Mobility of vehicles for transportation of heavy indivisible load in the Far North and methods of mobility estimation

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Abstract. The article presents a hierarchy of performance properties of vehicles for the transportation of heavy indivisible goods. Different methods can be used to determine the performance properties measures. The article presents the measurers of performance properties, the numerical values of which are obtained by using the method of mathematical modelling and simulation, the method of natural mathematical modelling and experimental methods of evaluation. The article identifies the problem of logistics in the Far North and in regions with no road infrastructure. The question under discussion is a burning question. The solutions to the problem have been discussed. One of the solutions to the problem is the development of new vehicles for the transportation of heavy indivisible loads in the Far North. For each vehicle it is necessary to take into account its functional purpose. Only a certain set of the most important performance properties should be taken into account. The most significant properties characterizing the mobility property are determined.

1. Introduction
At present, the Far North, which is rich in minerals, is being actively developed. In addition, other regions with a poor road network are also being developed. For the mining industries in these regions, there are a few problems associated with the need to transport large-sized equipment, shipping containers, construction materials and other heavy indivisible loads. One of the problems is the logistics in conditions with undeveloped road network. One way to solve the problem of transporting heavy indivisible loads by road and rail in these regions is to build roads and railroads, build the necessary infrastructure and maintain its operation, etc. However, the feature of the northern regions of the Russian Federation is hard environmental conditions with a lot of snow and extreme temperature fluctuations, so most vehicles that are traditionally used in the more southern territories of our country to transport loads cannot be operated in these regions. In addition, during the road and railroad building in the Far North it is necessary to take into account the following features of their use: frozen ground, weakly soils, high volume of snow in winter and increased volume of water objects due to the active snow melting in summer, etc. The above factors make it difficult or economically impossible to develop a road network in these regions. Thus, to solve the problem of transporting heavy indivisible loads in regions with an undeveloped road network and off-road conditions, the development of special vehicles is required.

The vehicle for transportation of heavy indivisible loads as any other vehicle is defined by a set of various performance properties: mobility, reliability, technical and economic properties and others. When estimating the performance of the taken technical solutions, it is necessary to consider a specific set of the most significant properties, which depends on the functional designation of the vehicle. The
The priority of the significance of performance properties is determined by the operating conditions. It is necessary to develop and scientifically explain the hierarchy of performance properties for the vehicles under consideration.

2. Hierarchy of performance properties of vehicles for the transportation of heavy indivisible loads in the Far North

Many scientists and scientific schools have researched the performance properties hierarchy of different vehicles and their significance. The works of the following scientists in the field of studying the significance of operational properties are well known: Y.L. Rozhdestvensky, A.V. Morozov, V.N. Naumov, M.Y. Dubensky, I.A. Pliev, M.V. Nagaitsev, M.R. Kalimulin, A.S. Dyakov, etc., as well as works of scientific schools of Bauman Moscow State Technical University, Military Academy of Armored Troops, JSC "Research Institute of Steel", 21 Research Institute of the Russian Federation Ministry of Defence, NAMI Russian State Scientific Research Center, Nizhny Novgorod State Technical University n.a. R.E. Alekseev etc.

Let us define a set of the most important properties of vehicles for the transportation of heavy indivisible loads. To do this, we consider their performance properties in more detail and develop a performance property hierarchy. This is necessary to be able to further analyse the design efficiency.

Vehicles for transportation of heavy indivisible loads are characterized by the following most important performance properties: properties by designation and operational and economic properties [1]. The properties by designation include only the property of mobility for such vehicles. The operational and economic properties include: capacity and payload, safety, reliability, ergonomics and economic properties (cost, unification level, duration of life cycle stages, etc.).

The developed hierarchy of performance properties contains 4 levels of performance properties, measurers and parameters. Figure 1 shows the top two levels of the hierarchy of performance properties.

![Figure 1. Hierarchy of top-level performance properties.](image)

For example, let us consider levels 1 and 2 of the hierarchy of operational and economic properties shown in Figure 2.
Figure 2. Operational and economic properties of levels 1 and 2.

Capacity and payload of vehicles are determined by the maximum permissible mass of transported load (capacity) and the maximum volume of transported load (capacity) [2]. The special feature of the considered vehicles is the necessary transportation of large-sized indivisible loads with known weight and dimensions, such as a transport container. The container simultaneously determines the available design space for the vehicle chassis and limits the possible design and layout solutions. In addition, the following technical requirements are considered: mass-dimensional limits, allowed values of total weight and axle load, as well as the strength and stiffness requirements of the carrying system and other requirements and constraints. Thus, due to the specific purpose and configuration and design limits, the property of capacity and payload may not be considered when assessing the significance of performance properties for the considered vehicles.

Safety is the most important complex property. Human life and health, safety of vehicles and goods, and environment depend on safety. The developed hierarchy of performance properties of vehicles for the transport of heavy indivisible loads is divided to active, passive, and environmental safety.

