Classification of factors influencing the reliability of the driver-vehicle-road-environment (DVRE) system in the conditions of mountain quarries

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Abstract. The article provides a classification of factors affecting the efficiency of the DVRE system in operating conditions in mountain quarries. A detailed classification of factors affecting the reliability of mining heavy-duty dump trucks operating in mining quarries for such groups of features as design, technological, operational and road-climatic is provided. In addition, the article provides a classification of factors based on controllability. To assess the influence of the stochastic nature of external influences that determine the dynamics of the interaction of the vehicle with the roadway, rational methods based on probability theory are substantiated. Three of them are recommended for an adequate assessment of the influence of external influences on the output indicators of a career heavy-duty dump truck, in particular for evaluating the process of interaction of a vehicle with a roadbed, which is probabilistic in nature. Among the recommended estimation methods are included such as the method of approximating the external load with a periodic function such as a sinusoid with certain values of the amplitude and period of oscillation, the method of expanding the periodic function in Fourier series and the probabilistic-statistical method, which is based on taking into account the action of many random factors characterized by a stable frequency.

1. Introduction

The vehicle is a fundamental and most vulnerable element of the DVRE system and acts as a dominant factor in the formation of the system efficiency.

The DVRE system is both large and complex. The DVRE system is complex because it contains ambiguous relationships and regularities of the interconnection between its elements, the system is multi-criteria, and the processes taking place in it are stochastic, it is difficult to model the DVRE system. The DVRE system can be classified as complex because of its multidimensionality, diversity of the nature of elements, connections, heterogeneity of the structure, as well as because the system operates in the conditions of a significant environmental impact uncertainty. Its complexity is exacerbated by the random nature of changes in its indicators [1-3].

Almost all input and output parameters of the DVRE system are stochastic. The stochastic behavior of the DVRE system reliability is formed from the probabilistic nature of the reliability of each of its
components. The probabilistic nature of the DVRE system reliability is especially clearly manifested when heavy duty vehicles are operated in high-mountain regions on gravel roads. Among the elements of the DVRE system, the “vehicle” subsystem is the dominant element determining the complex stochastic nature of the system in general. The main assessment parameter of the stochasticity level is the oscillations of the vehicle’s tractive resistance, which is caused by such factors as: uneven torque and braking moments, as well as the vehicle speed, complexity of the ground profile, road profile and the condition of the road carpet, random distribution of the normal load on the vehicle axles and wheels, as well as frequency of maneuvers, etc.

2. Methods and Materials
Depending on the design-engineering features, operational modes and road-climatic conditions, the dynamics of the vehicle interaction with the road may differ. At the same time, depending on the number of external loads acting on the vehicle, their weightage, nature of action and dynamism, the interaction between the vehicle and the road can be conditionally classified as simple, medium and complex. As for the nature of the interaction of a heavy duty truck with a haul road in high mountain conditions, it can be definitely classified as complex, depending on many different factors and varying in rather wide ranges. At the same time, we should take into account that when heavy duty haul trucks are operated during the construction of high mountain hydraulic facilities (or when working in a high mountain quarry), there appear new factors which significantly differ from those met when the vehicle is operated on a plain [4-8]. These factors include the probabilistic nature of external actions on the vehicle, characteristics of the road carpet, altitude above the seal level, peculiar road profile, the condition of the yard, etc. The variety of the factors affecting the life and reliability of heavy duty haul trucks operated in the conditions of mountain quarries can be conditionally divided into three groups: design-engineering, operational and road-climatic (figure 1).

The actions of design-engineering factors by the composition and structure of the influence on the reliability of haul trucks are aggravated in severe extreme conditions of their operation in mountain quarries [9, 10].

The actions of road-climatic factors on the reliability of heavy duty haul trucks in mountain conditions are characterized by their probabilistic nature and are preconditioned by the altitude above the sea level, unevenness of the roadway, plan and profile complex road geometry, frequency of maneuvers, driving skills, etc.

Based on controllability, it will be expedient to divide the factors affecting the life of heavy duty haul trucks operated in the conditions of mountain quarries into three categories: fully controlled, partially controlled and uncontrolled (figure 2). The classification based on the controllability feature significantly differs from the classification based on the cause-and-effect feature. Despite the differences, these two classifications are of unrivaled practical importance for establishing ways to improve the reliability of the DVRE system.

The most significant factors determining the life of heavy duty vehicles operated in mountain quarries include the categories of operational and road-climatic factors by the cause-and-effect feature, and partially controlled and uncontrolled factors by the controllability feature.

The climatic factors, which are characteristic of mountain quarries and significantly reduce the life of heavy duty haul trucks, include such factors as the ground profile, road profile, type and condition of the road carpet, ambient temperature and altitude above the sea level [2, 3, 11].

