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FORMATION OF A FUNCTION SERIES FOR ESTIMATES OF TRANSPORTATION ENERGY EFFICIENCY BASED ON BARTINI'S LT-TABLE ENTITIES

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Abstract

A function series for estimates of transportation energy efficiency is formed based on Bartini's LT-table entities. The study represents a follow-up of the method provided by the author to estimate transportation energy efficiency based on the Bartini's L6T-4 entity. The Bartini's LT-table, supplemented by Aleinikov, is adjusted using system representation of the energy series of entities: Energy–Linergy–Arergy–Volergy. Methodical specifics of obtaining transportation energy efficiency estimates for 1D, 2D and 3D spatial objects are considered. A numerical analysis of transportation in a 2D zone is carried out following a hypothetical example of daily commuting in the Saint Petersburg agglomeration.

Keywords

LT-systematization, Bartini's L^mT^{-4} entities, Energy, Linergy, Arergy, Volergy, megacity, agglomeration.

Introduction

Estimation of transportation and logistics energy intensity is a topical issue (Kotikov, 2006). The issue is becoming more relevant with an increase in movement speed, transportation scale, coverage, as well as with development of new types of vehicles, power plants and fuel (Kotikov, 2006).

Logistics made the way from one-off deliveries to supply chains (4PL) and reached the level of network deliveries (5PL). At this development stage, one of the possible ways of subsequent methodological improvement of the logistics apparatus is mastering methods of transfer from network models to field models. Another way, in the light of developing space and air (Kotikov, 2018; Leonov, 2010) transport, three-dimensional distribution logistics (high-rise warehouse terminals, office and residential skyscrapers, etc.), is development of the optimization modeling of three-dimensional networks and fields.

The listed aspects require to develop methods to estimate energy efficiency of engineering systems in terms of the requirements of the future technological paradigm. In his previous papers, the author of the article used the Bartini's LT-table L6T-4 entity to develop new methods for energy efficiency estimation (Kotikov, 2006, 2017a, 2017b, 2017c). The applicability of the method based on this entity to estimate linear deliveries of cargo was shown.

In this study, a task of developing criteria and techniques for 2D and 3D options of distribution logistics based on Bartini's LT-table entities and constructing a function series with dimensionalities ranging from 1D to 3D is set.

The author's adjustment of several concepts and terms introduced by his predecessors based on Bartini's LT-table entities is deemed to be important.

Method development

Proceeding from the Maxwell's idea (1873) on the possibility of constructing a system of measurement units based on only two units — length L and time T — Bartini systematized and arranged all physical values in

