RESEARCH ON VEHICLE COURSE STABILITY ON MOUNTAIN ROADS

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Abstract: *This study aims to develop a generalized indicator of vehicle course stability for mountain roads that simultaneously accounts for longitudinal and transverse road slopes, small-radius horizontal curves, the tire–road adhesion coefficient, vehicle dynamic parameters, and road transport and operational characteristics. Based on experimental investigations, a force-based calculation scheme describing vehicle motion under mountainous road conditions was developed. On this basis, a dimensionless course stability indicator was formulated, which characterizes vehicle stability as a function of road geometric parameters. For mountain roads with large longitudinal gradients and small-radius horizontal curves, an integral indicator combining road geometry and vehicle dynamics was obtained to assess vehicle motion stability on typical mountainous road sections.*

Keywords: *automobile, course stability, longitudinal and transverse slope, centrifugal force, turning radius, adhesion coefficient.*

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Introduction

Course stability is an essential component of active vehicle safety and reflects the ability of a vehicle to maintain a prescribed direction of motion under the influence of external disturbances. Vehicle operation in mountainous terrain is characterized by significant longitudinal and transverse road slopes, as well as frequent horizontal curves with small turning radii. Under such conditions, vehicle course stability is substantially altered. A vehicle traveling on a mountain road is simultaneously subjected to the longitudinal component of gravitational force, lateral inertial effects associated with mass distribution, and centrifugal forces arising during cornering.

The influence of road transport and operational indicators on vehicle motion dynamics under mountainous conditions is of particular importance. In most existing long-term studies, vehicle motion equations are formulated for flat road surfaces. However, according to the Construction Standards of the Republic of Armenia (RA Construction Standards)[1], road transport and operational indicators include pavement roughness (IRI index), a wide range of tire–road adhesion coefficients, pavement elasticity characteristics, transverse slopes for water drainage, and other parameters that are not explicitly incorporated into conventional vehicle motion equations.

At the same time, modern vehicles are capable of maintaining relatively high speeds even under difficult road-operating conditions due to the performance of contemporary internal-combustion engines. Under such circumstances, vehicle dynamics–and especially course stability–change significantly. This is confirmed by the substantial increase in road traffic accidents on the roads of the Republic of Armenia involving lane departure and roadway run-off, often resulting in severe consequences. Notably, many such accidents also occur on horizontal road sections [1,2].

Vehicle dynamics under the combined influence of these factors remain insufficiently studied; therefore, the present research is of both theoretical and practical significance.

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Materials and Methods

In the Republic of Armenia, the principal technical parameter for highway design in mountainous terrain is the permissible design speed: 70–90 km/h for categories IC–IA, 60 km/h for category II, 50 km/h for category III, and 40 km/h for category IV highways[2].

The design speed is defined as the maximum possible speed of a single vehicle that can be ensured by the main elements of the road under favorable weather conditions and normative values of the tire–road surface adhesion coefficient, while ensuring vehicle stability and driving comfort[3] [1].

In mountainous terrain, sharp changes in road alignment are permitted on category II–IV highways, resulting in the appearance of serpentines. The radii of horizontal curves in such sections may be as small as 15–30 m (depending on the design speed of 15–30 km/h) and may have a one-sided cross slope of up to 60 ‰ [4].

Even at relatively low speeds, vehicles operating in mountainous conditions experience significant lateral and longitudinal inertial loads that directly affect course stability.

The issue is particularly relevant for road trains, for which studies under mountain operating conditions are extremely limited. This is especially important for the Republic of Armenia, where approximately 75% of foreign trade cargo turnover is carried out by road transport, including road trains [1,2].

The objective of this study is to determine integral and dynamic indicators of course stability under mountain driving conditions characterized by small-radius curves and significant longitudinal and transverse slopes.

An integral indicator of course stability is proposed that incorporates both vehicle dynamics and road geometric parameters.

