speeds in mountainous areas of the M-39 highway of international importance

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Abstract:

The article considers the issue of determining the safe speed of vehicles in mountainous areas and the scientific justification of the need for its mandatory reduction. A complex mathematical model is proposed that takes into account the turning radius, pavement adhesion coefficient, traffic flow intensity, flow density, geometric coefficient and permissible risk level. Using the example of the mountainous areas of the M-39 highway, safe speed values are analyzed and practical recommendations are developed to improve traffic safety. Using this model, it is possible to determine the safe speed value for vehicles in mountainous road conditions, assess the probability of accidents and limit the speed in accordance with real road conditions. Based on the results obtained, safe speed values are calculated for the example of the mountainous areas of the M-39 highway and practical recommendations are developed to improve traffic safety. In particular, the need to introduce dynamic road signs, warning information panels and speed control devices in dangerous turns, sections with limited visibility and areas with deteriorating pavement conditions is justified. The article examines the scientific and practical issues of determining the safe speed of vehicles operating in mountainous road conditions and substantiates the necessity of its mandatory reduction in hazardous sections. Mountain roads are characterized by complex geometric parameters, sharp curves, steep longitudinal slopes, limited visibility, unstable pavement conditions and a high probability of traffic accidents. Therefore, the correct determination of safe vehicle speed in such areas is one of the important factors in improving road safety and reducing accident risks. On the basis of the analysis, practical recommendations were developed to improve traffic safety in mountainous road areas. In particular, the introduction of dynamic road signs, warning information panels, speed control devices and automated monitoring systems is scientifically justified for dangerous curves, sections with limited visibility and areas where pavement conditions may deteriorate due to weather or traffic load. The implementation of these measures can contribute to reducing accident probability, improving driver awareness, stabilizing traffic flow and increasing the overall safety level of mountainous highways.

Keywords:

mountain road, safe speed, turning radius, friction coefficient, traffic flow, accident probability, dynamic road sign

1. Introduction

Research and development work on improving road safety in the world is of great importance. In mountainous areas, the speed of vehicles should be much lower than on flat roads. However, many drivers do not comply with the recommended speed limits, which leads to dangerous situations. For example, on sections with a slope of more than 40%, the speed of trucks on slopes can be twice as high as on hills, which increases the risk of collisions. Road accidents in mountainous areas not only cause casualties and injuries, but also cause significant damage to the environment and the economy. For example, oil spills in truck accidents pollute mountain rivers and soil, and the restoration of road infrastructure requires significant financial costs.

Modern methods of ensuring traffic safety on mountain roads, such as the installation of barriers, the construction of protective galleries, and the use of intelligent traffic control systems, have been used in our republic for a long time. The introduction of such measures in Uzbekistan allows us to reduce the number of accidents and increase the efficiency of the transport system [1].

The development and justification of measures to reduce the speed of vehicles on mountainous road sections of highways is one of the urgent tasks aimed at increasing traffic safety, reducing accidents, and minimizing environmental and economic damage. The implementation of such measures requires an integrated approach, including improving road infrastructure, introducing modern technologies, and monitoring strict compliance with speed limits.

In accordance with the Strategy for the Development of the Public Safety System in the Republic of Uzbekistan for 2022-2025, as outlined in the Resolution of the President of the Republic of Uzbekistan No. PQ-190 dated 04.04.2022 "On Measures to Ensure Reliable Human Safety on Motor Roads and Sharply Reduce Fatalities", as well as in order to ensure the guaranteed protection of human life and health on motor roads from any incidents in the conditions of the new Uzbekistan, and in accordance with the Resolution of the President of the Republic of Uzbekistan No. PQ-316 dated 12.07.2022 "On Approval of the National Program "Safe and Smooth Road" for Implementation in 2022-2026", the digitalization of the traffic control system on motor roads, the integration of traffic light objects at intersections into the central management system, and the implementation of a

 <https://orcid.org/0009-0000-2124-2971>



single digital management system, as well as other tasks related to this activity. This dissertation work serves to a certain extent in the implementation of the tasks set out in regulatory and legal documents [1].