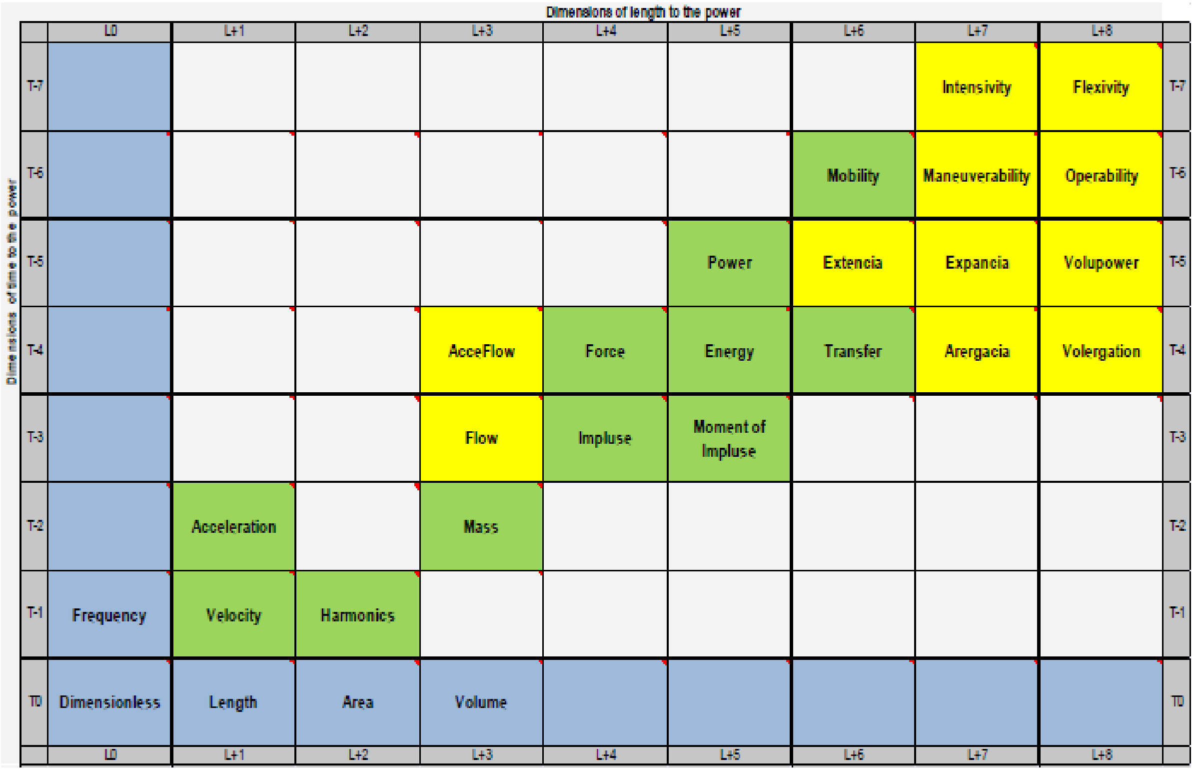

Figure 1. Matrix of physical laws and measurements

powers of L^m and T^{-n} in a special LT-table (Bartini, 1965). Let us specify the dimensionality of the following standard kinematic quantities in L-T coordinates: length — L^1T^0; mass — L^3T^{-2}; energy — L^5T^{-4}; moment of mass — L^4T^{-2}, m^4 / s^2 (in accepted units of transport work, t·km, through the conversion coefficient). In collaboration with Kuznetsov, Bartini suggested a quantity with dimensionality L^6T^{-4}, m^6/s^4, representing transmission of energy over a distance (*Transfer*) (Bartini, 1974). Later Obraztsova and Kuznetsov (Obraztsova, 1997) suggested a name for the transport version of this unit: "Tran" with dimensionality $[L^6T^{-4}]$ = (t·km)·km^2/h^2.

In 2006–2011, Aleinikov, in collaboration with his US scientific team, filled 11 empty cells of the Bartini's LT-table with the corresponding peer entities and developed physical laws for the conservation of those entities. After the addition of those entities, the original Bartini's LT-table took on a form depicted in Figure 1 (Aleinikov, 2011). The table cells filled with the above-mentioned 11 new entities are colored in yellow.

Since 2001, the elaboration of the methodological approach to the estimation of transport and transportation energy efficiency, considering the squared delivery velocity, has been associated with the development of Bartini's ideas on geometric LT-systematization of physics laws, as well as ideas of Obraztsova and Kuznetsov (Kotikov, 2001).

Several author's studies (Kotikov, 2006, 2017a, 2017b, 2017c) show that the vehicle output and energy consumption should be brought into correlation with each other (to obtain a dimensionless efficiency coefficient) at the level of the Transfer entity in the L6T-4 cell.

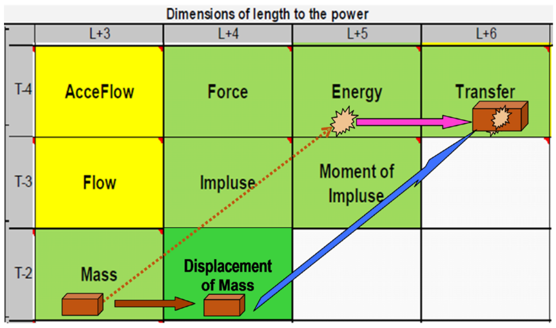

Figure 2. A diagram of output and energy consumption correlation at the level of the Transfer entity on the Bartini–Aleinikov's LT-table canvas (Kotikov, 2017a)

The author also points out that it is necessary to multiply the output (formed in the L4T-2 cell) by the squared velocity of cargo transfer, which corresponds to the diagonal transition within the table by two levels to the right and up: see a Bartini–Aleinikov's LT-table canvas fragment in Figure 2.

