EVOLUTION OF TROLLEY-BUS: DIRECTIONS, INDICATORS, TRENDS

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Abstract

Focus of customers only on the best model' parameters of urban wheel transport with electric drive (trolley-, electric- and hybrids) presented at the world market today leads to objective lag minimum in five and more years from the achievable technical/technological world level. This paper targeted to create on example of serially made trolley-bus (*T*-bus) models an objective dataset for determining and extrapolation the trends of its perfection physically informative indicators. The consecutive application of the ordinary least squares method and modified Kendall-Theil robust method to small selections of the offered indicator' trends received. Reasonable by the theory of similarity and dimensional analysis the model' structure and the kernel of perfection level index obtained and characterized by the possibility of its periodic upgrading in accordance with the customers and designers requirements. The classification of the drive axle generations in electric drive traction transmissions, considers analysis of its structure and construction's elements, proposed. On example of the known traction transmissions' structures the circuit-logical technique of taking notes its reliability at express diagnostics of the certain *T*-bus model perfection level developed. Further increasing of some numeric markers of energy efficiency, load capacity, comfort, ergonomics and operational reliability of the *T*-buses by adequate linear trends is confirmed. Accented, that the open access to the dataset of the vehicle' perfection level indicators is one of the foremost challenges in methodology of its *CAE*-methods optimal design and have practical significance to improve such products.

Key words: vehicle' model perfection level, diagnostics, physically informative indicators, traction transmission reliability

HIGHLIGHTS

- New methodology for determine the set of objective physically informative indicators for the *T*-bus' model perfection level is proposed.
- Open access dataset of the *T*-bus models technical/technological perfection' indicators created, corresponding evolution trends for serially made *T*-buses obtained.
- An original model for diagnostics of the *T*-bus design perfection level developed and its kernel by the theory of similarity and dimensional analysis proved.
- New classification of the drive axle' generations and the circuit-logical technique of the traction transmissions reliability diagnostics proposed.

NOMENCLATURE AND GLOSSARY

a, b, c	exponents for independent variables
g	acceleration of gravity, m/s^2
J_S	seat's capacity of *T*-bus
J_Σ	total passengers capacity
k	constant coefficient
L_{pR}	normative noise level in inside of reference vehicle, dBA
L_{pA}	noise level in inside of evaluated vehicle, dBA
L_T	average lifetime distance of the *TB*, km
L_W	manufacture' warranty, years
m_Σ	mass of loaded vehicle, t
N_Σ	total capacity of installed *TEM,* kW
n	space dimension of vehicle' technical/technological perfection indicators
P_j	probability of failure-free operation the system' element *j*
P_{SR}	reliability index value of reference system
P_{ST}	reliability index of the evaluated system
Q_j	system' element *j* probability of failure
$q_{i,}$	dimensionless indicator *i* of perfection
R^2	regression metrics
R_{tc}	turning circle radius, m
T_j	load torque, kN·m
t	model year of evaluated sample
u	gear ratio
$V_{max},$	maximal speed of *T*-bus with network mode operation and in autonomous mode, km/h
V_{am}	
W_{max}	maximum acceleration of *T*-bus, m/s^2
$\gamma,$	index of perfection and its values in the first and the second approaches
γ', γ''	
η	mechanical effectiveness
Ω	set of physically informative parameters and characteristics
AM-W	aggregated motor-wheel
ATVS	active torque vectoring system
CAE	computer-aided engineering

CNG	*ICE* with gas fuel
D	diesel, *D*-drive, *D*-bus
DA	drive axle
D-G	diesel-generator
DSH	hybrid bus with *D-G*
E	electric bus, *E*-drive, *E*-bus
EMD	electromechanical inter-axial differential
FC	fuel cell
GREET	greenhouse gases, regulated emissions and energy use in transport
ICE	internal combustion engine
IGBT	insulated-gate bipolar transistor
IHG	in-line helical gear
IM-W	integrated motor-wheel
KTRM	Kendall-Theil robust method
MD	mechanical differential
M-G	motor-generator
MTG	multi-threaded gear
OLSM	ordinary least squares method
PWG	planetary wheel gear
TB	traction battery
TEM	traction electric motor
TSC	traction super capacitor
TT	traction transmission

1. INTRODUCTION

At beginning of the XXI century the demand for using the electric drive (*E*-drive) at solution of economic and environmental problems, caused by internal combustion engines (*ICE*), has increased substantially. The wheel transport world market promptly changes towards increase in a segment of models with hybrid and full *E*-drive (fig. 1) [31].

The forecast of the Institute for Energy Research, USA, 2014, on the 2022 and the next years have been used such guideline:

- Buses with *ICE*, series hybrids with diesel-generator (*D-G*) and parallel hybrids (duo-buses), as a product in the market fall stage.
- Urban *T*-buses and series hybrids capable of operating from the contact network and autonomy with dynamic recharge in the limits of a city cycle in proportion on a run up to 50:50, as a product in the market mature stage.
- Plug-in full *E*-buses (without generator) and series hybrids using two/three autonomy energy sources (motor-generator *M-G*, recharged traction batteries *TB*, traction super capacitors *TSC*, fuel cells *FC*), as a product in the market development stage.

Today, the forecast come true, thanks to the accelerated development of new branch of components for *E*-drive and alternative energy sources. The percentage of purely *E*-power urban wheel transport will be increasing, with this heavily dependent on the development of mobile energy storage systems and the associated energy chain and infrastructure.

