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CALCULATION OF FREIGHT RAIL TRANSPORT ENERGY EFFICIENCY BY BARTINI CRITERION L6T-4

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Abstract

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. Author's approach to the calculation of freight rail transport energy efficiency is based on the use of Bartini Criterion L6T-4 and the entity of *Transfer* with *Tran* dimensionality. The energy efficiency factor of cargo movement is represented in the form of the ratio between the inevitable dissipation of the cargo movement energy and total costs of the energy supply of transportation, incurred by the railway complex.

As an example, the calculation of *Bothnia Line* railway complex freight transport energy efficiency was performed. Assessment of the railway complex freight transport energy efficiency at a speed of 120 km/h performed with the use of *Transfer* equals to η = 15.8 %. This allows assessing the technological paradigm of the railway transport as very far from the perfection.

Keywords

Rail transport, squared speed, *Transfer*, *Tran*, energy efficiency, life cycle.

Introduction

The objective of the author's studies (Kotikov, 2001, 2005a, 2005b, 2006a, 2006b, 2017) is to develop a new methodological approach to the assessment of energy efficiency of transport and provided transport services considering the squared speed of the transport object delivery. This approach is related to the development of Robert Bartini's ideas on *LT*-systematization of physics laws on the basis of a pair of coordinate parameters Length (*L*) – Time (*T*) (Bartini, 1965, 1974). The core of this approach is to form the ratio between the transferred transport output to the destination point (considering the squared speed of the freight transfer — transfer service S) and the specific embodied energy consumption of the transport complex for this freight transfer. Convergence of dimensionalities of two mentioned ratio variables is provided at the Transfer principle entity level with the dimensionality *L6T-4* (Aleinikov, 2007) of Bartini *LT*-table.

The case study that was examined in the work (Kotikov, 2017) with the example of freight delivery by means of a single truck KamAZ-5320 at a speed of 60 km/h has shown low energy efficiency (from the point of view of utilization of the full taken solar energy) of such freight transportation — up to 11 %.

In the present article, attempts to assess the energy efficiency of freight delivery by means of rail transport are made. Methodical extension with regard to the article (Kotikov, 2017) is the active use of the Life Cycle Assessment (LCA) for transport complex and execution of the design study covering energy costs of the main functional constituent elements of the complex: creation, technical support, working process (ISO 14040-2006 and 14044-2007; Arvesen, 2012; Chester, 2010; Jeswani, 2010; Kuczenski, 2016; Merchan, 2017; Yue, 2015).

Problems and methods

A fragment of R. Bartini *LT*-table (Bartini, 1965) in the interpretation of A. Aleinikov (Aleinikov, 2007) serves as a methodological canvas for the study (Kotikov, 2017) and is given in Figure 1.

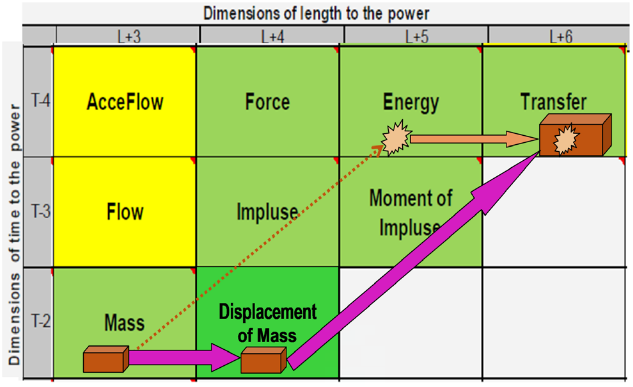

Figure 1. Part of matrix of physical laws as a canvas for analysis

The upper branch in Figure 1 (Mass – Energy – Transfer) reflects the freight mass transfer Mnet to the composition of the transport carrier, thus, forming the mass:

$M_{gross} = M_{net} + M_{carr}$. Here M_{carr} is a specific part of the transport carrier mass, associated with the freight mass M_{net}. Hereinafter, the mass M_{gross} with the energy consumption E_{Σ} is transferred over distance *L* to the destination point, thus, forming real value for *Transfer* S_{gross} index.

Here $E_{\Sigma} = E_{Emb} + E_{Supp} + E_{Input}$, where E_{Emb}, E_{Supp} and E_{Input} — utilization of specific parts of energy, respectively:

- embodied in the transport carrier and infrastructure;
- designed for technical support;
- input and directly consumed for transportation.

All three components are in shares associated with the mass Mgross and transportation distance *L*.

The dashed line from Mass to Energy means a relation between the Demand (object mass transfer) and Supply (availability of transfer means and infrastructure with preliminary embodied energy, as well energy for support and input).

The lower branch in Figure 1 (Mass – Displacement of Mass – Transfer) represents a pro-cess of the formation of the ideal, illusory assessment of transport service *Transfer* S_{net} (net-process) for abstract transfer of net-mass of the freight Mnet over distance *L* at speed *V*. Strictly speaking, the Customer is interested in the implementation of these factors (he is not interested in transfer of gross-mass M_{gross}, realized by an energy-intensive carrier under the conditions of the real transport complex).