Identification of method variables and indicators according to the diagram in Figure 2 is given in Table 1. Let us note that the Linear transport work (Output W_1) and Linear transport service S_1 in this loop (see arrows in Figure 2) are taken with index "$_1$", which means D1 dimensionality and point-like nature of a serviced spatial object.

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Table 1. Identification of method variables and indicators according to the diagram in Figure 2

	L^3	L^4	L^5	L^6
T^{-4}		Force, N	Energy *E*, J	Transfer, Trn (Linear transport service S_1, t·km³/h²)
T^{-3}		Impulse	Moment of impulse	
T^{-2}	Mass, m³/s² (Mass *M, t*)	Moment of mass (Linear transport work (Output W_1), t·km)		

Further development of the methodology is construction of a series of estimates for spatial spheres' servicing based on Bartini's LT-table entities

In author's studies (Kotikov, 2001, 2006, 2017a, 2017b, 2017c), a methodology for energy efficiency estimation regarding vehicles and means of transport upon linear transportation (over the network) of transportation objects, with account for cumulative energy consumption during the life cycle of vehicles, was formed.

However, in areas with high business activity and the large number of goods and people, the pattern of distribution is as if "blurred" by the law of large numbers, smoothed down, switching from the network configuration to the field one. Some other transport phenomena also have field character: dispersion of exhaust gases over the area; noise fields; irrigation of agricultural fields, fire areas, etc. Visualization of transition from the network model to the field model is shown in Figure 3.

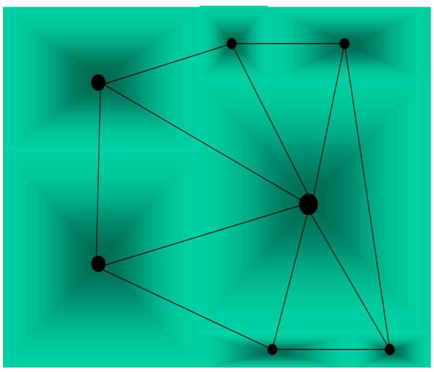

Figure 3. Transition from the network model to the field model

A similar picture becomes more and more relevant in a three-dimensional version: e.g. dispersion of exhaust gases in the volume over the city, coal heaping in open terminals, distribution of people in the 3D volume of a skyscraper (up to 10 thousand people in dozens of skyscrapers in Shanghai), etc.

By analogy with the linear case, when the author used the Bartini's LT-table *Transfer* L6T-4 criterion (see Table 1) to estimate cargo transportation energy efficiency, we will develop criteria for cases of utilizing the energy spent on transportation, upon the area (2D) and volume (3D) distribution of goods and/or people massifs.

For this purpose, let us use the Bartini–Aleinikov's matrix (Figure 1). Let us select the {L3–L8; T-2–T-4} fragment. As it was shown previously (Kotikov, 2017a, 2017b, 2017c), in case of linear transportation of cargo/people to a delivery/destination point, the *Transfer* entity (table cell) was used for the concentration of service S_1 and corresponding energy consumption *Trn*. In the energy layer of entities (T-4 row), it is the following product: Energy × L = Transfer (L6T-4 entity).

In case of cargo/people distribution throughout the area of delivery, it will be required to multiply the energy consumed by L². It is Arergacia = Energy × L × L (L7T-4 entity) on the Bartini–Aleinikov's canvas (Figure 1) (in another article, Aleinikov uses the Arergation term).