None of the mentioned concepts is far "the best" therefore, in the near future (2025…2035) hypothetically can apply for the leading positions every *E*-drive hybrid with alternative energy sources, including contact network, *TB, TSC, FC, M-G* with gas fuel (metan) etc.
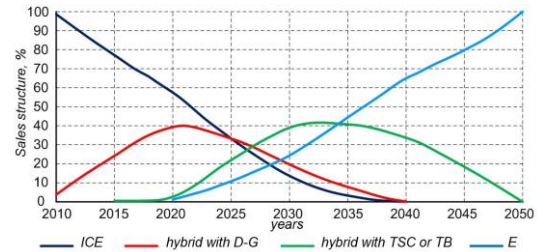

Fig. 1. Forecast of sales structure in USA of wheel transport with various types of drive and energy generation [31]

First of all this are highly effective traction electric motors (*TEM*) of alternating current on permanent magnets, compact and economic inverters of the electric power on semiconductors, electric power capacitors on base of Li-ion rechargeable *TB*, *TSC* and multilevel intellectual control systems combinations. The *TEM* typically is more durable than the *ICE* and cause less secondary damage from vibration, so the *T*-buses tend to be long-lived compared to the *D*- ones. The main advantages of the *E*-drive application display the following indicators:

- The environmental friendliness – by Euro-5 standards the *E*-drive compared to the *D*- one is significantly better (table 1) [25, 30]. Also the lack of exhaust allows the *T*- and *E*-buses to operate and stop in underground locations.
- The energy efficiency of the *E*-drive provides minimum level of energy consumption (fig. 2) [28]. According the dataset of Solaris Corporation the power consumption at operation of standard 12 m *E*-bus is up to 2.52 kWh/km that it is less compared to the *D*- one for 43 % and respectively for 29 % compared to hybrid one with the *D-G* in identical service conditions [11].

Table 1. Indicators of environmental friendliness of *T*-bus and *D*-busPollutants	Local emissions, g/km		Global emissions, g/km		
	T-bus	*D*-bus	*T*-bus [1]	*T*-bus [2]	*D*-bus
SO_2	0	1.07	0.86	0.43	1.7
NO_2	0	23.6	1.31	0.66	24.2
CO	0	0.47	0.61	0.31	4.8
CO_2	0	1204	912	456	1314
Soot	0	0.47	0.25	0.13	0.5
Note. Electricity is produced at power stations: [1] – thermoelectric; [2] – hydroelectric					

High energy efficiency due to higher efficiency of the *TEM* and the possibility of energy recovery to the electric network or *TB* (up to 20 %) with electrodynamics braking [11]:
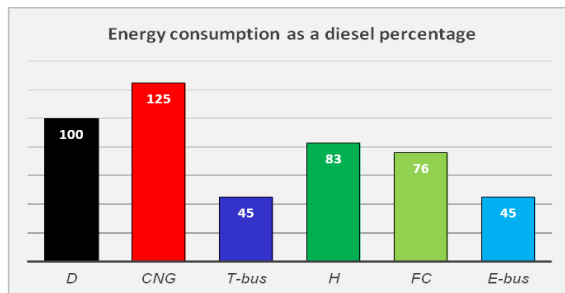
Fig. 2. Power drive energy consumption comparison [28]: *D* – diesel; *CNG* – *ICE* with gas fuel; *H* – hybrid average; *FC* – hybrid with fuel cells

- Noise pollution – unlike trams, the gasoline- and *D*-buses, the *T*- and *E*-buses are almost silent, lacking some noise of an *ICE* or wheels on rails. According to the results of the "*TROLLEY project*" for the Central Europe (Poland, Czech Republic, Slovakia, Austria, Hungary, Slovenia, Germany, Italy and Ukraine) significantly lower values of the *E*-drive acoustic emission to the environment (up to 10...18 dBA) in comparison with the *D*- one by experiments proved [28, 31].
- Useful ability of the *E*-drive to overcome steep rises (up to 12 %), especially in winter, when used in cities with allowed speed up to 50 km/h.
- Using the *T*-bus for running the dedicated roadways or the claimed by the Siemens Corporation optical guidance system give the ability to maintain higher speeds on very narrow corridors and to automatically dock at curved stops with a better than 50 mm gap at the platform.

To build up a time-dependent evaluation model, describing the impact of the *E*-drive vehicles popularity on the following four aspects: the total amount of pollution produced by all vehicles in traffic, the production cost of vehicles, the efficiency of public transportation and the total amount of energy required by all vehicles on streets is aimed [21, 36].

To overcome the known *T*-bus technology' drawbacks (insufficient maneuverability, infrastructure' high cost and negative influence of electric networks on the aspect of streets – intersections often have a "webbed ceiling" appearance, due to multiple crossing and converging sets of wires) the leading world manufacturers initiated production, capable of operating autonomy with dynamic recharging from contact networks that ensures their maneuverability approaching the urban' bus level.

In Germany, May 2019, started the *E*-autobahn intended for the movement of cargo truck-hybrids with dynamic recharge of *TB* from the contact network [20]. The site of 5 km long between the airport of Frankfurt and industrial park near Darmstadt is open for tests. It is expected that 40-tones truck-hybrids will be able to save on fuel to 20.000 Euros at a run 100 thousand km. Project

"*Elisa*" is developed by the Siemens Corporation, the similar projects also kept by the BMW Corporation.

The new models of *T*-buses and hybrids with dynamic recharge are equipped with some of the following autonomous power sources: the *TB* (Li-ion or nickel-metal hydride Ni-MH, energy density up 320 kWh, course stock of 10 to 40 km, manufacture warranty up to 8…10 years or 150…200 thousand km) and/or the *TSC* with high power density charging.

Today, about 300 *T*-buses' contact networks in 47 countries operated, most of them are located in Europe, South America and Asia. The famous transnational corporations of the *T*- and *E*-buses serial production are located in Germany, Switzerland, Belgium, France, Italy, Poland, Czech Republic, Canada, China, Ukraine and Belarus.