The research methodology is based on deriving an analytical expression for vehicle course stability under conditions of variation of the main factors that determine course stability in real operating conditions. Russian researchers assess vehicle course stability [3-5] using the integral steering wheel rotation angle during vehicle trajectory correction. In European countries, the assessment of course stability is based on the ISO 7401 and ISO 4138 standards[5,6,7]. Both approaches are acceptable and have been developed for flat road conditions. However, there are no studies addressing roads with complex mountainous terrain [6,7].

It is necessary to conduct analyses for continuously varying road parameters, such as the adhesion coefficient, vehicle speed, and the radius of horizontal curves, among others. As motivating factors, the condition of the road pavement, icing, crosswinds, and variable climatic conditions are considered, which in aggregate influence changes in the value of the adhesion coefficient.

Results and Discussion

The analysis of vehicle course stability on mountain roads is based on force equilibrium during straight-line and curved motion in the presence of longitudinal slopes. Under these conditions, the vehicle is affected by kinematic forces associated with curved motion and by gravitational forces acting at an angle to the road surface.

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[2] HH SHN 32-01-2022 "Avtomobilayin chanaparhner" Hayastani Hanrapetutyan shinararakan normer, 2022 (in Armenian).
[3] Ibid.
[4] Ibid.
[5] ISO 7401. This International Standard specifies open-loop test methods for determining the transient response behaviour of road vehicles. 2011.
[6] ISO 4138. This International Standard specifies open-loop test methods for determining the steady-state circular driving behaviour of passenger cars. 2015.
[7] ISO 7975. Passenger cars - Braking in a turn - Open-loop test method *specifies an open-loop test.* 2019.

Experimental investigations were carried out using the KP-514 mobile road laboratory and the PKRS-2 measurement system. A gyroscopic sensor was used to measure road azimuth, curvature radius, and longitudinal and transverse slopes, with a measurement accuracy of ±10%.

Experimental studies were carried out using a mobile laboratory vehicle KP-514 and a PKRS-2 complex (Fig.1). The change in the angle of the center of gravity vector during the straight course of the vehicle was considered as the vehicle drift, and the deviation angle was considered as a change in the course direction.

a. b.

Fig. 1. *KP-514 and PKRS-2 complex mobile laboratory.*
a. *the laboratory vehicle on a steep descent,* b. *the laboratory vehicle on a small-radius curve landing section*

The research was conducted on a characteristic section of 808 m of the national highway H-3: Yerevan-Garni-Geghard Monastery (38.1 km). The changes in the azimuth of the road traveled during straight travel and turns were studied.

1. The road passes through rugged terrain and has large longitudinal slopes and small-radius horizontal curves.
2. Changes in the vehicle's course stability were presented in tabular form (Table).

Table. The change in the course stability coefficient according to the sections of the road studied

Measured length of the road (m.)	Beginning (m)	The end (m)	Azimuth A°		The deviation of A°	Inclination angle (i %)	Course stability coefficient (K_c.)	Road section characteristics
			on the road at the beginning	at the end of the road				
20	0	20	195.440	198,360	2.92	0	1.12	straight uneven
53	20	53	198.360	200.430	2.07	7	0.695	large longitudinal slope
343	53	343	200.430	200.460	0.03	4	0.53	landing with a small radius curve
390	343	390	183.970	183.780	0.190	3	0.65	horizontal curve with a small radius
582	390	582	183.780	185.820	2.040	8	0.57	landing with a small radius curve
662	582	662	185.810	185.960	0.140	9	0.93	small radius uphill curve
808	662	808	185.960	184.270	1.620	1	1.05	low visibility

Measured data showed that the deviation angle varied from 0.03° to 2.92°. Vehicle speed ranged from 35 to 51.3 km/h, while the adhesion coefficient varied from 0.49 to 0.70. Road slopes ranged from 0 to 9%, and curve radii varied between 25 and 50 m.

The goal of the research is to develop a generalized indicator of automobile course stability that simultaneously takes into account the influence of the following factors:

- longitudinal slope of the road - i,
- the turning radii - R,
- transverse slopes - i_0,
- the adhesion coefficient - φ,
- the dynamic parameters of the car - D.