The design solutions providing passive safety include: keeping the survival space, reducing inertial loads during the impact, limiting movements of people and displacement of goods in the vehicle. They also include external passive safety design solutions. The listed factors are more applicable to the vehicle cabin design, to the task of saving the survival space and to the question of providing the necessary stiffness and strength of vehicle structural elements. At the current stage of science and technology progress the question of passive safety is widely discussed [3-12]. Known scientific methods and tools are used in the evaluation of passive safety. Therefore, the required passive safety parameters are defined in the technical requirements and the only fact that can be estimated is whether it is possible or impossible to satisfy the requirements.

Environmental safety of vehicles includes several actions to reduce the impact of the vehicle on the ground, toxicity and emissions. The requirements to the emissions of internal combustion engines, noise levels and other requirements are determined by regulating documents. Therefore, we will assume that the parts and assemblies used in these vehicles satisfy such requirements. In addition, the interaction of the running gear with the ground is discussed in detail in papers [13-16]. It is also necessary to consider the functional purpose of these vehicles. Thus, the environmental safety issue can be excluded from the analysis of the performance properties significance.
Therefore, when evaluating the performance of vehicles for the transportation of heavy indivisible goods, the parameters of passive safety and environmental safety are equally feasible or not feasible for all vehicles under consideration, so they are excluded from further analysis.

Active safety systems are designed to reduce the probability of failure or accident. Active safety is aimed at improving performance. Active safety is aimed at improving vehicle performance. It influences on the properties of stability, controllability, manoeuvrability and braking properties and is closely associated with the mobility property. Therefore, we will consider issues related to these performance properties in the analysis of the complex mobility property in terms of its increasing. We will not review the other requirements for lighting, alarms, etc., because we will assume that all the vehicles in question satisfy them.

The reliability is a complex property, which includes a combination of the following properties: safety margin, repairability, fatigue life and preservation ability. The reliability measures can simultaneously consider several (complex) properties or they can represent the measures that define only one property of reliability. As a rule, reliability parameters are previously defined by requirements of technical specifications. The task of reaching the reliability parameters at the design stage is only an engineering task. Besides, there are a lot of papers about the reliability issue [17-19]. Therefore, we will assume that reliability parameters will be reached for all vehicles under consideration at the current level of science and technology progress. Thus, in the future, we will not consider the complex property of reliability to determine the significance of the performance properties of vehicles for the transportation of heavy indivisible loads.

The ergonomic properties are formed taking into account the increase of operational efficiency and health protection of the driver and passengers. Engineers create designs that take into account human parameters. The ergonomic properties also refer more to the design issue of the cabin and the issue of secondary suspension, so we will not consider them in the analysis of the significance of performance properties.

The economic properties are formulated, taking into account the functional purpose of the vehicle. They will be defined mostly by economic properties of the transported cargo, so we will not consider the cost of the chassis, unification and life cycle stages in the analysis of the significance of performance properties.

Thus, in a complex performance analysis of the design and configuration solutions of the considered vehicles, the operational and economic properties can be excluded from the analysis.

Let us consider levels 1, 2 and 3 of the hierarchy of performance properties, defined by the purpose of the vehicle. Mobility is a property that characterizes the ability of the vehicle to cover a target distance for a target time without additional resources to keep it moving [1, 20-22]. Mobility is a complex property. The mobility structure of vehicles for the transportation of heavy indivisible loads is determined by more simple properties: cross-country ability, agility and self-supportability shown in Figure 3.

The performance property of cross-country ability determines the ability to move in difficult road conditions and off-road conditions, as well as the ability to pass different obstacles [22]. Cross-country ability is a complex property that is divided into more simple properties: flotation, cross-sectional flotation, fordability. The structure of the cross-country ability is shown in Figure 4.
Analyzing the papers [1, 2, 23-26], we can select the single properties, measures and parameters of flotation and cross-section flotation of vehicles for transportation of heavy indivisible loads. These properties are listed in Table 1 and Table 2. The fordability is determined by the depth of the ford with a hard bottom.
Table 1. Measuring the property of the flotation.

| Measure | Units   |
|---------|---------|
| **Traction properties** |         |
| Adhesive force | kN       |
| Adhesive force coefficient | -        |
| Total tractive force | kN       |
| Effective tractive force | kN       |
| Effective tractive force coefficient | -        |
| Drawbar force | kN       |
| Specific drawbar force | -        |
| Traction and speed characteristics | -        |
| **Traction-energy properties** |         |
| Vehicle power | kWh      |
| Specific power of vehicle | kWh/t    |
| Traction drawbar power | kWh      |
| Specific traction drawbar power | kWh/t    |
| Rolling resistance power | kWh      |
| Resistance to motion power | kWh      |
| Rutting power | kWh      |
| Relationship of rolling resistance power to vehicle speed | -        |
| **Ability to drive on snow** |         |
| Maximum depth of snow | m        |
| Minimum turning radius without loss of cross-country ability | m        |
| **Ability to drive on a supporting surface with poor load-bearing capacity** |         |
| Pressure of running gears on the on a supporting surface | kg/cm²   |
| Average contact pressure | kg/cm²   |