In Ukraine urban *E*-drive transport traditionally plays an important role. At present its share is 42...56 % of the total volume of passenger traffic and in regional centers – up to 60 %.

As the main component of competitiveness of the passenger vehicle in the world market are recognized its *technical/technological level* (hereinafter *the perfection level*) and *quality of serially made production*, which are in a complex reflecting extent application of the latest scientific and innovation developments in design and manufacture. The certain vehicle' model perfection level is determined by the comparison values of its perfection' indicators relatively the reference sample.

Customers, designers and operating companies are extremely interested in objective information about the perfection level of the *T*- and *E*-bus' models available in the world market because of their high cost, intensive operating conditions, significant periods of use and depreciation. Such information should contain steady in time set of limited number indicators, facilitating the certain model reasonable choice when ordering, scheduling maintenance intervals and determining effective directions to extend the periods of reliable operation [4, 23]. As is known, because of the intense competition between producers, much of this information, in particular regarding operational reliability, has very limited access, that's a technical secret.

The purposes of this study are:

- To form an open access dataset of objective physically informative indicators the *T*-bus design technical/technological perfection, determine and confirm statistically the stability of the corresponding trends.
- To develop and prove the model structure of the perfection level index of the *T*-buses, allowing its specification and expansion taking into account the main requirements of customers, designers and manufactures.
- To develop a technique of accounting of aprioristic reliability of units, modules and other

"criteria elements" of the *T*-bus system at express-diagnostics the certain model perfection level.

2. MAIN FEACHERS OF *T*-BUS' EVOLUTION

From analysis of the online available open access information established that the *T*-bus' today production characterized by some *organization feathers and technical/technological trends,* namely:

- Creation of joint transnational corporations in order to concentrate financial and other resources by application of innovative technologies and upgrading of produced models for expansion of sale markets.
- Unification of produced urban *T*- and *E*-bus' models along the length (size 12 m is defined as standard, 8...11 m – as midi, > 18 m – as large).
- Expanding the manufacturing of large models provides improved its profitability by unifying components and equipment, reducing the complexity of technological processes and operating costs.
- Development of new models with multi-articulated body as the most efficient regards the passenger traffic on urban and suburban routes.
- For use in the central part of megacities continued manufacturing of midi models with the classic wagon configuration.
- Transition since 1995 to the manufacturing of models only with low floor or low entry provides the level 320...350 mm of the first step above the ground, the possibility of kneeling at stops, increased comfort and the average speed of transportation up to 40 %.
- Preferentially use of asynchronous *TEM* with two typical control systems – pulse and *IGBT* based, that saves up to 40% of electric power and provide reduction in the shock load on the traction transmission (*TT*).
- Transition since 2010 to the manufacturing the *T*-bus models with the *TB* and/or the *TSC*, providing its autonomy at level 10… 20 km at an average speed of 15…20 km/h.
- Initiated since 2013…2015 the manufacturing of the *T*-buses and cargo hybrids capable of operating autonomy with dynamic recharge from contact networks, that ensure their maneuverability approaching the *D*-bus level at urban routes.
- Deepening unification of all models by component systems, units and modules namely: the frontal and back pendants have become exclusively spring-pneumatic, the steering received hydraulic amplifier, drives that enable optimum use of space and a high degree of maneuverability, such as the wheel-hub drive, are taking center stage, etc.

The certain feathers and trends of the *T*-bus evolution determine corresponding requirements for its main subsystems, firstly – the *TT* structure and design systematically associated with the relevant indicators of energy efficiency, environmental friendliness, ergonomics and operational reliability, maintenance and repair costs.

By the method of energy transformation and power transmission, most of the *TT* structures in the *T*-bus' models are electromechanical, which in comparison with mechanical or hydro-mechanical ones characterized by the following advantages:

- Free choice of wheel formula and simplicity of circuit layout for various types of electric transport with lowered floor level.
- Greater reliability and regulatory durability due to less complex design (no clutch and gearbox).
- Higher maneuverability, traction and dynamic characteristics, providing for articulated-body *T*-buses with increased passenger capacity thanks to application of two drive axles (*DA*), smooth adjustment of traction force, relative simplicity of automation control systems and active safety.
- Higher energy efficiency due to minimal energy losses in the process of transformation, transmission to the driving wheels and electro-dynamic energy recovery during braking.
- Lower costs for manufacturing, operation and maintenance.

At the same time, the electromechanical *TT* has some disadvantages in comparison with the electric one:

- Larger mass of the constituent units, modules and mechanisms, which requires additional measures for vibration isolation.
- A priori smaller operational reliability of the *TT* system consisting of some elements and connections, which are oscillated, worn out and heated during the work.

The high power density in narrow installation spaces for the *TT* system is a complex problem remains relevant and requires new solutions, based of case of scientific researches and statistics of operational datasets [4, 8 and 23].

3. METHODOLOGY OF DIAGNOSTICS THE *T*-BUS MODEL PERFECTION LEVEL

In designing practice of urban passengers' transport for comparison of models by its technical/technological perfection usually a limited set Ω of physical informative parameters and characteristics used, which numerical values for each sample contain in available to customers in open access corporate catalogs, for example:

$$\Omega = \left(J_\Sigma, J_S, m_\Sigma, N_\Sigma, L_{pA}, V_{max}, V_{am}, W_{max}, D_{am}, R_{tc}, \right.$$
$$\left. L_T, L_W, ... \right), \qquad (1)$$

where J_Σ – total passengers capacity; J_S – seats capacity; m_Σ – mass of the loaded vehicle; N_Σ – total installed capacity of the *TEM*; L_{pA} – noise level in inside; V_{max}, V_{am} – maximum speeds of the *T*-bus in contact network mode and in autonomy;

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W_{max} – maximum acceleration of transport; R_{tc} – the turning circle radius; D_{am} – distance in autonomy mode; L_T – the average lifetime distance of *TB*; L_W – manufacture' warranty.