Transfer of the transport object itself is absolutized. The object is transferred from the initial to the final point with conditional consideration of energy costs for overcoming of the Earth's gravitational field (proportional to the squared speed of the transfer). Everything connected with energy costs for manufacture of the transport carrier structure, erection of the traveling construct, overcoming of the carrier motion resistances, motion control, technical operation, etc. is put to the "upper branch". This provides a possibility of numerical assessment of the correlation between the transport object transfer by means of real transport under real conditions and the absolutized motion of the transport object which is the utmost effective to the geoid of the Earth.

The ratio $\eta = S_{net} / S_{gross}$ characterizes the level of excellence of the carrier type in the existing technological paradigm within the scales of the development of solar energy.

Let us make an attempt to calculate energy efficiency index η for rail transportations.

A distinctive feature of the calculation for the specific embodied energy of the transport complex using the author's method is the reduction of energy costs for the life cycle of all complex components to the life cycle of the transport carrier. Under consideration of the total mileage of the transport carrier within its life cycle, this provides a direct possibility to calculate energy costs for the performance of a particular transportation.

Case Study

Calculation for high-speed rail transport shall be conducted on the basis of the data of *Bothnia Line* located in the north of Sweden and put into operation in 2010 (Stripple, Uppen-berg, 2010; Trafikverket, 2017). It is a single-track high-speed rail line laid along the hilly and creeky coast from *Hoga Kusten* Airport through *Ornskoldsvik* to Umea.

The line allows movement at a speed of up to 250 km/h. However, operating speeds for freight traffic are limited at a level of 120 km/h (a calculation shall be performed for this speed below).

General characteristics of *Bothnia Line*:

- length of the trunk line — 190 km;
- total length of 140 bridges — 11 km;
- total length of 16 tunnels — 25 km;
- maximum axial load — 25 tons at a speed of 120 km/h;
- basic traction type — electric (95 %), 15 kV, 16 2/3 Hz AC;
- rolling stock — locomotive RE460 (*Loc 2000*) with standard cars;
- signal system — *European Rail Traffic Management System* (ERTMS);
- declarative annual volume of transported freight — 2,623,665 t/year;
- transport operation — 506,367,424 t-km/year;
- construction budget — 15 bln.

Warranty period for locomotive RE460 (*Loc 2000*) — 40 years. This time period shall be used as a basis for the Life Cycle Assessment, which, in its turn, shall define the energy efficiency index by analogy with operation (Kotikov, 2017).

As it can be seen from the general characteristics, Bothnia Line is sufficiently energy intensive object. The study (Stripple, Uppenberg, 2010) includes the detailed calculation of energy costs for construction (E_{Emb}), technical support of the infrastructure (E_{Supp}) and operation (E_{Input}) of this railway. These researchers performed an analysis of energy consumption as per the chain Extraction and processing of raw materials — Transportation — Manufacture of semifinished products — Transportation

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— Manufacture of structural elements — Transportation — Creation of *Bothnia Line* railway components.

The following components were included in the railway life cycle analysis:

1. Railway track foundation analysis.
2. Railway track analysis.
3. Railway electric power and control system analysis.
4. Railway tunnel analysis.
5. Railway bridge analysis.
6. Passenger station and freight terminal analysis.
7. Passenger and freight train traffic analysis.
8. Railway infrastructure analysis.
9. Railway passenger and freight transport analysis.

Let us provide the Life Cycle Assessment results with regard to energy consumption (Stripple, Uppenberg, 2010) in Figure 2. The figure shows general calculation results for the whole life cycle including energy consumption for construction elements, maintenance elements and all operation elements.

It can be seen that the entire system functioning life cycle requires energy consumption $E_{\Sigma LC}$ = 2.3 • 10^{10} MJ, including, for example, energy consumption for transport operations by means of constructed railway 1.21 • 10^{10} MJ (52.6% of all energy consumption).

The pre-defined annual volume of transported freight amounting to 2,623,665 t/year with forecast number of trains per year of 7,679 allows for the following: 2,623,665/7679 = 341.7 t/train. Thus, total transport operation of the locomotive for the whole life cycle on the railway *Bothnia Line* W_{LC} = 341.7 • 9,600,000 = 3,280,320,000 t•km.

The transport service *Transfer* of the size of 1 *Tran* is equal to the effective work spent for moving of a freight with the mass of 1 ton over the distance of 1 km with an average-travel speed of 1 km/h. Dimensionality of a unit of this service — t•km^3/h^2 (Kotikov, 2001, 2017).

Further, 1 *Tran* = 1 t•(km/h)^2•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 transport object over 1 km under conditions of the Earth's gravitational field at a speed of 1 km/h.

Train *Re 460 (Loc 2000)* while moving 1 ton of freight at a speed of 120 km/h over a distance of 1 km, provides the volume of services $S_{net.km}$ = 1 × 1 × (120^2) = 14,400 *Tran* = 14,400•77.16 = 1,111 MJ/t•km. That is, the "absolutely net" energy costs related to the service for transportation of the named 1-ton freight for a distance of 1 km at a speed of 120 km/h are equal to $S_{net.km}$ = 1,111 MJ (and they do not depend on the type of the transport carrier, but charac-ter-ize the level of energy scattering during movement of 1 ton weight at a distance of 1 km in the gravitational field at a delivery speed of 120 km/h).