2. Research methodology

The assessment of the speed of vehicles in mountainous areas from a safety point of view and the justification of the need for mandatory reduction is a complex scientific and practical process. This process requires a comprehensive consideration of the geometric parameters of the road, traffic flow intensity, traffic composition, adhesion properties of the road surface, longitudinal slope, turning radius and the probability of danger.

In mountainous areas, the radius of curvature of the road is dangerous, small-radius turns, large longitudinal slopes, variability of weather and surface conditions directly affect the stable movement of vehicles. In such conditions, the maximum speed selected by the driver does not always correspond to the safe speed. Therefore, there is a need to determine the permissible speed of vehicles depending on the turning radius, correlate it with road conditions and the probability of danger, and develop an improved methodology for calculating the safe speed value.

In this study, a methodology was proposed based on the integration of road-geometric, transport-operational and safety factors into a single mathematical model to determine the need for mandatory reduction of vehicle speed in mountainous road areas. The main essence of the methodology is to determine the safe speed of movement through a comprehensive assessment of the turning radius of the road (R), longitudinal slope (i), traffic flow intensity (q), traffic composition coefficient (k), road surface adhesion coefficient (ϕ), risk level (Phazard level) and calibration coefficient (k_1) [2].

This methodology is aimed at ensuring the safety of vehicle movement in mountainous road areas, in which road geometry, traffic flow, road surface condition and risk probability are integrated into a single calculation system. As a result, the difference between the permissible speed of vehicles and the safe speed in areas with dangerous curvature radius is determined, creating the opportunity to make scientifically based decisions on mandatory reduction of speed. Based on their research, it is intended to address the following issues:

- identify and systematize the main factors affecting the speed of vehicles on mountainous road areas;
- assess the geometric parameters of the study area, including the turning radius, longitudinal slope and condition of the road surface;
- determine the coefficients of traffic flow intensity and traffic composition and assess their impact on safe speed;
- determine the impact of the turning radius on the permissible speed of vehicles and justify a linear regression model in the form of ($v=a+bR$);
- take into account the coefficient of adhesion between the road surface and the tire for dry, wet and slippery/dirty road conditions;
- develop a safe speed model combining traffic flow, road geometry, surface condition and risk probability;
- justify the need for mandatory speed reduction by comparing the calculated permissible speed and safe speed values;

- development of practical recommendations for determining safe speeds and introducing dynamic road signs developed by us in mountainous areas.

In order to assess the speed of vehicles in mountainous areas from a safety point of view and justify measures to reduce the number of road accidents by mandatory speed reduction, it is important to properly organize experimental and test work. This chapter describes the test equipment, measured parameters, research program, and the procedure for processing the results obtained for conducting experimental and test studies [4].

The main purpose of the experimental and test works is to determine the relationship between the permissible speed of vehicles, geometric parameters of the road, traffic flow intensity, pavement condition and traffic safety in mountainous road areas. In this case, the turning radius of the road, longitudinal slope, adhesion coefficient between the road surface and the car tire, traffic flow composition and real traffic speeds were taken as the main research indicators.

Experimental works are carried out in designated dangerous turning areas of the mountainous road area. As a research area, a road area with a turning radius of 989-1013, high traffic flow intensity and a high probability of traffic accidents is selected. In the test area, the speed of vehicles, traffic flow composition, road surface condition and geometric parameters are simultaneously recorded [3].

Test equipment. When carrying out experimental and test works, it is advisable to use the following measuring and monitoring equipment. The equipment measures the permitted speed of vehicles, road geometry, and traffic flow parameters. The data is then fed into a model for determining safe speeds.

Main parameters to be measured. The following parameters will be recorded during the experiment:

- turning radius of the road (R), m;
- road gradient (i), %;
- real speed of vehicles (v), km/h;
- traffic flow intensity (q), vehicles/h;
- traffic composition coefficient (k);
- road surface adhesion coefficient (ϕ);
- geometric coefficient (K_g);
- risk level (Prisk level);
- safe speed (v_{safe}), km/h.

