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ESTIMATION OF TRANSPORTATION ENERGY EFFICIENCY BY BARTINI CRITERION L6T-4

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Abstract

The review of performance and energy effectiveness of transportations reveals the lack of the squared delivery speed in their structure. The need to attract the squared speed as the major factor in forming the assessment of the energy intensity of the object motion and the medium resistance is noted. The author's approach to forming assessments of the transport energy intensity based on the use of Bartini's LT-systematization and the entity of *Transfer* with the measurement unit of *Tran* is considered. The energy effectiveness factor of cargo movement is represented in the form of the ratio between the inevitable dissipation of the cargo movement energy and costs of the energy supply of transportation, incurred by the automotive transport system.

As an example, the calculation of the transportation by KamAZ-5320 automotive vehicle is carried out. The value of the energy effectiveness of transportation with the speed of 60 km/h, calculated with the use of Transfer, amounted to η = 11.6 %. This allowed assessing the technological paradigm of the modern automotive transport as very far from the perfection.

Keywords

Automotive transport, energy, squared speed, LT-systematization, Tran, energy effectiveness, life cycle.

Introduction

There is no real-world object which could exist without a resource, the measure of which is energy (the value which characterizes the capability to perform an action). The main result of activities of the human society of all times is the concentration of energy.

Transport uses more than a quarter of all used energy resources of the planet for its operation. The process of energy advance from primary sources through a variety of power converters to a fleet of transport vehicles, and its subsequent transformation by this transport in transportation activities is essentially a logistical process (Kotikov, Lozhkin, 2006). The role of the global logistics manager belongs to the scientific and technical community of the planet. Transport workers adjoin this management at the last stage, i.e. execution of transportation operations and delivery of transportation services.

The main operational task of the transport operator is to deliver shipment to its destination right on time. At the same time, there is a constant struggle for increasing speeds of goods delivery within strategic and historical contexts.

Subject, problems and methods

Transportation is a very energy intensive type of activity. Assessment of its energy intensity is a relevant task of several centuries. In practice, a number of generally accepted indices are used for the assessment of the performance and energy effectiveness of transportation: t-km, km/l, mpg, kJ/t-km, BTU/(ton-mile), and others (International Energy Outlook, 2016; Transportation Energy Data Book, 2016). However, as a rule, they do not consider the object delivery speed directly, meanwhile, this is a very important factor of logistics. Besides, considering the energy cost factor, the most important is not even the speed, but the squared speed, since the energy of any motion (and the medium resistance to this motion) is proportional just to the squared speed of this process realization.

However, there recently appeared a possibility to develop a new methodological approach in assessing the energy effectiveness of transport and transport services provided by it, which would take into account the squared speed of the object delivery. This approach is related to the development of Robert Bartini's ideas on geometric LT-systematization of physics laws on the basis of a pair of coordinate parameters Length–Time (L–T) (Bartini, 1965; Bartini, Kuznetsov, 1974).

In 1855–1873, J. Maxwell advanced the idea that for construction of a system of measurement units only two units are required: the length and the time. In particular, he defined the dimensionality for the mass [L3T-2] (along with the designation of the dimensionality of any physical value in the form of square brackets).

Comprehension of this assertion lasted for a century: and since 1965, a number of publications by Roberto di Bartini, P. G. Kuznetsov, A. G. Aleinikov and others appeared, who obtained a number of important results (Bartini, 1965, Bartini, Kuznetsov, 1974; Obraztsova, Kuznetsov, Pshenichnikov, 1997; Aleinikov, 2007).

The kinematic system of physical quantities, proposed by Bartini (Table of Bartini (TB), see TB fragment in Table 1) (Aseev, 2012), consists of vertical columns representing a series of grades of *L* length and horizontal lines showing grades of *T* time. The intersection of each column and each line gives the dimensionality of one or another physical quantity of [L^R T^S] dimensionality, where R and S are integers.