The longitudinal profile of mountain haul roads is an alternation of rises and falls of different sizes and lengths, the complexity of which is preconditioned by the following circumstances [3]:
- a sufficiently large difference in the altitude above the sea level in individual road sections, where the longitudinal road grades reach 10-12% and even higher values in some short sections (both in the cross-section and longitudinal directions);
- construction of a road on mountain slopes, when the choice of the route of the constructed road is determined by the complex mountain terrain and landscape;
- random arrangement of the yard, etc.
Out of the many factors determining the reliability of heavy duty trucks operated in severe road-climatic conditions, the probabilistic nature of external actions on the vehicle is an important factor. Strictly speaking, all the factors determining the reliability of heavy duty trucks operated in severe road-climatic conditions are probabilistic in one or another way or fluctuate randomly. Despite this, the main factor forming the complex stochastic nature of external actions on the vehicle used for transport operations in the conditions of constructing high-altitude hydraulic facilities is the oscillation in the vehicle's tractive resistance. In turn, oscillations of the vehicle's tractive resistance are caused by the following factors: uneven torque and braking moments, as well as vehicle speed, complexity of the ground profile, road profile and road carpet condition, random distribution of the normal load on the vehicle axles and wheels, as well as frequency of maneuvers, etc.

As proposed by academician V N Boltinsky, oscillations of resistance forces of a heavy duty vehicle used for transport operations in the conditions of mountain quarries can be divided into two categories [4-6]:

**Figure 1.** Classification of factors affecting the life of heavy haul trucks operated in the conditions of mountain quarries.
• high-frequency (short-term periodic oscillations with a period of \( T \leq 1\ldots2 \) s and an insignificant amplitude), which can be overcome by the mass inertia of the heavy duty truck and almost do not affect the oscillations of its tractive resistance.

• low-frequency (oscillations with a period of \( T \geq 1\ldots2 \) s), mainly preconditioned by the joint manifestation of the above factors, which significantly affect the oscillations of the vehicle’s tractive resistance. They include: uneven moments on the wheels, vehicle speed, complex ground profile, road profile and extreme road carpet condition, random distribution of the normal load on the vehicle axles and wheels, as well as frequency of maneuvers, etc.

![Factors Influencing the Reliability of the DVRE System](image)

Figure 2. Classification of factors affecting the life of heavy haul trucks operated in the conditions of mountain quarries by the controllability feature.

Moving along such a road, a heavy duty haul truck is subject to the influence of the torque and braking moment which are probabilistic in nature.

Taking into account the probabilistic nature of external actions on the vehicle, the vehicle contacts the roadway in an unstable and dynamic mode, which significantly contributes to the development and acceleration of the decrease in energy, technical and economic indicators, as well as its safety margin and durability. The decrease depends on the value of the variation coefficient of the wheel torque and the tractive force of the vehicle. We can assume that the vehicle’s variation coefficient can be in the range of 10-15% depending on the complexity of the operating conditions (it increases with an increased load), while the energy, technical and economic indicators, as well as the safety margin and durability of heavy duty haul trucks, will decrease to 10%.
The influence of the oscillations of external actions determining the dynamics of the vehicle’s interaction with the roadway, depending on the sample size, the nature of the process, the condition of the object under study and other factors, is assessed by several methods based on probability theory. Three of them can be recommended for an adequate assessment of the influence of external actions on the output indicators of a heavy duty haul truck, in particular for assessing the process of the vehicle’s interaction with the roadway, which has a probabilistic nature:

- the method of approximating the external load with a periodic sinusoid-type function with certain values of the amplitude and period of oscillations [4];
- the method of expanding a periodic function in a Fourier series [5];
- the probabilistic-statistical method which based on taking into account the action of sets of random factors characterized by a stable frequency [6].

The first method proposed by academician V N Boltinsky to simulate the effects of the unsteady external load on an agricultural unit using a periodic function at fixed values of the amplitude $A_m$ and period $T_m$ of oscillations, can be used to simulate the effects of the unsteady external load (torque, power) on the wheels of a heavy duty vehicle, i.e.:

$$M_i(t) = \bar{M}_k + A_m \sin mt = \bar{M}_k (1 + 0.5\delta_M \sin mt),$$

where, \(\bar{M}_k = 0.5(M_{\max} + M_{\min})\) is the average value of the modulus of resistance on the vehicle wheels; \(A_m = 0.5\bar{M}_k\delta_M\) is the amplitude of oscillations; \(\delta_M = 2A_m / \bar{M}_k\) is the irregularity degree of the value \(M_k\); \(m = 2\pi / T_m\) is the frequency of a periodic oscillation; \(T_m\) is the oscillation period of the value \(M_k\); \(M_{\max} = \bar{M}_k (1 + 0.5\delta_M)\) and \(M_{\min} = \bar{M}_k (1 - 0.5\delta_M)\) are the maximum and minimum values of the modulus of resistance on the vehicle wheels.