The condition of the road surface is assessed in dry, wet and slippery or contaminated conditions. The calculations assume the values of dry surface ($\phi=0.75$), wet surface ($\phi=0.55$), and slippery or contaminated surface ($\phi=0.35$).

A special experimental and test program has been developed to determine the safe speed of vehicles in mountainous road areas and to scientifically substantiate the need for mandatory speed reduction. This program is aimed at determining the geometric and operational parameters of the road, assessing the traffic flow regime, and calculating the safe speed.

Table 1

Contents of the pilot study program

B	Program Structure	Research Implementation Process
1	Choosing a research area	In mountainous areas, areas with small turning radius, steep slopes, and high risk of traffic accidents are selected.
2	Determining the geometric	The turning radius (R), the slope (i), the cross slope and the road design



	parameters of the road	elements are measured. These indicators are evaluated as the main factors affecting the stability of the vehicle on a dangerous curve.
3	Road surface condition assessment	The condition of the road surface is assessed in terms of dry, wet, or slippery/dirty conditions. For each condition, the coefficient of adhesion (φ) between the road surface and the tire is selected.
4	Determining the intensity and composition of transport flow	The number of vehicles, the share of cars and trucks, buses and other types of transport during a specified period of time are recorded based on real-time observations and flow-measuring devices.
5	Measuring the real speed of vehicles	Using GPS, radar, or video surveillance, the actual speeds of vehicles on a road with a dangerous radius of curvature are determined. The values obtained are used to justify the free speed model.
6	Calculate maximum movement speed	The permissible speed is determined based on a linear regression model depending on the turning radius: $(v_{allow} = a + bR)$
7	Determining safe speed	Safe speed is calculated taking into account traffic flow intensity, traffic composition, road surface adhesion coefficient, road slope, and risk level.
8	Analyzing results and making decisions	The permitted speed and the safe speed are compared. If ($v_{safe} < v_{free}$), the need for a mandatory speed reduction in this area is justified.

The program includes the implementation of the following tasks:

Stage 1. Identification stage (2022-2023):

- determination of the number and parameters of dangerous turns, service structures, and dangerous road sections in the mountainous road area selected as the object of research;

- determination of the slope and condition of the pavement;

- determination of the intensity of the traffic flow and the composition of the traffic based on visual and automatic monitoring tools.

Stage 2. Experimental stage (2023-2024):

- measurement of dangerous turn radii in the mountainous road area under study;

- recording the speed of vehicles in real time using GPS, radar or video surveillance;

- calculation of safe speeds taking into account the coefficient of adhesion of the pavement, road slope, and traffic flow parameters.

Stage 3. Final stage (2024-2025):

- justification of the need for mandatory speed reduction by comparing the permitted speed with the safe speed.

The experimental tests were carried out under the following conditions:

- dry coating conditions;

- wet pavement conditions;

- slippery or contaminated pavement conditions;

- time intervals with low, medium and high traffic flow.

The experimental results obtained on the basis of this program allow to determine the maximum and safe speed of vehicles in mountainous road areas, to assess dangerous areas and to scientifically substantiate measures to reduce the number of road accidents by mandatory speed reduction.

The mountainous area of the M-39 international highway, located in the area of 989–1013 km, passing through the territory of Jizzakh region, was selected as the object of research. These areas are characterized by complex geometric parameters, large longitudinal slopes, dangerous radii of curvature and limited visibility. In particular, as a result of high-speed movement of vehicles, the risk of road accidents increases in these areas [5,6].

The following parameters were measured and analyzed during the research:

Table 2

Measurable parameters

№	Measured parameter	Mar - king	Measurement method
1	Turning radius	R	Geodetic surveying, road plan analysis
2	Slope	i	Inclinometer, level or total station
3	Roadway width	B	Laser rangefinder, tape measure
4	Traffic flow intensity	q	Video surveillance and counting method
5	Movement speed	v	Radar, GPS or video analysis
6	Road surface friction coefficient	φ	Assessment by coating condition
7	Accident probability	P_{av}	Calculation based on a mathematical model

The main objective of the study was to assess the impact of road geometric parameters and traffic flow conditions on vehicle traffic safety and to determine the effectiveness of mandatory speed reduction measures.