Table 1. Matrix of physical laws and measurements

Time \ Space	L^1	L^2	L^3	L^4	L^5	L^6
T^{-6}			$L^3 \cdot T^{-6}$	$L^4 \cdot T^{-6}$	$L^5 \cdot T^{-6}$	Speed of capacity transition (mobility)
T^{-5}		Change of pres-sure	Surface capacity	Speed of force change	Power	Speed of energy transition
T^{-4}	Pressure gradient	Pres-sure	Angular accelera-tion of the mass	Force	Energy Work	Speed of transition of im-pulse moment **(tran)**
T^{-3}	Mass speed Current density	Gradient Viscosity	Mass discharge rate Current	Impulse	Mo-ment of Im-pulse	
T^{-2}	Linear accele-ration	Poten-tial of gravi-tational field	**Mass**			
T^{-1}	Linear speed	Speed of change of the square	Volume discharge rate	Speed of volume tran-sition		
T^0	Length	Square	Volume			

Horizontal lines of the table are trends of spatial resources. Dimensionalities of properties of all trend elements comprise the multiplier L+1, which is inherited from one property to another from the left to the right and is called the gene of the length. Similar to spatial trends, the concept of time trends is introduced; these are columns of the table. The time gene T-1 is transmitted from the bottom upwards from one property to another in columns. Also, the concept of real-field resources (RFR) is defined in the Bartini's table: it is the diagonal of the table, it runs from the left bottom to the right top. RFR trends form seven diagonals containing physical properties with dimensionalities of LmT-n, at |m+n| ≤ 3. All RFR trends transmit the velocity gene L1T-1=V+1 from generation to generation. The sum of power exponents of values laying on a separate trend coincides and differs from the sum of power exponents of values of neighboring trends by a unit (http://www.ruleright.ru/ruls-171-1.html).

Let us note the dimensionality of the following classical units: length — L^1T^0; mass — L^3T^{-2}; energy — L^5/T^4; power — L^5/T^5; transportation work in t-km — L^4T^{-2}.

Bartini also proposed the magnitude Mobility with the dimensionality of L^6T^{-6}. Further, Bartini together with P. G. Kuznetsov proposed a unit with the dimensionality of L^6T^{-4}, which represents *Displacement* (transmission at a distance) of energy (Bartini, Kuznetsov, 1974). Later, the name for the unit of Displacement was proposed (Obraztsova, Kuznetsov, Pshenichnikov, 1997); it was called "Tran" with the dimensionality of [L^6T^{-4}] = (t·km)·km²/h².

A. G. Aleinikov with his research group developed the BT (Aleinikov, 2007), having introduced nine new conservation laws into it. Also, Aleinikov suggested to call the unit of Mobility L^6T^{-6} as *Bart*, and the unit L^6T^{-4} as *Transfer* with the unit of measurement *Tran*.

We will follow this terminology in this article. Figure 1 shows the very part of the matrix of A.G. Aleinikov's laws we need as a canvas for our research.

According to the Figure 1, formation of the entity of *Transfer* can be represented as the product of the cargo mass *M* by the distance *L* (transfer of the cargo mass over this distance) with the formation of the mass displacement W_P in t-km, followed by multiplying the mass displacement W_P by the squared velocity V2, realized during this transfer (Kotikov, 2001; Kotikov, 2005a; Kotikov, 2005b; Kotikov, Lozhkin, 2006). If we take the mass displacement W_P as a measure of transport inertia, the conformity of motions can be noted: $W_P \cdot V^2 = S \sim M \cdot V^2 = E$.

Just like the squared velocity acts as a factor, reflecting the level of the capability to perform work (action) in the gravity field, for a physical body (with the mass as a measure of the body inertia), is also can act as a coefficient, reflecting the level of the capability to perform work (actions) in the economic field, for transportation (with the *Displacement of Mass* as a measure of inertia).

The use of *Transfer* should lead to such a stimulation system, which generally requires a higher rate of transportation. *Transfer* most accurately reflects the energy essence of the transportation process. This determines its role as a balancing energy criterion between supply and demand of transport services, since economic estimates of both demand and supply are ultimately based on energy resources and their costs. After all, the desirable high level of demand for the delivery speed meets with the needed energy costs (both depend on the squared delivery speed).