The second method proposes to assess the influence of external actions by the method of expanding a periodic function in a Fourier series, the essence of which is as follows: if the periodic function \(f(t)\) with the period \(T_o\) satisfies the Dirichlet conditions, it can be approximated by the expression:

$$f(t) = A_o + \sum_{k=1}^{\infty}(A_k \cos k\omega_o t + B_k \sin k\omega_o t),$$

where, \(A_o\) is the constant term (average value of the function); \(k\) is the external harmonic order (k = 0; 1; 2; ...; \(\infty\)); \(A_k\) and \(B_k\) are the coefficients of a trigonometric Fourier series; \(\omega_o = 2\pi / T_o\) is the circular frequency of the first harmonic; \(t\) is the period of the first harmonic equal to the period of the function.

The coefficients \(A_o, A_k\) and \(B_k\) are determined from the expressions:

$$A_o = \frac{1}{T_o} \int_{T_o/2}^{T_o/2} f(t)dt;$$

$$A_k = \frac{2}{T_o} \int_{T_o/2}^{T_o/2} f(t) \cos k\omega_o tdt;$$

$$B_k = \frac{2}{T_o} \int_{T_o/2}^{T_o/2} f(t) \sin k\omega_o tdt.$$

To achieve the required accuracy and simplify the assessment of the influence of external actions on a heavy duty haul truck using the second method, in many cases it is sufficient to consider the first 10 ... 12 harmonics of the periodic function \(f(t)\).
The vehicle operation in the conditions of mountain and high mountain quarries can be assessed by
a complex probabilistic-statistical method using analytical dependencies according to the vehicle’s
deterministic (installation) features.

To determine the vehicle power or the vehicle wheel torque in the operating conditions, we can
apply the formula proposed by Professor S I Iofinov [11-14].

\[ N^o = N_0 \cdot \lambda_d \cdot \lambda_t \cdot \lambda_v, \quad (4) \]

where, \( N_o \) is the operating vehicle power according to the installation (deterministic) feature; \( \lambda_d \) is the
dynamic coefficient (proposed by academician V N Boltinsky), which takes into account the decrease
in the vehicle power under unsteady loads; \( \lambda_t \) is the time coefficient, which takes into account the
decrease in the vehicle power caused by wear, adjustments and aging of the vehicle; \( \lambda_v \) is the
probabilistic coefficient, which takes into account the change in the vehicle power caused by the
probabilistic nature of the factors determining the life of heavy duty vehicles in mountain conditions.

3. Results and Discussion

To determine the main probability and statistical estimates of the influence of factors determining the
vehicle life in severe road-climatic conditions of operation, it is advisable to use the method of random
argument functions, in which the input \( x \) and output \( y \) variables are determined by the deterministic
functional dependence \( y_i = f(x) \), which is established during the approximation of the vehicle’s typical
(installation) feature [15, 16].

Taking into account the probabilistic nature of the factors affecting the operation of the vehicle \( x_i \),
the output variables \( y_i \) are random values, the quantitative characteristics of which are generally
calculated by the following formulas:

- **mean value**
  \[ \bar{y} = \int_{-\infty}^{\infty} f(x) \phi(x) dx; \quad (5) \]

- **variance**
  \[ D(y) = \int_{-\infty}^{\infty} [f(x) - \bar{y}]^2 \phi(y) dx; \quad (6) \]

- **mean-square deviation (standard)**
  \[ \sigma_y = \sqrt{D(y)}; \quad (7) \]

- **variation coefficient**
  \[ \nu_y = \frac{\sigma_y}{\bar{y}}. \quad (8) \]

Notably, the low-frequency components of operational and road-climatic factors change according
to the normal distribution law \( y = f(x) \), which probability density function is calculated from the
expression

\[ \phi(x) = (\sigma_x \sqrt{2\pi})^{-1} \exp\left[-\frac{(x-\bar{x})^2}{2\sigma_x^2}\right], \quad (9) \]

where, \( \bar{x}, \sigma_x \) and \( \sigma_x^2 \) are the mean value, standard, and variance of the random value \( x \), respectively.

Thus, to obtain basic estimates of the reliability and durability of heavy duty vehicles taking into
account the probability and statistical nature of the factors affecting their reliability, we should...
establish the laws of distribution of the input $\phi(x)$ and output $\phi(y)$ variables, as well as the connecting functions $f(x)$ included in expressions (5) ... (9).

4. Conclusions
1. The factors related to operational and road climatic groups and determining the life of heavy duty vehicles in the conditions of mountain quarries are almost never manifested separately, and in most cases there is a complex combination of many factors. To this end, to determine the life of heavy duty vehicles in severe operational and road-climatic mountain conditions, it is necessary to use the system approach to assess the joint action of the factors.

2. To simulate the influence of a complex combination of many factors on the reliability of the vehicle as a dominant subsystem in the DVRE system, we can use the torque on the vehicle axles (vehicle power in serviceable conditions) or the vehicle’s tractive force as a combined indicator.

3. The vehicle power in serviceable conditions connected with the probabilistic nature of the factors determining the mileage changes in inverse proportion to the growth of the variation coefficient.

4. The power loss connected with an increase in the probabilistic nature of the factors is largely spent to reduce the reliability of the DVRE system in general, and to reduce the reliability of the vehicle and the road in particular.

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