According to the international standards, the branch technical regulations and other normative documents for M_3 category vehicles, *the main parameter* determining the dimensions of the *T*-bus, its mass, wheel formula, maneuverability and power of *TEM*, is the total passenger' capacity J_Σ [31]. It is this characteristic in the conditions of traffic speed limits that is decisive in determining the social effects of the vehicle application – the volume of traffic and environmental friendliness. All parameters that reflect the comfort and ergonomics of human transportation, energy efficiency of the transportation process, resource saving in the manufacture and operation of the vehicle, as well as other characteristics, the total number of which for modern transport reaches 80...100, are subordinated and systematically related to *the main parameter* J_Σ [24]. For example, in the frequent start-stop cycle of the *T*-bus operation mode, most of the energy consumed by the *TEM* is in acceleration cycle part and then dissipated in braking. Two main variables affect this energy: the total mass of the loaded vehicle m_Σ and its maximum speed value V_{max}.

Reliability of vehicles is convenient to analyze and evaluate as reliability of complex systems consisting of subsystems (body, chassis, electrical, mechanical, pneumatic and hydraulic), units, modules, elements (*TEM, M-G, TSC, TB*, frequency control unit, speed sensors, *DA*, gears, bearings etc.) [4, 6].

At the present stage of intensive updating of vehicle' production the process of statistical dataset formation about reliability of their new systems is limited by the necessity of long period of tests and operation. Therefore, in the majority of corporate catalogs there is no any information on indicators of reliability of vehicle in general and also of its most loaded and responsible subsystems, units, modules etc.

According to the current standards the *T*-bus considered such that it has fulfilled its resource after running 600 thousand km from the time of commissioning or after a full depreciation period of 10…12 years. Long-term experience in the operation of the *T*-buses shows that the costs of maintaining are several times higher than the initial cost of vehicle. In particular, maintenance and repair of the electromechanical *TT* is up to 40 % of the *T*-bus' total operating costs. Hence, the problem of ensuring the operational reliability, diagnostics its technical state and predicting its resource is topical [26, 35].

Today, designing process and the organizations of the batch oriented production of urban transport is connected with considerable capital investments, and the full cycle of manufacturing of a new model, including scientific research, development of the project and testing, doesn't exceed 2...3 years. Such short terms are, as a rule, insufficient for accumulation of statistical information about the perfection of vehicles with long life cycle, and wrong assessment leads to substantial damages. Therefore, it is very important correctly estimate the intensity of expected functional and consumer properties at an early stage in the design phase.

There are various approaches to solving this problem, with the following in common:
- Identify a necessary and sufficient set of functional and consumer properties that determine the perfection level of the vehicle' model.
- For each property, an adequate indicator, characterizing its intensity, to prove.
- For each of the alternative projects the numerical values of the benchmark of perfection to established, according to which the analogs compared and the most acceptable one, to accept.

Most of the known methods for diagnostics the perfection level of vehicles, as well as other products of mechanical engineering, based on comparing the aggregate of the quality indicators of the model to evaluate with the corresponding set of indicators for the reference sample and using of expertly established weighting coefficients [17, 21].

In accordance with the *ISO* Recommendations for the reference sample make a really achievable set of values of perfection indicators of objects that require comparison [22].

Must regulated clearly the selection of the comparison base largely determines the result of the evaluation and further decisions hence this process. The basic model should be promising if it takes a lot of time (more than 3 years) to develop new models, providing for the introduction of an amendment to the projected improvement of its key indicators by the time of development and operation. Given the closed nature of any information on prospective samples, as well as the proximity of known methods for diagnostics and forecasting main aspects of quality, the condition of strict regulation of choice of base sample remains unrealized in practice.

More objective on today method of diagnostics the technical/technological level of high-tech engineering products is based on the system hierarchical model in space of n rated dimensionless indicators $0{,}1 < q_i \leq 1{,}0 \, \forall \, i = \overline{1; n}$ without the use of expertly established weighting coefficients [10]. At the same time, practically unlimited number of indicators q_i is determined only by the altitude of the hierarchical model being formed, taking into account the requirements of consumers and production possibilities. The determination of indicators q_i values for reference

samples is based on regression models and corresponding trends over long time intervals.

The ordinary least squares method (*OLSM*), most common in regression analysis practice, is very sensitive to the number of independent variables and the presence of emissions, which leads in most cases to a decrease in the accuracy of the estimated characteristics and the results of their extrapolation. To improve the accuracy of analysis and extrapolation of results in small samples the modified Kendall-Theil robust method (*KTRM*) as nonparametric alternative to *OLSM* define of linear regression equation $\hat{Y} = \hat{b}_0 + \hat{b}_1 X$ applied [7].

An iterative process, aimed at finding effective independent variables, used to predict the values of dependent indicators, represents the formation of such models practically tested in the simulation of mechanical systems in gears, railway wheel boxes, aviation simulators etc. [9, 10].

4. OPEN ACCESS DATA COLLECTION

4.1. Characteristics and specific indicators of the *T*-bus model perfection level

Wide choice of *T*-buses available in the world market, only in the period 2010-2016 proposed 22 models (including 14 ones manufactured in China and Ukraine), that indicates intensive search of ways of increasing of similar models competitiveness not only by the price competition, but mainly by the technical/technological innovations [2, 11, 15, 30].

Relevant problem of applied researches for scientific ensuring the specified processes is definition of steady trends of requirements of consumers to the main physically informative indicators of vehicle perfection and justification of possible ways of their achievement with real technical, technological and economic capabilities of production.