To solve the problem posed, it is necessary to:

1. Create a calculation scheme for the forces that affect a car when making a turn on a slope.
2. To develop a dimensionless indicator of course stability (K_c), which will reflect the stability of the vehicle to lateral obstacles, according to the geometric parameters of the road:

$$K_c = \int (\delta_\sum \cdot \alpha_y \cdot R \cdot i \cdot \varphi), \quad (1)$$

where, $\delta_\sum$ to the steering wheel is the total angle of rotation, α_y is the lateral acceleration, R is the turning radius, i is the longitudinal slope of the road, φ is the coefficient of adhesion.

To investigate the calculation scheme, let's consider a coordinate system related to the road, with the forces acting on the car in the x,y,z coordinate system (Fig.2) [7-10]:

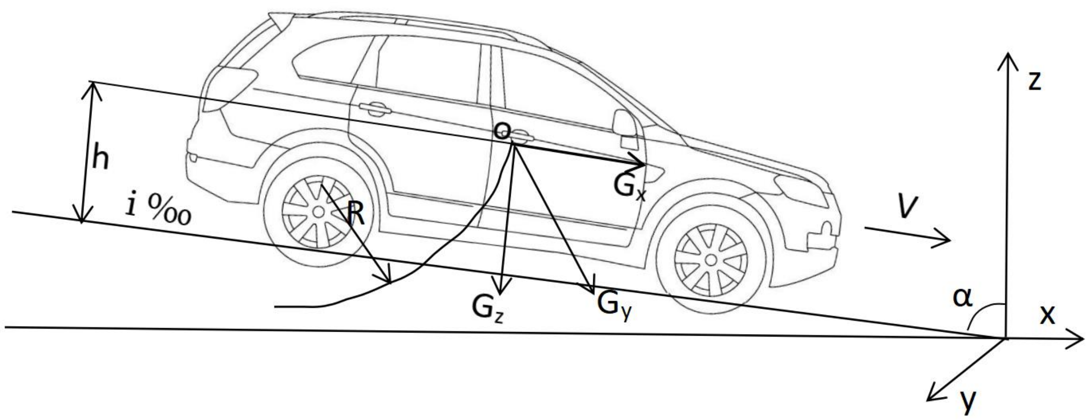

Fig. 2. *Forces Acting on a Vehicle During Cornering on a Longitudinally inclined Road*

The x-axis is directed in the direction of the longitudinal slope of the road, the y-axis is directed in the direction of the transverse slope of the road (direction of centrifugal forces), and the z-axis is perpendicular to the road.

In this system, the following forces act on the automobile:

1. The force of gravity, G = m·g, which has 2 components:
   - longitudinal $G_x = G \cdot \sin i$, (2)
   - normal $G_z = G \cdot \cos i$, (3)

where m is the mass of the car, g is the acceleration of gravity, i is the longitudinal slope of the road.

2. The centrifugal force of inertia F_c arises when moving along an arc of radius R and velocity v:

$$F_c = \frac{mv^2}{R} . \quad (4)$$

This force causes the car to skid and tends to turn the car perpendicular to the outside of the turn.

3. The lateral grip force of the tires F_y is the resistance of the road directed in the opposite direction of the centrifugal force and ensures that the car is kept in the intended trajectory, which ensures the car's resistance to sideslip:

$$F_y = \varphi \cdot G_z \,. \tag{5}$$

4. The lateral bending force (lateral force) can partially counteract the force F_c:

$$G_y = G \cdot sin\alpha \,. \tag{6}$$

5. The resistance force acting on the wheels is distributed to each wheel in proportion to its normal load:

$$\Delta Z_{1\text{-}4} = \frac{m \cdot h \cdot \alpha_y}{l} \,, \tag{7}$$

where h is the height of the center of gravity, l is the track width (the distance between wheels on the same axle).