The turning radius of the road is the main parameter in determining the safe speed of vehicles. The radius value was determined from the geometric plan of the road and using geodetic measurements on site.

The turning radius was estimated using the following formula:

$$i = \frac{h}{l} \cdot 100\% \quad (1)$$

where: i = road slope;

h - height difference;

l - horizontal distance.

The study adopted the basic value $i=12\%$.

The width of the road carriageway affects the stability and safety of the traffic flow. The width of the carriageway



was determined using a tape measure and the distance between the two edge lines was measured (Figure 1).



Fig. 1. The process of measuring the longitudinal slope of the road, the width of the roadway, and the flow of vehicles

The speed of vehicles was determined using a radar speedometer and video surveillance, and the results of experimental observation were recorded. The turning radius and slope of the road were determined using an electronic tachometer laser neville.

Table 3

Parameters calculated as a result of the experiment

№	Parameter	Symbol	Value
1	Car flow	q	1750 cars/hour
2	Slope	i	12 %
3	Turning radii	R_1 R_2 R_3	250 m 300 m 320m
4	Permitted speed	$v_{ruxetil}$	100 km/h
5	Current density	k	18 cars/hour
6	Model fitting coefficient	k_1	10^{-6}
7	Minimum level of accident risk	$P_{risk\ level}$	$0,025 \approx 2,5\%$
8	Geometric coefficient	K_g	1,12
9	Coefficients of association	φ_1 φ_2 φ_3	0,35 0,55 0,75

We will calculate the safe speed separately for 3 different conditions of adhesion coefficients ($\varphi_1=0.75$, $\varphi_2=0.55$, $\varphi_3=0.35$) for dangerous turning radii of 250 m, 350 m, 320 m at 994 km, 997 km and 1004 km of the mountainous areas of the M-39 international highway passing through the territory of Jizzakh region, which was taken as the object of research. We will calculate the safe speed using the following formula [7]:

For the determined safe speed values, the accident probability is recalculated. Pav.probability is calculated using the following formula:

$$P_{prob.accid} = 1 - e^{-\lambda} \quad (2)$$

$$\lambda = -k_1 \cdot q \cdot k \cdot \left(\frac{v_{xavf}}{v_{erkin}} \right)^2 \cdot \frac{(1+i)}{\varphi} \quad (3)$$

In the proposed model, the probability of an accident is determined by the parameters of the traffic flow, the speed ratio, the longitudinal slope of the road and the coefficient of adhesion of the pavement. Since the safe speed formula is formed exactly in accordance with the given permissible risk level, when the found safe value v is inserted into the formula for the probability of an accident, the result is the equality $P_{probability} = P_{risk.level}$. This confirms the internal logical consistency of the model.

The coefficient of adhesion in dry weather conditions (dry asphalt/concrete) for a turning radius $R=250$ m is determined by the formula (2,3) for the safe speed for 3 different adhesion coefficients ($\varphi_1=0.75$, $\varphi_2=0.55$, $\varphi_3=0.35$): The calculation results are given in Appendix 1. The accident probability for the found safe speed values is recalculated by the formula (3.4). The calculation results are given in Table 2

Table 4

Safe speeds depending on the coefficient of friction of the turning radius ($R=250m$)

Turning radius, m	Coefficient of friction	K_g	$v(\text{safe})$ speed km/h	$P_{prob. acc}$
$R=250$ m	$\varphi_1=0,75$	1,12	72,85 km/h	0,025
	$\varphi_2=0,55$	1,12	62,51 km/h	0,025
	$\varphi_3=0,35$	1,12	49,75 km/h	0,025

Thus, for a turning radius $R=250$ m, the following speeds were found to be unsafe in dry weather conditions: 73 km/h for the coefficient of friction $\varphi_1=0.75$, 62.51 km/h for the coefficient of friction $\varphi_2=0.55$, and 49.75 km/h for the coefficient of friction $\varphi_3=0.35$ (Figure 2).