With the use of open access information sources systematized and generalized a set of parameters of serially produced *T*-buses models for a period over 60 years. Also are used some data of the Electric *T*-bus group about deliveries and the order by consumers the most popular models in the period 2000-2019 [29].

From the analysis of evolutionary changes of a lot of parameters and characteristics of perfection for a general sample of the 58 *T*-bus models established some stable evolution changes in the capacity of passengers J_Σ and seats J_S, the total mass (weight) of the vehicle m_Σ, the *TEM* capacity N_Σ and normative noise level L_{pA} in inside (table A, Appendix). For the automatic filtration of such information that in many cases has free mode text form the mining log-by-log methods of content examination effectively applied [23].

For a possibility of statistical analysis of the *T*-bus evolution the general sample set in the period

1990-2016 model' year have been differentiated on 5 clusters reflecting indistinct sets of three countries (Canada, China, Ukraine) and two interstate unions (*EU* + Switzerland) and *CIS* (Belarus + Russia), defining various distinctions economic, climatic, opportunities for cooperation, national standards etc.

The slope $\hat{b}_1$ computed by comparing each data pair to all others in a pair wise fashion. A data set of l (*X, Y*) pairs will result in $l(l-1)/2$ pair wise comparisons. For each of these comparisons a slope $\Delta Y/\Delta X$ computed. The nonparametric slope took the median of all possible pairs of slopes.

The intercept $\hat{b}_0$ by the following mode defined:

$$\hat{b}_0 = Y_{med} - \hat{b}_1 X_{med}, \qquad (2)$$

where X_{med} and Y_{med} are the medians of *X* and *Y* respectively.

These are the advantages of *KTRM* in contrast to *OLSM* regression. The *KTRM* lines dues not depend on the normality of residuals for validity of significance tests and not strongly affected by outliers. The root mean square error (*RMSE*) is standard deviation of residuals, indicates lack of precision in the population of residuals errors. The smaller is the *RMSE* of the model, the more accurate the predictions and the better is the model.

Because of consecutive application of the *KTRM* the trends of some stable in time specific indicators of vehicle' perfection established, namely:

- The relative mass m_Σ / N_Σ reflects the system requirements to cost indicators of production and operation of modern vehicles, impact of a complex of factors with opposite gradients, associated with the process of updating the manufactured models, demonstrate a steady downward to minimum 60…80 kg/kW in articulated body models (fig. 3). Noted, that since 1990 practically all considered models correspond to requirements for vehicles category M_3 indicator of specific power $N_\Sigma / m_\Sigma \geq 5,0 \, \text{kW/t}$, equivalent to $m_\Sigma / N_\Sigma \leq 200 \, \text{kg/kW}$ [32].

- The relative power of the TEM N_Σ / J_Σ reflects main requirements for traction-dynamic characteristics and the vehicle' maneuverability on urban routes tends to steady growth to maximum 3…4 kW/pass in articulated-body models (fig. 4).

- The relative seat' capacity J_S / J_Σ reflects the complex requirements for comfort and safety of traffic tends to steady growth to maximum 45…50 % in articulated-body models (fig. 5).

- The relative noise in inside of vehicle L_{pA} / L_{pR} reflects a set of ergonomic requirements related the driver' working conditions, comfort of passengers and the harmful impact on the environment,

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demonstrate a steady downward to minimum 0,15…0,3 dBA/kW in articulated-body models (fig. 6).

The relevance of increasing the profitability of urban transport is completely coordinated with emergence in the market of new *T*-bus articulated-body models with highest values of the accepted specific indicators.

Most of the *T*-bus' models from general sample the period 1990-2016 (table A) are already quite light (relative curb mass without passengers and cargo is under 100 kg/pass), but nonetheless still over twice heavy as the aircrafts.
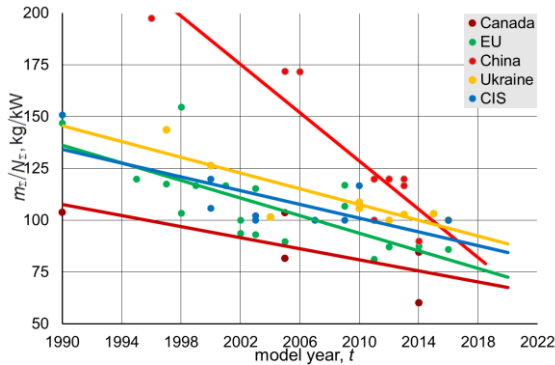

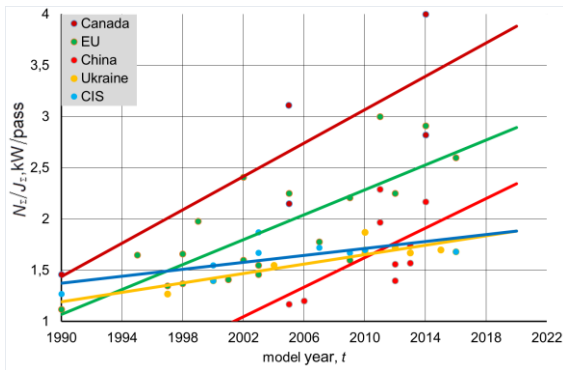Fig. 3. Trends of indicator m_Σ/N_Σ (R^2=0.53…0.85)