The stability condition of the car is fulfilled if the sum of the lateral forces does not cause an increase in the lean angle. The lateral stability condition must satisfy the following expression:

$$F_y + G_y = F_c \,, \tag{8}$$

or in the open form:

$$\varphi \cdot G_z + G \cdot sin\alpha = \frac{mv^2}{R} \,. \tag{9}$$

From here, you can calculate the permissible speed of a car when turning on a mountain slope:

$$V_p = \sqrt{R \cdot g \cdot (\varphi \cdot cosi + sin\alpha)} \,. \tag{10}$$

Let's consider the dimensionless indicator Kc for vehicle movement in different modes and evaluate the vehicle's course stability based on the road's longitudinal slope (i), movement's radius of curvature (R), and transverse slope (α).

Using expressions (9) and (10), we can derive the vehicle's course stability rating (K_c):

$$K_c = \frac{F_y + G_y}{F_c} = \frac{\varphi \cdot g \cdot cosi + g \cdot sin\alpha}{v^2 / R} \,, \tag{11}$$

The stability criterion is defined as follows:

- $K_c > 1$: stable vehicle motion,
- $K_c = 1$: motion at the stability limit,
- $K_c < 1$: loss of tire adhesion and onset of sideslip.

Using the measured data, we calculate the vehicle's course stability according to formula (11) for the area:

$$K_c = \frac{\varphi \cdot g \cdot cosi + g \cdot sin\alpha}{v^2 / R} = \frac{0.47 \cdot 9.8 \cdot 0.999 + 9.8 \cdot 0.017}{14.6^2 / 50} = \frac{4.6 + 0.17}{4.26} = 1.12 \,.$$

The remaining precincts were calculated in the same way.

It means that the stability of the car is sufficient: $K_c = 1.12$ is greater than 1 according to formula (11). The calculation of the course stability is correct, and it is confirmed by experiments.

According to the data in the table, we construct a diagram of the change in the vehicle's course stability coefficient, K_c, according to the research site (Fig. 3).

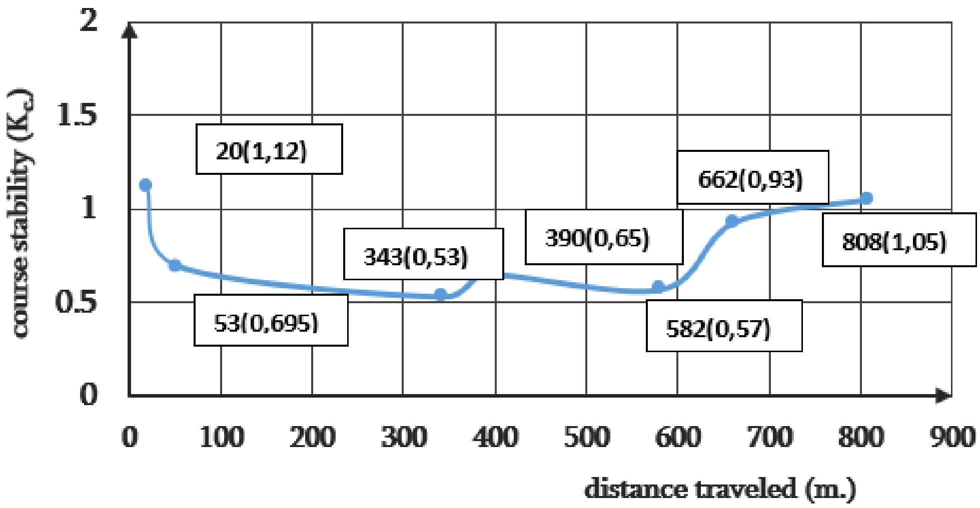

Fig. 3. *Vehicle stability control Diagram of change according to the tested site*

Conclusion

1. The proposed dimensionless coefficient K_c represents an integral indicator combining road geometric parameters and vehicle dynamic characteristics. It enables assessment of vehicle motion stability on mountain road curves.
2. Application of the proposed method makes it possible to identify hazardous road sections (black spots) in mountainous terrain and can be effectively used in the development of traffic safety improvement measures.

Conflict of Interest

The authors declare no conflicts of interest.

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