Transport Performance for Rough Terrain Sustainable Development

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Abstract: The article analyzes the issues of a quantitative assessment of the transport movement efficiency across the rough terrain. As a quality criterion, the vehicle energy costs are taken, conditioned by doing against rolling friction forces and load weight of the load. Simplifying assumptions for formula expressions of forces are formulated. Qualitative conclusions about the action of these forces depending on the road inclination angle were presented. The attainability domain concept is introduced for a specified consumption value of the resource. A transport indicator has been defined to compare accessibility areas with similar areas on the plain. A numerical method for determining accessibility areas was proposed, based on representing the relief using a weighted graph and determining the shortest distance tree within it. An integral over the territory indicator of the transport potential of a rugged terrain is considered.

1 INTRODUCTION

Modern socio-economic realities in the world are such that rough terrain territories (RTT), other things being equal, are usually considered less favorable for living, people, and business activity than their plain counterparts, like the difference between coastal and inland territories (Bezrukov, 2008). As a result, they are less populated and less attractive for doing business, with the exception of traditional types of activity, mainly, agriculture.

Meanwhile, to explain what is happening from a purely theoretical point of view, analyze why such a situation has developed, understand what factors result in a decrease in the potential for the social and economic development of RTT, sometimes turns out to be a non-trivial problem. However, without its solution, it is impossible to answer the question of how to increase the investment attractiveness of RTT, to attract people or living and win the world competition in the attractiveness of certain places. Finally, it is necessary to provide the socio-economic basis for RTT sustainable development for extended period of time, as the classics understood it (Meadows et al., 1972; Meadows, 1992; Forrester, 1974).

RTT occupy a significant part of the land. At the same time, they are often able to offer a whole range of unique characteristics for living and economy (Ivashkina and Kochurov, 2018; Wolfe, 2019). Therefore, it seems reasonable to use their potential for all mankind, integrate it into the world labor division (Podberezkin and Podberezkina, 2014)

The RTT development issues are very multifaceted and require an integrated approach to develop practical recommendations for each specific territory, depending on the profile of its properties and target objectives. This article will consider one of the most important factors for territory functioning - its potential in terms of the transport movement efficiency.

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2 RESEARCH METHODOLOGY

2.1 Impact of Rough Terrain on Transport Efficiency

The role of transport in the socio-economic development of the territory is so important that it can be named as one of the main reasons slowing down the economic growth of many RTT (Golts, 1981). In this case, this or that type of transport is not so important as its indicators when used for moving a unit of cargo or a passenger per unit of distance. These are issues of pure efficiency of movements. In this sense, the article continues research of work (Bobrik L.P. and Bobrik P.P., 2016).

As different types of vehicles have their own characteristics, a significant scatter of results can be obtained for different studies. To get qualitative conclusions, the article will consider road transport in its most general form as an example. The findings can be generalized with minor accuracy corrections for other types of movements. In the simplest case, we assume that the vehicle (V) is counteracted by two main forces: the rolling friction force of the wheel and the vehicle weight with its load. Since, as a rule, during movement RTT, the speed of movement is low, this allows, in a first approximation, to exclude from consideration the force of air resistance, parasitic vibrations of mechanisms, friction forces in bearings and restrict ourselves to only these two forces.

2.2 Rolling Friction

The rolling friction force is generally very complex and requires many different factors. Among these, surface types appear to be significant. But for our purposes, as will be shown below, to assess the influence of the rolling friction force on the efficiency of movements, it will be possible to use a simple formula.

$$F_{кач} = k\, {mg}/{r} \qquad (1)$$

Here m is the total vehicle mass and its load, g is gravity acceleration, r is the vehicle wheel radius. We will focus on the dependence on the vehicle mass and its load. As each vehicle has a constant wheel radius, this formula implies a linear form of this dependence for each specific vehicle.

The proportionality factor k varies significantly (by several times and even by orders of magnitude) depending on surface types, evident from Table 1.

Table 1: Approximate values of rolling frictional resistance for pneumatic car tires and various types of road surface (source: Wikipedia).

Road surface and its	Rolling resistance
Asphalt concrete in excellent	0.015-0.018
The same in satisfactory	0.018-0.020
Gravel surface	0.02-0.025
Cobblestone	0.035-0.045
Unformed road, dry	0.03-0.035
The same after rain	0.05-0.10
Sand, dry	0.15-0.30
Sand, wet	0.08-0.10
Snow road	0.025-0.03
Ice	0.018-0.02

From this table, an important conclusion can be made that if we do not take abnormal cases like dry sand, then the rolling friction force for cars usually amounts to several percent of the total vehicle weight with the load. As the car wheel radius rarely exceeds a third of a meter, then further in the article the total rolling friction coefficient of 6% of the body weight will be taken by default.

2.3 Lifting a Load Uphill

The main transport difference between a plain and RTT in terms of movement efficiency is the presence of slopes or hills. On the plain, such areas are also present, but the angles are much less marked, they are present less frequently so that they can be neglected in the first approximation.