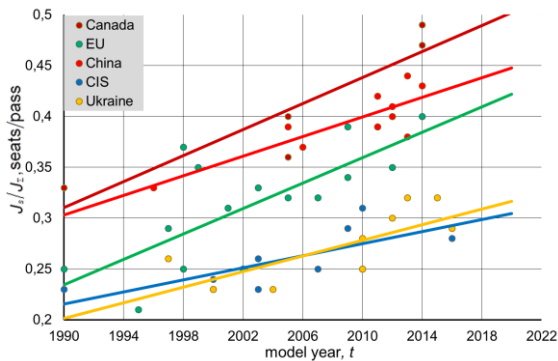Fig. 4. Trends of indicator N_Σ/J_Σ (R^2=0.51…0.71)

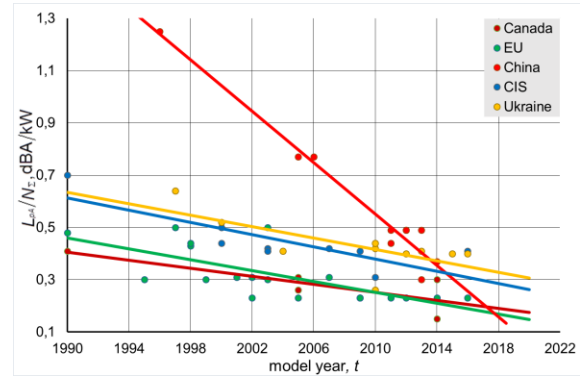Fig. 5. Trends of indicator J_s/J_Σ (R^2=0.51…0.83)

Fig. 6. Trends of indicator L_{pA}/N_Σ (R^2=0.51…0.96)

So there is scope for reducing the *T*-bus mass either by using lightweight materials or thinner elements with its optimum design and manufacturing. On the example of comparison the two *E*-drive models of pick-up track (basic on *GREET* 1 and lightweight on *GREET* 2) the possibility of decrease in mass the test vehicle up to 26 % confirmed [3].

Design recommendations on some effective constructive/technology solutions namely are given:
• Replacement of steel elements of the pick-up track' body by carbon fiber composite provides decrease in mass up to 52 %.
• Replacement of the *TB* Ni-MH or Li-ion (with the chemical composition of 2006 model year) on ones with more modern models provides decrease in their mass up to 30 %.
• Replacement of steel *DA* on ones of cast Al provides decrease in their mass up to 47 %.

Air resistance is not a significant energy consumer in urban traffic, but nonetheless in seeking to minimize energy use better dynamic shape should not be overlooked in designing new *T*-bus models.

Established trends of all specific indicators also specify the *TT* loads increasing, indicate the need for new conditions the regulatory indices of transferred power, mass, vibration resistance, durability, availability, operational reliability etc.

As a guide the *TT* energy efficiency can be improved by reducing the number of friction interfaces in the drive chain and mainly by use of gears with the internal gearing characterized by the highest value of mechanical effectiveness index η. Using of the compact multi-threaded gears (*MTG*) makes it possible to reduce the main gear' and semi-axle' dimensions and mass of up to 25...50 % [19].

4.2. Diagnostics of *T*-bus model' perfection level

According to the methodology of quality measurement, the *index of perfection level* of the evaluation object usually displays several dissimilar service properties of the object, close in importance [4, 8, 10, 24 and 36].

In many cases n indicators of the object' properties $q_i \, \forall \, i = \overline{1;n}$ are interrelated, that's, they are united by a certain functional dependence. If such dependence theoretically or empirically can be established, then the perfection level estimated by dimensionless index $\gamma = f(q_i) \forall \, i = \overline{1;n}$.

Such index for the *T*-bus, which decides whether to produce or purchase a certain model, should be a complex indicator combining the main parameter J_S , as well as the necessary and sufficient set of indicators, that takes into account the basic physically informative parameters of vehicle perfection (1). The gradients of temporary trends of such indicators can be identical or opposite according to the sign (fig. 3 – 6).

The relationship between a function defined through dimensional indicators can based on the similarity theory and the well-known π-*theorem* in the following formulation:

"*Any constant physical relationship between dimensional quantities can be formalized as a ratio of dimensionless quantities*".

When solving problems using the dimensional analysis method, a complete absolute or completeness, depending on the number of variable task parameters and the number of established basic units of measurement obtained. For example, if the desired function depends on 4 variables with 3 basic units of measurement (mass *M*, length *L*, time *T*), then the problem of determining such function has a complete solution up to a certain value of the constant coefficient *k*=const [27, 33].

The desired function taken in the form of product of three independent variable arguments, each of which has an unknown exponent, that's,

$$\gamma = k(N_\Sigma)^a \cdot (m_\Sigma)^b \cdot (V_{max})^c . \qquad (3)$$

Matching dimension formula for equation's (1) both parts with the basic units *M*, *L*, *T*, as a result of identical transformations of the power dimension $\left[\dfrac{\mathrm{N} \cdot \mathrm{m}}{\mathrm{s}} = \dfrac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^3} \right]$, and acceptable for problems with the physical nature of the relationships between the variable arguments by the value of the coefficient $k = g^{-1}$ (*g*=9.8 m/s² – the acceleration of gravity), has such form:

$$\frac{L}{T^2} = \left(\frac{M \cdot L^2}{T^3} \right)^a \cdot M^b \cdot \left(\frac{L}{T} \right)^c . \qquad (4)$$

It follows from formula (3) that all three variables are expressed in terms of three basic measurement units therefore the task posed has not only a complete but also an absolute solution. According to the identity condition for each dimension with its grade on the left and right sides of the equation (4) for the exponents for *L*, *T*, *M*, the system of equations $2a + c = 1; \, 3a + c = 2; a + b = 0$ and it solution $a = 1; b = -1; c = -1$ obtained.

The index of perfection of the valuation objects should reflect the necessary and sufficient number of parameters and characteristics, which significantly affect certain trends in their evolution (fig. 3-6).