In case of cargo/people distribution throughout the volume of delivery, it will be required to multiply the energy consumed by L³. It is Volergation = Energy × L × L × L (L8T-4 entity) on the Bartini–Aleinikov's canvas (Figure 1).

Let us specify characteristics of new concepts (Arergation (Arergacia) and Volergation) in the form suggested by Aleinikov in 2007 (Aleinikov, 2007).

The Arergation entity (derived from **ar**ea + **erg**on) represents area distribution of energy. Its measurement unit is *Sergal*. The Law of Arergation Conservation has the following form:

Arg = Trn × L = L7T-4 = const;

1*Sergal* = 1Tran × 1m = 1J × 1m².

The Volergation entity (derived from **vol**ume + **erg**on) represents volumetric distribution of energy. Its measurement unit is *Natal*. The Law of Volergation Conservation has the following form:

Vrg = Arg × L = Trn × L2 = L8T-4 = const;

1*Natal* = 1*Sergal* × 1m = 1*Tran* × 1m² = 1J × 1m³.

This is a powerful scientific innovation. However, the following critical remark can be made (which in no way derogates from the merits of the Aleinikov's school): the names of entities are non-systematic. Moreover, Aleinikov even used people's names for measurement units. To construct a series, a systematic approach is preferable even in name creation. Let us try to perform this task.

Let us assign to the entities of the energy series (elements of the Bartini's LT-table T-4 row) names consonant with the *Energy* term (where the -gy particle carries the general meaning of the entity):

- let us replace *Transfer* with ***Linergy*** (derived from **lin**ear + **erg**on);
- let us replace *Arergation* (also known as Arergacia) with ***Arergy*** (derived from **ar**ea + **erg**on);
- let us replace *Volergation* with Volergy (derived from **vol**ume + **erg**on).

Using the above, we can build a diagram (see Figure 4) on the Bartini's LT-table canvas.

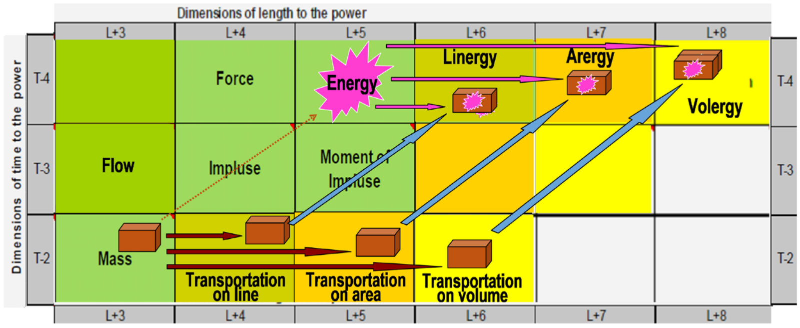

Figure 4. A new toponymy of entities and connection between them

Besides, we will use the -ation suffix (used in English for the formation of verbal nouns with process meaning) to identify the corresponding transfer processes (similar to the Transport–Transportation pair of related concepts):

- for linear transfer of energy — ***Linergation***;
- for energy distribution throughout a 2D area — ***Arergation***;
- for energy distribution throughout a 3D sphere – ***Volergation***.

It is presented in Figure 5 which can be considered a detailed elaboration of the diagram in Figure 4. Loops 1, 2, 3 in the corresponding table cells compare energy consumption for an idealized cargo transfer with the actual reduced energy consumption of the transportation system (see the methodology suggested by the author (Kotikov, 2017c)).

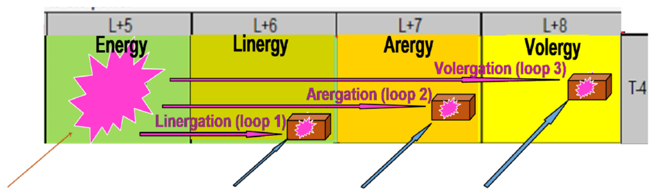

Figure 5. Detailed elaboration of Bartini's LT-table T-4 energy series concepts

Notations of quantities representing entities (similar to how *A, E,* or *W* represent the entity of *Energy*) are as follows:

for *Linergy*: *Lrg* with measurement unit Jm1 (derived from $J \times m^1$);

for *Arergy*: *Arg* with measurement unit Jm2 (derived from $J \times m^2$);

for *Volergy*: *Vrg* with measurement unit Jm3 (derived from $J \times m^3$).