Table 2. Measuring properties of the cross-section flotation.

| Measure | Units   |
|---------|---------|
| **Ability to overcome individual obstacles** |         |
| Maximum width of the ditch to be passed | m        |
| Maximum height of the vertical wall to be passed | m        |
| Maximum height of the counterscarp to be passed | m        |
| **Ability to overcome gradients** |         |
| Maximum angle of climbing | degree   |
| Maximum angle of slope climbing | degree   |
| Maximum angle of going downhill | degree   |
| **Geometric parameters of the vehicles** |         |
| Vehicle geometric parameters |         |
| Ground clearance | mm       |
| Front and rear overhangs | mm       |
| Angles of front and rear overhangs | degree   |
| Longitudinal angle of passability | degree   |
| Longitudinal radius of passability | mm       |
| Transverse radius of passability | mm       |
| Flexibility angles of the road train in vertical and transverse planes | degree   |
| **Cornering ability** |         |
| Minimum turning radius of the vehicle | m        |
| Minimum distance from the center of rotation to the wheel axis of the outermost wheel track | m        |
| Overall turning radius | m        |

The performance property of the agility determines the ability of the vehicle to reach the destination of the route as fast as possible within the limits of the cross-country ability [1]. The complex property of agility includes simpler properties which are typical for the considered vehicles: responsiveness,
ability to drive over rough terrain, stability and control [1]. The structural diagram of the agility is shown in Figure 5. Analysing the papers [1, 2, 26-31], we can highlight the main single properties, parameters and measures of agility, which are shown in Tables 3 - 5.

**Figure 5.** The structure of complex agility property.

**Table 3.** Measuring the property of the agility.

| Measure                                           | Units  |
|---------------------------------------------------|--------|
| **Acceleration characteristics**                  |        |
| Maximum speed                                     | km/h   |
| Specific power                                    | kWh/t  |
| Traction and dynamic characteristics               | -      |
| Maximum overcome coefficient of resistance        | -      |
| Acceleration time to specified speed              | s      |
| Acceleration path to a specified speed            | m      |
| Maximum acceleration during acceleration           | m/s²   |
| **Braking characteristics**                       |        |
| Braking distance                                  | m      |
| Braking time                                      | s      |
| Maximum braking deceleration                      | m/s²   |
| **Dynamic climbing**                              |        |
| Limit length of the climb                         | m      |

**Table 4.** Measuring the ability to drive over rough terrain.

| Measure                                           | Units  |
|---------------------------------------------------|--------|
| **Cargo vibration safety**                        |        |
| Maximum speed                                     | km/h   |
| Specific power                                    | kWh/t  |
| **Physiological capabilities**                    |        |
| Frequency of natural body oscillations            | Hz     |
| Maximum acceleration in the driver's seat         | m/s²   |
Table 5. Stability and control properties measuring.

| Measure                                                                 | Units   |
|------------------------------------------------------------------------|---------|
| **Stability and controlled in a straight motion**                      |         |
| Critical braking speed                                                 | km/h    |
| **Stability and controllability during motion along a curvilinear trajectory** |         |
| Critical speed for turning manoeuvres                                  | km/h    |
| Critical driving speed when executing a "repositioning" maneuver       | km/h    |
| Critical speeds of steady-state curvilinear sideways rollover          | km/h    |
| Critical speeds of steady-state curvilinear lateral sliding motion     | km/h    |
| Critical speeds in directional and trajectory stability                 | km/h    |
| Static trajectory controllability characteristic                       | -       |
| Sensitivity to steering wheel rotation                                 | -       |

Autonomous performance property determines the ability of the vehicle to move without additional tools to support mobility [1]. The main property is the driving distance. It is divided by simpler properties: fuel (energy) travel, specific fuel (energy) capacity, and fuel tank (battery) capacity.

3. Conclusion

The developed performance hierarchy can be used to determine the priority of significance of the vehicle properties. Different methods can be used for a complex efficiency analysis of different possible design solutions. The most preferable, simple and taking into account all the properties of the vehicle is the method of the analytic hierarchy process. Analytic hierarchy process method is proposed for further benchmarking efficiency of vehicles for heavy indivisible loads transportation.

By comparing the performance properties, it is possible to generate a set of possible technical designs of newly developed vehicles for transportation of heavy indivisible loads. A comparative assessment of the performance of each possible design solution for newly developed vehicles is not possible without the development of its mathematical models and simulations. To solve the problem described above, a complex of natural-mathematical modeling can be applied. This approach makes possible to simulate the vehicle motion along statistically defined routes under a "driver-operator". The "driver-operator" is in front of the computer and everything happens in "real time" mode. It is required to have a task list and technical requirements for the designed vehicle to create a technical design of newly developed vehicles for transportation of heavy indivisible loads.

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