If to accept the index γ (3) as the criterion of functional similarity the serially made *T*-buses, then the necessary and sufficient number n of dimensionless indicators $q_i \, \forall \, i = \overline{1;n}$; $0,1 < q_i \le 1,0$ is provided. Each of indicators displays a certain property of the vehicle' model and allows some periodic updating in accordance with priority requirements of consumers, designers or manufactures.

Taking into account, for example, three specific indicators J_S / J_Σ , L_{pR} / L_{pA} , P_{ST} / P_{SR} , a kernel of model (3) supplementing, the hypothesis of their paired independence on preference by consumer, designer and manufacturer, an expression for the index γ as a function of 9 variable arguments obtained

$$\gamma = \frac{N_\Sigma \cdot 10^3}{m_\Sigma V_{max} g} \left(\frac{J_S}{J_\Sigma} \right) \cdot \left(\frac{L_{pR}}{L_{pA}} \right) \cdot \left(\frac{P_{ST}}{P_{SR}} \right), \qquad (5)$$

where L_{pR} / L_{pA} , P_{ST} / P_{SR} – the noise level in for the reference sample relatively certain *T*-bus' model; P_{ST} / P_{SR} – defined level of reliability for the certain model relatively reference sample.

For the preliminary analysis of the available dataset accepted values L_{pR}=72 dBA (for today the lowest noise level among the available general selection), indicator of system reliability $P_{ST} / P_{SR} = \mathrm{const} = 1,0$, i.e., the number of variable arguments *n*=7 of the index function $\gamma' = f(q_i)$, assumed as the *first approach*.

From the analysis of the trends follows that for today the highest values of the index γ′ by models from Canada, *EU* and China are determined (fig. 7).

The following stage of development the offered model (5) is connected into accounts the features of modern *T*-buses models by formation the sufficient electrical, electronic, mechanical and other systems and subsystems (inverters, the *TEM*, *TT, TB, TSC*, etc).

The technique of definition the next approximation of index γ taking into account the structural reliability of the *TT* system is considered.

4.3. Evolutionary changes in *TT* system

The specified set of low floor models and certain trends in power, mass, comfort and ergonomics indicators led to a *number of evolutionary changes in the structure and design of the TT* system, which are conveniently combined and classified as follows (table 2):

- Module of drive' axle (*DA*), used in the *T*-buses from about 1958 model year (hereinafter *DA* the 1st generation), has a structure borrowed from

buses and trucks (the beam, the cardan shaft, two semi-axles, main gearing, mechanical differential (*MD*), two single-stage spur planetary wheel gears – *PWG*) (fig. 8, a).
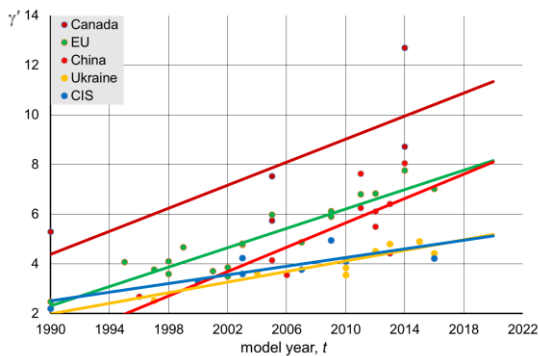

Fig. 7. Trends of the index γ in the first approach – γ′ (R^2=0.59…0.85)

- Since 1995 the *DA* received a lower beam, in-line helical gear (*IHG* instead of *PWG*) and the corresponding name – portal drive axle (hereinafter *DA* the 2nd generation). Purpose – for the *TT* with a group drive from the *TEM* through the cardan shaft, conical transmission with a circular tooth, the inter axle conical *MD*, the semi-axles connected with the *IHG* (two-stage helical cylindrical gear with branching, the slow gear is directly connected to the drive wheels (fig. 8, b).
- In 2007-2016 designing, tests and development of serially production of the electric portal *DA* based on motor-wheels with aggregated asynchronous *TEM* with water/glycol cooling, the *IHG* and the *PWG* without the cardan shaft, the semi-axles, final drive and *MD* (hereinafter *DA* the 3rd generation), are successfully complete. Purpose – for electromechanical transmissions with individual drive for each drive wheel (aggregated motor-wheels – *AM-W*), in which the *TEM* are connected with the two-stage *IHG* and a single-stage *PWG* (transmissions of cylindrical, helical, fixed rings are located in the hubs of the *AM-W* and the carrier is connected with a drive wheel, fig. 9).
- In 2014 the production of portal *DA* based on wheel-hub drive (integrated motor-wheels *IM-W*) with synchronous *TEM* on permanent magnets with water/glycol cooling and disk brake with hydraulic drive, the beam includes two *IM-W* (hereinafter *DA* the 4th generation, fig. 10). Purpose – for electrical *TT* with an individual drive in particular in *E*-buses for shuttle-service.

Therefore, the electromechanical *TT* of modern *T*- and *E*-buses with a group or individual drive scheme can consist of the *TEM* of direct or alternating current, universal joints, as well as one or two *DA* with non-lowered or portal (lowered) beam. In transmissions with a group drive scheme,

the *DA* module can consist of a main transmission of a conical/hypoid type, a conical differential, semi-axles the same or different lengths and split gears.

For the *DA* the 1st generation with non-lowered beam, the central location of the main gear and the inter-axle mechanical differential with the axle shafts having the same length, which ensures the symmetry of the dynamic load of the transmission along the sides of the *T*-bus, are characteristic. All this placed in the hull, forms a beam of the *DA* (fig. 8, a). The use of compact multi-threaded gears (*MTG*) makes it possible to reduce the dimensions and mass of the main gear and semi-axles by 1.5...2.0 times. The *DA* half-axles have different lengths, which makes possible take the cardan shaft away from the middle of the passenger compartment, place the *TEM* on the rear cantilever part of the *T*-bus body closely to the *DA*, allows for partial lowering of the cabin's floor, simultaneously simplifies the *TT* design and improves its reliability (fig. 8, b).