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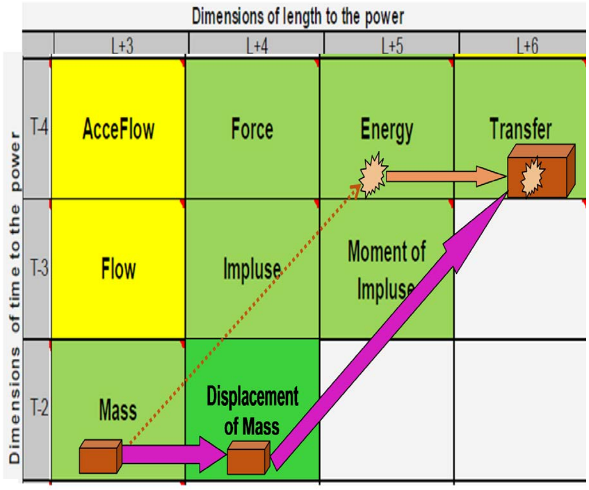

Figure 1. Part of Matrix of physical laws as a canvas for analysis

That means that *Transfer* is able to act as an appraiser of the transport service. Availability of the multiplier in the form of the squared speed in the structure of *Transfer* means for the customer that meeting the desired level of the delivery speed will cause an increase in the tariff rate (depending on the energy consumption), which would be in proportion to the increase in the squared speed of delivery.

The transport service *Transfer* of the size of 1 *Tran* is equal to the effective work spent for moving of a cargo with the mass of 1 ton over the distance of 1 km with an average-travel speed of 1 km/h. The dimensionality of this service unit is $t{\cdot}km^3/h^2$. Further, 1 tran = 1 t · $(km/h)^2{\cdot}km$ = 1,000 kg × $(1/3.6)^2$ m^2/s^2 × km = 77.16 J·km. Thus, 1 *Tran* can be represented as the energy with the value of 77.16 J, necessary for moving a 1-ton transportation object over 1 km under conditions of the Earth's gravitation field.

We meet two types of the capacity in the system of the cargo transportation: the capacity of the actual transport flow and the capacity of haulage operations and terminal and logistics facilities. Both capacities are aimed at achieving a common goal, i.e. to provide the necessary speed of delivery for the national economy (tor the supply chain).

The cargo transportation process includes a variety of loading and unloading operations and warehouse delays, which can take up to 80% of the total delivery time in the chain. It is inefficient to compensate cargo delays in auxiliary operations with the help of the higher speed of movement, as this leads to a sharp increase in fuel consumption and wear of the power installation. *Transfer* can play an important criterial role in optimizing distribution of energy costs for the realization of these two types of the flow capacity in the transport infrastructure. Also, the role of *Transfer* in the assessment of energy effectiveness as the transportation process in general, as well as its separate stages, can turn out to be high as well.

Case Study

Here is an example of forming the energy effectiveness assessment of the cargo transportation with KamAZ-5320 automotive vehicle.

The total energy consumption of the automotive transportation system for preparation and realization of the cargo transportation is aggregated based on components of energy consumption in the following fields:

1) manufacturing of automotive vehicles;
2) construction and maintenance of motor roads;
3) provision of fuel and operational supplies for transportation;
4) maintenance of machinery operation and activity of personnel;
5) traffic management;
6) loading and unloading, transport and storage operations;
7) communication and management of the transportation and logistics process;
8) disposal of transport structures as completion of their life cycle (LC).

However, the case study is restricted with the first four spheres. Let us use the methodological best practices and data of authors' works (Kotikov, 2001, Kotikov, 2005a, Kotikov, 2005b, Kotikov, Lozhkin, 2006).

If we compare the value of the Transport Service (in *Tran*), produced by one vehicle, with the total energy, consumed by the automotive vehicle system in transportation of cargo, then the energy effectiveness factor (EEF) of this transportation can be obtained.