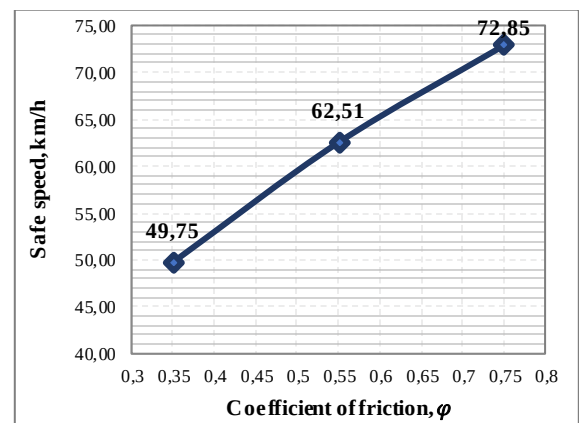


Fig. 2. Safe speed diagram depending on the friction coefficients for a turning radius of $R = 250$ m

The calculation results show that the accident probability is $P_{prob.acc}=0,0247$, which is close to the permissible value $P_{risk.level}=0,025$. Thus, the calculated speeds for a radius of 250 m are considered marginally safe for this road area.

3. Conclusion

According to the calculation results, it was found that the safe speed of vehicles on a mountainous road section with a

turning radius ($R=250$) m directly depends on the condition of the road surface. In dry weather conditions and with a coefficient of adhesion ($\phi_1=0.75$), the safe speed was 73 km/h. At a value of ($\phi_2=0.55$), which represents the condition of the wet surface, the safe speed decreased to 62.51 km/h. In dirty or slippery conditions, i.e. with ($\phi=0.35$), the safe speed was 49.75 km/h.

These results indicate the need to reduce the speed of vehicles as the adhesion properties of the road surface deteriorate. Especially on mountainous road sections with a small turning radius, high speed negatively affects the stability of the vehicle and increases the risk of sideslip, skidding and loss of control. Therefore, it is important to set the speed in curves with a radius of ($R=250$) m in accordance with the condition of the road surface.

As a result of the calculation, it was found that the probability of an accident ($P_{av,probability}=0,0247$), which is very close to the permissible risk level ($P_{risk,level}=0,025$). Therefore, the speeds determined for this radius are considered to be the marginal safe speed values. In other words, when driving above these speeds, the probability of an accident may exceed the permissible risk level [9,10].

The results obtained show that on turns with a radius of ($R=250$) m, the speed of 70–73 km/h on dry surfaces is relatively close to the safe limit, while on wet surfaces the speed should be reduced to around 60 km/h, and on dirty or slippery surfaces to 50 km/h. Therefore, it is advisable to adapt the speed to real road conditions on such road sections by using dynamic road signs, warning information panels and speed control devices.

The scientific significance of the approach proposed in the study is that the issue of determining safe speeds in mountainous road areas is solved by assessing the road geometry, traffic flow and pavement condition in a single system. In current practice, the speed limit is often set based on the general road category or administrative requirements. In this study, the speed limit is calculated in relation to the turning radius, adhesion coefficient, flow density and accident probability. This allows for more accurate and justified decisions to be made for dangerous sections.

The practical significance is that the developed model can be used by road organizations, traffic safety agencies and project organizations to assess dangerous mountainous road sections. The model provides justification for the need to set a speed of 70 km/h on which section and 50-60 km/h on which section. This methodology also serves as a practical basis for selecting the location of dynamic road signs, installation points for electronic information panels and speed control devices [12].

Based on the results of the study, it is recommended to use a three-level approach to speed control in mountainous areas. The first level is preventive warning, in which the driver is informed in advance before dangerous turns and slopes. The second level is a mandatory speed limit, in which a road sign is installed corresponding to the calculated safe speed. The third level is automatic control, in which drivers' compliance with the speed is monitored using radar, video fixation and sensors [12]. Thus, the developed mathematical model, calculation algorithm and practical recommendations can be considered as a comprehensive solution aimed at increasing traffic safety on mountainous roads, warning drivers in advance about dangerous situations and reducing the number of road accidents. To adapt this approach to the conditions of other mountainous roads, it is enough to include geometric, transport and pavement indicators of the

relevant section in the model.

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