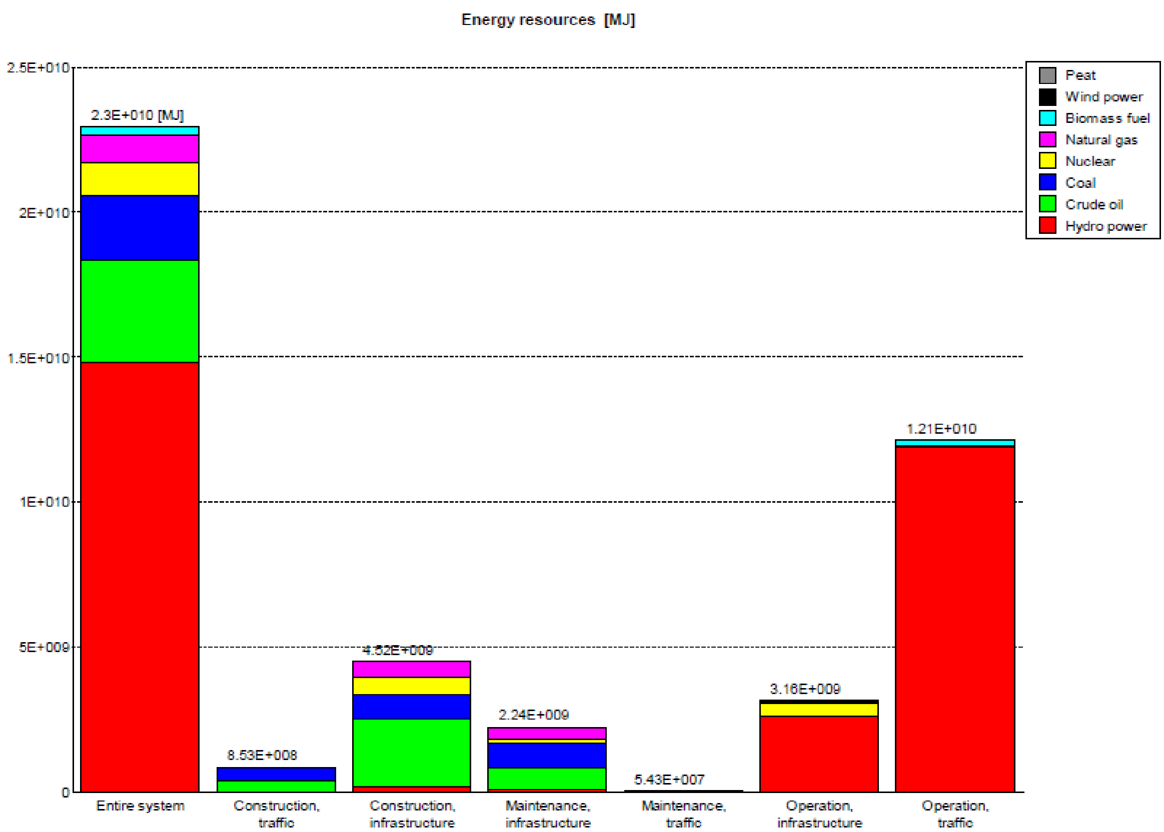

Figure 2. Use of initial energy resources for provision of the Bothnia Line railway life cycle

Then, total transport service of the railway for the life cycle (upon transportation of freights at a speed of 120 km/h) shall amount to S_{LC} = 1,111 MJ/t•km × 3,280,320,000 t•km = 3.644 • 10^9 MJ.

Thus, 2.3 • 10^{10} MJ of energy shall be embodied into the railway complex to render the transportation service — performance of transport operation of a value of 3,280,320,000 t•km with transportation of freights at a speed of 120 km/h (with the inherent dissipation of 1.111 MJ of energy for every ton of freight for every 1 km of transportation distance).

The value η = S_{LC} / $E_{ΣLC}$ = 3.644 • 10^9 MJ / 23 • 109 MJ = 0.158 = 15.8 % represents the energy efficiency index for the process of transportation at a speed of 120 km/h performed by the railway complex of *Bothnia Line*.

Conclusion

The obtained numerical value of energy efficiency of railway transport η = 15.8 % is rather conventional because the chosen example has sporadic character. Moreover, the provided study allowed, in the author's opinion, firstly, developing a methodical basis for the assessment of energy efficiency of transport objects on the basis of the entity *Transfer* of dimensionality L6T-4 and, secondly, comparing energy efficiency levels of two transport modes (as per the studies (Kotikov, 2006, 2017), for motor transport, η = 5–11%).

Apparently, levitation and space transport shall have high energy efficiency due to high transfer speeds and low resistances of motion environments. However, the data base for the corresponding assessments is of non-distinct character yet.

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