In the case of a horizontal surface, the vehicle weight with a load does not generate any additional forces to the rolling friction force that impede movement, which is a natural advantage of such areas. But in rough terrain, extra effort is required when lifting. At the same time, for the downward movement, there is practically no compensation for the energy consumption, since the speed shall be limited for reasons of road safety, and the engine operates at approximately the same mode as when ascending to the same angle.

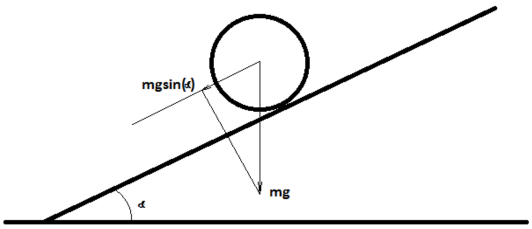

Figure 1: The forces acting on the vehicle during lifting.

If we consider the model problem (see Figure 1) when lifting a load on an inclined plane, then it is easy to conclude that an additional force is required for lifting, proportional to the sine of the lifting angle

$$F_{тяги} > F_{кач} + F_{тяж} = k\,{}^{mg}\!/_{r} + mg\sin(\alpha) = mg(K_{кач} + \sin(\alpha)) \tag{2}$$

It is known from the school mathematics course that at small angles (expressed in radians), the sine behaves almost like a linear function. But, as we must quantitatively assess the lifted load effect on the force required to move, we will propose a graph of the fraction of the gravity force that needs to be overcome depending on the ascending angle.

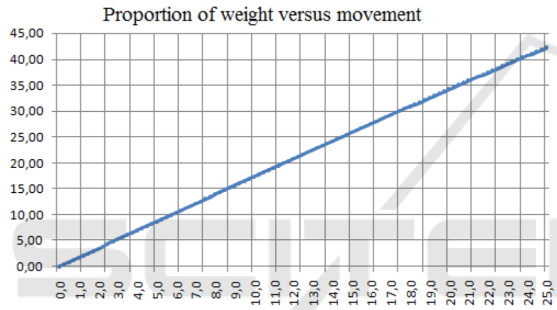

Figure 2: Weight proportion when moving uphill.

Although at first glance, the dependence is very similar to a linear one, it is not. From a practical point of view, the most important conclusion is that the force, required for movement, can be tens of percent of the body weight. For example, with an ascending angle of just over 10%, about 17% of the weight should be lifted. And thus the additional force can be higher than the rolling friction force, which, as can be seen from the section above, is a percentage of the body weight, even by an order of magnitude. The gravity effect becomes commensurate with rolling forces already at a few degrees.

This result is qualitative. It shows how unfavorable the rough terrain is in terms of transport as compared to a plain. For a similar movement in the mountains, it is required to apply the force, which is higher by an order of magnitude.

It is for this reason that road engineers are forced to build bridges and tunnels, so that there are no sections with a steep rise, although these are very expensive facilities to build and maintain (Biondini and Frangopol, 2012).

3 RESEARCH RESULTS

3.1 Accessibility Areas

One of the main quantitative approaches to assessing the efficiency of a particular mode of transport or their combinations is the approach based on the concept of accessibility areas (Bobrik, 2018).

In the most general case, the accessibility area is taken as the territory that can be reached from a specific point, after spending a certain amount of a particular resource. These resources may include time, travel costs, fuel costs, comfort levels, and many others. That is, this is precisely a general approach that can generate different definitions, depending on the problem.

For example, for megalopolises, transport accessibility is often calculated within an hour, which is largely explained by the physiological reasons of the human psyche, since after an hour the trip for passengers begins to seem tiresome. For international and intercity trips, as well as in geopolitics, the accessibility area per day is becoming more significant. For railway freight transport, it is not time that is of great importance, but the cost of transportation. Therefore, it is relevant to consider the accessibility area, for example, for a $ 1,000 tariff.

As it is obvious from the examples above, the accessibility area is a point characteristic. There are various methods of how to match this area with a certain numerical characteristic so that quantitative comparisons can be made in the future. The most common way is to estimate an accessibility area using its square area. But it is not the only one.

At the same time, quite significant fluctuations of this numerical indicator for different points can be observed for the territory. In this case, the average value of the accessibility area, averaged over the territory of districts or other small territories, gives a general idea of the transport of the territory. The averaging can be performed, among other things, over calculated ones (for example, a square cell), and not necessarily by administrative entities. It makes it possible to plot maps with any degree of detail or generalization.

Within the framework of this approach, it is possible to formulate an inverse problem. How many resources will be required to reach the accessibility area with the required numerical characteristic. For example, if for one city a million inhabitants can be reached on average in 50 minutes, and for another in 70 minutes, then we get a very visual characteristic for determining where it is better to start a new business from in terms of the transport component.

For rough terrain, the accessibility area can change very dramatically, at times, when laying roads with bridges and tunnels. It forms conditions for accelerated socio-economic development (Dettwiler and Schnelli, 1999). On the contrary, territories that received recharge based on their transit position to a large extent, with the appearance of bypass tunnels, can reduce their socio-economic potential (Knoflacher, 2001).