Identification of new method variables and indicators according to the diagram in Figure 4 is given in Table 2.

Table 2. Identification of method variables and indicators according to the diagrams in Figures 4 and 5.

	L^3	L^4	L^5	L^6	L^7	L^8
T^{-4}		Force, N	*Energy E*, J	*Linergy, Lrg* (Linear transport service S1, t·km³/h²)	*Arergy, Arg* (Transport service of area distribution S_2, t·km⁴/h²)	*Volergy, Vrg* (Transport service of volumetric distribution S_3, t·km⁵/h²)
T^{-3}		Impulse	Moment of impulse			
T^{-2}	Mass, m³/s² (Mass *M*, t)	Linear transport work (Output W_1), t·km	Transport work throughout area (Output W_2), t·km²)	Transport work throughout volume (Output W_3), t·km³)		

Case Study

Let us give an example of calculation for two-dimensional distribution of transport work throughout the area (with regard to transportation in the megacity territory).

For a start, let us consider a simple analogy — area irrigation with a sprinkler with one sprayer (see Figure 6) (Frolova, 2017). The service of water distribution throughout the area of sprinkler coverage S2 consists in supplying a mass of water with a certain supply rate and more or less uniform distribution of this mass over the service area.

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If we refer to the sprinkler, then its *Arergy* is the energy spent by the system of water supply to deliver it to the nozzle and spray, multiplied by the spraying area. The service rendered by the system under consideration consists in area irrigation. This service is proportionate to the area serviced. That is why in this case the area is rightfully included into the *Arergy* criterion as a multiplier.

The scheme can be complicated by various sprinkler options and their systems (stationary sprinklers with multiple sprayers; single mobile sprinklers; systems of mobile sprinklers) providing both grid and contour irrigation (when irrigation is carried out using mobile devices moving only along the perimeter road (see Figure 7)) (Frolova, 2017). This latter option can be used as an analogue for the megacity issue.

Figure 6. Field character of water distribution using a stationary sprinkler with one sprayer

Let us note here that in all cases water (agent) is taken from some source (resource), and the calculation of *Arergy* should account for cumulative energy consumption not only for the actual spraying, but also for the operation of mobile devices, provision of water resources in the source (a canal, a reservoir), or, more precisely, energy consumption in the entire irrigation system.

The scheme under consideration can be easily applied to transportation and logistics in a zone or region. The simplest cases are production points, distribution centers, etc. But in case of production and distribution networks, point sources located at network nodes, jointly serve the territory by analogy with spraying (irrigation). Transportation in a city when importing the mass of commodities along outbound routes can be given as an example.

Let us return to Table 2. Linear transport output W_1 represents standard transport work in t·km.

Similarly, to bring the output for the area served W_2 (see Table 2) in correlation with the corresponding energy consumption, we multiply it by the squared velocity of cargo transfer; this corresponds to the diagonal transition within the table from the L5T-2 cell by two levels to the right and up — to the cell of the *Arergy* L7T-4 entity (Table 2).

Let us consider a hypothetical numerical example. The Leningrad Region represents a source of daily commuting for the core of the Saint Petersburg agglomeration. Let us accept the ground part of the administrative area of Saint Petersburg with an area of approximately 900 km^2 as this core.

This area is filled with industrial enterprises, educational institutions, trade enterprises and other places of visit. Although people move within the city network, let us "blur the network to make it seem like a field" (see Figure 3) and accept input flow distribution within the agglomeration core to be uniform.