Each of these four spheres has its own life cycle. Assessments of EEF generalized for four spheres, built on the basis of the life cycle of the transportation vehicle, will be the most adequate. Finally, accomplishing the calculation procedure, let us reduce all parameters to one kilometer of the automotive vehicle travel, since Tran/km has the dimensionality of Energy.

A KamAZ-5320 truck, carrying 8 tons of cargo with the speed of 60 km/h and running 50 thousand km per year, fulfills the annual volume of services $S_{year} = 8{\times}50000{\times}(60^2)$ = $1.44{\cdot}10^9$ tran = $1.44{\cdot}77.16{\cdot}10^9$ = 111.1 GJ·km. Covering the warranty run of 350 thousand km per 7 years (conditionally, it is the life cycle of the motor vehicle), it performs the volume of services for cargo transportation of S_{LC} = 111.1×7 = 777.7 GJ·km = 2.222 MJ x 350,000 km. That is, the “absolutely net” energy costs related to the service for transportation of the named cargo for the distance of 1 km with the speed of 60 km/h are equal to S_{km} = 2.222 MJ (and they do not depend on the type of the transport vehicle, but characterize the average level of energy scattering during movement of 8 ton weight at a distance of 1 km in the environment (in the gravity field) at the delivery speed of 60 km/h).

Let us consider the automotive vehicle as a cargo carrier, moving along a motor road: this is a structure with energy E_s provided during its production; the road with a part of the energy $E_{m.r.}$ put in it (reduced to a specific automotive vehicle); fuel, the energy E_{fuel} of which is used for movement of the automotive vehicle along the motor road in a viscous air medium and surrounding transport flows; expended operational supplies with energy $E_{o.s.}$ provided in them; energy costs for maintenance and repair, taking into account the energy provided in spare parts during their manufacturing and installation on the motor vehicle $E_{m.}$ and $E_{r.}$; other associated energy costs $E_{o.a.e.}$ The sum of the considered items of energy inputs is as follows:

$$E_{\Sigma LC} = E_s + E_{m.r.} + E_{fuel} + E_{o.s.} + E_{m.r.i.} + E_{o.a.e.} \quad (1)$$

The total energy costs for manufacturing of one KamAZ-5320 are E_s = *523 GJ*.

Total consumption of energy resources for construction of 1 m² of a motor road is $E_{r.c.}$ = 535 MJ/m².

Total energy consumption for one-time repair of the road surface is 290 MJ per 1 m². Considering the life cycle of the motor road of 30 years and repair interval of 7 years, i.e. three repairs, energy costs for repair works will be 290×3=870 MJ/m². That means that the energy put in 1 m² of such road is 535 + 870 = 1,405 MJ/m², taking into account all maintenance and repair operations performed on this road during its life cycle of 30 years. Then, 7 years of the automotive vehicle life cycle per 1 m² of the road will require the following energy consumption: 1,405 x 7/30 = 328 MJ/m².

Taking the width of the road lane of 4 m, the energy of 328 MJ/m²×4m = 1,311 MJ/m is put into one running meter of the lane during the life cycle of the automotive vehicle. Taking conditional traffic intensity along the lane as 2,000 vehicles/day, 2,000 × 365 × 7 = 5,110,000 automotive vehicles would run through the section of the lane in 7 years. Then, one motor vehicle traveling one running meter of the lane would consume the following energy of the road: 1,311 MJ/m/5,110,000*vehicle = 0.257 kJ/m·vehicle. Our automotive vehicle, having run 350 thousand km, uses $E_{m.r.}$ = 0.257 kJ/m·vehicle × 350,000,000 m = 90 GJ of energy put in the motor road).

Provision of fuel and operational supplies. Let us take the fuel rate of the automotive vehicle as 34 liters per 100 km, then the total fuel consumption for 7 years would be QF = 34 × 3500 = 119,000 liters. The amount of the chemical energy contained in the fuel is 119,000 liters × 35.3 MJ/l = 4,201 GJ. Besides, according to (Kotikov, Lozhkin, 2006), production of 1 kg of diesel fuel takes energy of 3.5 kWh/kg. Consequently, the industry inputs 3.5 kWh/kg × 0.83 kg/l × 3.6 MJ/kWh × 119,000 l = 1,244 GJ for manufacturing of 119,000 liters of fuel. Thus, the total amount of primary energy recovered through the fuel is E_{fuel} = 4,201 +1,244.5 = 5,445 GJ.