3.2 Quality Functional

A general approach based on accessibility areas can be applied to assess the transport potential of RTT. It will also allow for a quantitative comparison with a similar flat area. For this, first of all, it is necessary to strictly define the functional of the quality of movement. For RTT, it is proposed to take the energy consumption during the trip as a basis (Drozdov, 2014).

On a road with a slope, there is a sharp asymmetry in energy consumption when driving in opposite directions. Some drivers believe, that when driving along a mountain serpentine, you should stick to heuristic rule to go downhill in the same gear as when going uphill with the same inclination angle. If, when climbing to overcome the rolling force, it is necessary to additionally add overcoming the gravity of the load and the vehicle, which, as shown above, can require many times more energy, then when moving downhill, there is practically no relief, or it is much less than the additional energy consumption when lifting.

Therefore, in the simplest case, at an infinitely small displacement with a horizontal shift, the dl length and liting dh, we will calculate the energy consumption dE by the formula

$$dE = F_{качения}\, dl + F_{тяжести}\, dh \qquad (3)$$

On the same site, but with a slope, the energy consumption will be assumed to be

$$dE = F_{качения}\, dl\ . \qquad (4)$$

The proposed formulas are rough and even incorrect for many types of vehicles. For example, for rail transport, recuperation devices are quite common, when, when driving downhill, electrical energy is generated back into the mains. Although in less amount than was spent on the lifting to the same height. Among vehicles of various types, there is a very high spread in the values of energy consumption when driving downhill and when climbing. Usually, on steep slopes, the vehicle speed decreases, i.e. energy costs become higher than when driving on a plain. When moving on foot, there is practically no acceleration of movement.

Summarizing, the proposed formulas describe the average situation for a wide range of vehicles. They can only be used as a first approximation to obtain some general conclusions. However, even these formulas are already sufficient to get some conclusions when moving across rough terrain in the general case.

If some path γ is divided into infinitely small linear sections, then in this case the total energy consumption on the path will be calculated according to the classical integral formula of mathematical analysis

$$E_\gamma = \int_\gamma dE \qquad (5)$$

This formula allows us to calculate the total cost of energy when moving between two points, depending on the chosen path. If we determine a path where the minimum energy consumption will be achieved, then by doing so we can calculate the energy distance between any two points on the territory.

4 DISCUSSION

4.1 Representation of a Rough Terrain by a Graph

In the general case, a territory with a variable landscape is digitally set using a two-dimensional array, where each pair of geographic coordinates is assigned a numerical value of the height above sea level.

Let us take an arbitrary point P of the territory with coordinates (x, y) and height above the horizon $h(x, y)$. The problem is to calculate the shortest distances from point P to all the nearest points. To do this, let us assign an oriented symmetric graph to a specified territory G.

Divide the territory into squares with dx sides and dy, and calculate the height of the square as the height of its center. We assume that from the center of the square you can move to the adjacent squares to the left - right and up - down, as well as along the diagonals. If we designate a square as a vertex of a graph G, then each vertex in it will be adjacent to eight adjacent vertices, except for the boundary squares. The topology of connectivity in the graph looks like a cross on the British flag.

Let us determine the length of each edge of the graph according to formulas (3-4). If the height of point P is less than the height of adjacent point Q, then the length of the edge (P,Q) is calculated by formula (1), and the length of the edge (Q,P) is calculated by formula (2). And vice versa in the opposite case.

To determine the minimum distance between vertices P and Q, one can use Dijkstra's algorithm, widely used in practice (Kristofides, 1978; Ore, 2009). It determines the entire shortest-distance tree (SDT) (Emelichev, 1990) for the entire set of points in the area. Among the branches of this tree, there is also a path on which the minimum energy consumption between points P and Q is achieved. Moreover, there can be several such paths.

4.2 Indicators of Transport Quality of the Territory

The SDT obtained as a result of computer calculations makes it possible to answer a number of questions about the quality of the territory in terms of transport.

The SDT for each point allows you to determine the accessibility area for a given energy consumption by formula (5). P D_p It is also possible to calculate its area $S(D_p)$. As for a flat territory the accessibility areas represent a circle, comparing the area $S(D_p)$ with the area of a circle, we get the first indicator of the transport potential of the territory.

$$K_1 = \frac{S(D_p)}{S_{circle}} \qquad (6)$$

The physical meaning of the indicator K_1 is in how many times a smaller area we can achieve at a given level of energy consumption in comparison with a flat territory.

For the transport characteristics not of single point P, but of a certain territory G, you can consider the average value of the indicator K_1 on it.

$$K_2 = \frac{1}{S(G)} \int_G K_1(P)dP \qquad (7)$$

If a mountain village is selected as a territory, and the administrative region in which it is located is selected as the accessibility area, then using the indicator K_2 it is possible to assess the transport discrimination of the inhabitants of this village in comparison with the plain.

5 CONCLUSIONS

The article presents a new approach for assessing the transport potential of an area with rough relief, based on the concept of accessibility areas.

Two quantitative indicators are proposed that characterize the degree of transport discrimination in the territory.

An algorithm for the computer calculation of indicators was developed.

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