Electric trains of the Saint Petersburg railway junction carry 80 million people per year. Let us assume that half of them — 40 million — are those who commute daily. The average train speed is 60 km/h. The average trip length is 60 km, i.e. the average time per a trip is 1 hour.

Annual transport work in the area (Area output W_2) is equal to:

W_2 = 40,000,000 passengers × 900 km^2 = 36·10^9 pass-km^2 = 36·10^{15} pass-m^2.

Area transport service:

$S_2 = W_2 \times V^2$ = 36·10^9 pass-km^2 × 60^2 km^2/h^2 = 1,296·10^{11} pass·km^4/h^2 = 1,296·10^{11} pass·km^4/h^2 = 36·10^{15} pass-m^2 × (60/3.6)^2 m^2/s^2 = 36·10^{15} × 277.777 = 10,000·10^{15} pass·m^4/s^2.

Despite the fact that servicing of passenger flows is different from servicing of cargo flows, we will additionally calculate the mass characteristic of the passenger flow. Taking a ratio of 1 ton ≈ 14 people (i.e. the person's mass is 71.43 kg), we can calculate the mass equivalent of the area transport service:

S_2 = 10^{19} pass·m^4/s^2 × 71.43 kg/pass = 71.43·10^{19} m^2·(kg·m^2/s^2) = 0.7143·10^{21} Jm2.

Let us calculate energy consumption. One carriage has 100 seats. Usually, trains have 4–12 carriages. Let us take 8 carriages, i.e. 800 passengers per one train. The hourly power of an electric drive of a train having 8 carriages amounts to 3,200 kW (SCBIST, 2018). In order

Figure 7. Contour irrigation: a) intermittent; b) continuous

to transport 40 million passengers, we need 40 million passengers/800 passengers/train = 50,000 train trips, one hour each.

Total energy consumption: 3,200 kW × 50,000 h = 160,000,000 kW·h =$16{\cdot}10^7$ kWh × 3,600 kJ/kW·h = $576{\cdot}10^9$ kJ= $576{\cdot}10^{12}$ J.

Transfer of this energy to the serviced area (transition from the L5T-4 cell to the L7T-4 cell, i.e. transition from the *Energy* entity to the *Arergy* entity) can be presented as follows:

Arg = $576{\cdot}10^{12}$ J × 900,000,000 m^2 = $518.4{\cdot}10^{21}$ Jm2.

Now, having two indicators (S_2 and *Arg*) for the L7T-4 cell of the Bartini's LT-table, we can determine the weight coefficient of energy efficiency regarding transport service in the agglomeration core by the mass of daily commuting:

$\eta_{Arg} = S_2 / Arg = 0.7143{\cdot}10^{21}$ Jm2 / $518.4{\cdot}10^{21}$ Jm2 = 0.00138 = 0.14%.

We should note that the equivalence of dimensions (Jm2) made it possible to calculate the dimensionless coefficient of energy efficiency. This will be rather convenient when comparing different options in optimization calculations for similar systems.

We should also note the very low value of the energy efficiency coefficient obtained. This can be explained by expectations of comfort during passenger transportation, and not by the mass density of the train load (in case of cargo transportation, instead of passengers, with full load of carriages, the η_{Arg} indicator would increase by 14 times). The mass density of the load will have a linear influence on the coefficient. At the same time, the delivery speed will have a quadratic influence: this will allow to estimate the Linergy (L6T-4) and Arergy (L7T-4) criteria.

Conclusion

Perhaps, the Arergy entity, the L7T-4 element of the Bartini's LT-table, for the first time has found its analytical application for calculating energy efficiency of transport services in the economic area — the core of the megacity agglomeration. The nature of quantitative estimation in the example is rather conventional.

However, in the author's opinion, the created method of territory servicing estimation is viable and subject to further development.

The author of this article is aware that he does not create any new entities. He is just confident in the fact that reformatting of unsteady concepts created by the predecessors will make it possible to construct and analyze future analytical models in the activity field under consideration in more transparent and understandable ways.

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