Operational supplies. The oil consumption is 2% of fuel consumption, i.e. 119,000 liters × 0.02 = 2,380 liters. The energy expended to produce such amount of oil is 50 kW×h/kg × 0.85 kg/liter × 3.6 MJ/kWh × 2,380 liters ≈ 364.3 GJ. Consumption of the antifreeze is 200 liters, which corresponds to the input energy of 4 kWh/kg × 1.07 kg/l × 3.6 MJ/kWh × 200 L ≈ 5 GJ. Consump-tion of lead is 70kg, which corresponds to the input energy of 23 kW·h/kg × 3.6 MJ/kWh·h × 70 kg ≈ 6 GJ (consumption of the antifreeze is 200 l, which corresponds (at specific energy costs for pro-duction of antifreeze of 4 kWh/kg) to the input energy of 4kW·h/kg × 1.07 kg/l × 3.6 MJ/kWh × 200 l ≈ 5 GJ. Consumption of the lead is 70 kg, which corresponds (at specific energy consumption for the lead production of 23 kW·h/kg) to the input energy of 23 kW·h/kg × 3.6 MJ/kWh·h × 70 kg ≈ 6 GJ. In total, $E_{o.s.}$ = 364 + 5 + 6 = 375 GJ.

Energy costs for maintenance and repair. Energy equivalent of materials (steel and cast iron, aluminum, copper, rubber, varnishes, chemicals, fuel) for repair and recovery needs of KamAZ-5320 (without spare parts) within its life cycle is 77.2 GJ / 350 thousand km.

Energy equivalent of materials (steel and cast iron, aluminum, copper, rubber (without tires)) in the form of spare parts for repair of the KAMAZ-5320 automotive vehicle is 34.7 GJ / 350 thousand km. Direct energy costs for maintenance and repair of the automotive vehicle KamAZ-5320 are 139 GJ / 350 thousand km.

Then, the total energy consumption for maintenance and repair (taking into account the energy put in spare parts during their manufacture and installation) is $E_{m.r.i.}$ = 77.2 + 34.7 + 139 = 251 GJ.

The sum of all energy costs, put in the transport service S = 777.7 GJ·km performed with the motor vehicle in accordance with the equation (1), is $\boldsymbol{E_{\Sigma LC}}$ = 523 + 90 + 5,445 + 375 + 251 = 6,684 GJ = 6,684 x 77.16 = 515,737 *Tran*. Calculating for 1 km, this value is $E_{\Sigma km}$ = 6,684 GJ / 350,000 km = 19.1 MJ/km.

Thus, to provide a transport service, i.e. the movement of the 8 ton weight cargo by means of KamAZ 5320 automotive vehicle with the speed of 60 km/h, with an inherent dissipation of the energy of the cargo movement per a kilometer of 2.22 MJ into the environment, 19.1 MJ of energy would be required to be put in the Motor transportation complex. The value η = S_{km} / $E_{\Sigma km}$ = 2.22 / 19.1 = 0.1162 = 11.62% is the index of the energy effectiveness of the transportation process fulfilled by the Motor transport complex, with KamAZ-5320 automotive vehicle in particular, at 60 km/h.

Conclusion

It would be quite reasonable to assume that when taking into account the energy costs for traffic management, loading and unloading, transport and storage operations, management of transport and logistics process, disposal of transportation system, the value of energy effectiveness η = $\boldsymbol{S_{km} / E_{\Sigma km}}$ will decrease. This is due to the fact that taking into account corresponding energy inputs will increase the denominator of the equation, and the inevitable decrease in the transportation rate (speed of delivery in the chain) will reduce the numerator of this equation.

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