Modules of the *DA* the 1st and 2nd generations contain gears with a total gear ratio *u*=5.11…10.67, which is realized by the central hypoid (*u*=3.09) or conic (*u*=2.72) transmissions and planetary wheel or *IHG* (*u*=3.46...3.55). Due to the insufficient balance between torque, mass and volume of *TEM* for each *AM-W* in the *DA* the 3rd generation the multi-stage gear boxes (*IHG* and *PWG*) provide a transmission ratio of the *TT* at the level of 20...23, maximum torque $2\,2\times485$ Nm and the necessary compactness of the whole structure.

Differential kinematics connection between the pair of driving wheels of each electric *DA* and traction force distribution between the two electric *DA* is provided by the active torque vectoring system (*ATVS*) – the single system of torque vectoring and braking forces control [15].

The full electric *TT* structure based on the *DA* the 4th generation with *IM-W* (fig. 9) not require the cardan shaft, semi-axles and multistage gears. The *IM-W* design can be used in two options – like a rotary or non-rotating motor-wheel, the corresponding wheels can be single-track (equipped with wide tires) or dual-track. Modules of the *DA* the 4th generation compared to the *DA* the 3rd generation provides the following advantages:

- Increased energy efficiency due to higher in 5...7 % value of mechanical effectiveness and the possibility of energy recovery for charging the batteries during electro-dynamic braking.
- Greater vibration resistance and a lower mass of the *DA* in general. For the known serial models of the *DA* 4th generation the nominal noise level is set 65 dBA.

So far the lack of data about the reliability of the *DA* the 4th generation, its limited load capacity, regulatory resource and known high electric danger at service limited their widespread use in *E*-drive vehicles.

Table 2. Classification features of the *TT* systems in the *T*- and *E*-buses

Features, examples	Floor level of vehicle			
	not lowered (>480 *mm*)	lowered (320…350 mm)		
1. The motion energy		electromechanical		electrical
2. Drive scheme, kinematics connection, wheel formula	group, differential, 4×2, 6×2, 6×4	group, differential, 4×2, 6×2, 6×4, 8×4	individual, *ECS*, 4×2, 6×2, 6×4	individual, *ECS*, 4×2; 6×2
3. *TT* constituents (engines, modules, parts)	*TEM*, cardan shaft, module of *DA* with not lowered beam	*TEM*, cardan shaft, module of *DA* with not lowered beam	*AM-W*, module of *DA* with lower beam	*IM-W*, module of *DA* with lower beam
4. *TEM* type and design	permanent current	permanent or alternating current	asynchronous 3-phase, water-cooled, aggregated with gears	synchronous on permanent magnets, wheel-hub drive
5. Type of differential kinematics connection	mechanical, electromechanical	mechanical, electromechanical	electric	electric
6. Presence and location of the main gear and mechanical differential	central	offset	–	–
7. Presence and types of split gears	single-stage spur *PWG*	*PWG* or two-stage *IHG*	*PWG* and two-stage *IHG*	–
8. Examples of schemes	Fig. 8, a	Fig. 8, b	Fig. 9	Fig. 10

4.4. Circuit-logical model of the *TT* reliability

At absence in open access any information on indicators of the *TT* system's reliability for a preliminary comparison its structures at design the probabilities of fail-less operation of all the elements assumed to be the same, i.e. $P_j = 0,95 \, (j=1,...,J)$. In the structures with two independent *DA* assumed, that constant reservation ensure transport operating at reduced speed. If the "*a*" part of the elements not duplicated in the *TT* system, and other the "*b*" part duplicated, the probability of failure-free operation determined by such formulas:

$$P_{ST} = P_a \cdot P_b; \quad P_a = \prod_{j=1}^{a} P_j; \quad P_b = \prod_{j=1}^{b}\left(1-Q_j^2\right), \quad (6)$$

where Q_j – the probability of the *j* element failure.

The calculations results allow roughly compare the known *TT* structures according to the operational reliability indicator and consider it when determining the index γ (table 3).

Taking into account the values of indicator P_{ST}/P_{SR}, which reflects the reliability of the *TT* system, the number of variable arguments of function (5) increased. The highest value of the system indicator of fail-safe operation P_{SE} =0,931 distinguish full electric *TT* with a wheel formula 4×4 thanks to fewer sources of failure and *structural reservation* by two *DA* the 4th generation. This structure allows the vehicle to continue at a lower speed when one of the *DA* fails.

As a reference sample of comparison los electromechanical *TT* with the wheel formula 6×4, 8×4 based on the *DA* the 1st, the 2nd and the 3rd generation and characterized by the highest among the known analogs indicator' value P_{SR} =0,883 (table 3) is adopted. The smallest values

(P_{SE} =0,735…0,773) to the *TT* with wheel formula 4×2 or 6×2 based on *DA* the 3rd generation without structural reservation corresponds.

The second approach γ″ of the index γ and corresponding regression lines (fig. 11) confirms significance effect of the certain *TT* structure reliability on the *T*-bus' perfection level. In particular, compared γ″ with the first approach γ′ (fig. 7) there is a certain excess of the EU models from China's analogs.

Analysis of the circuit-logical models of the *TT* system function' reliability showed that when designing the following solutions used:

- *Structured redundancy* by introducing additional elements that ensure the preservation of the system's operability when one or several elements turned on in parallel failed.
- *Parametric redundancy* ensuring the preservation of the operability of the system or its elements by facilitating operating modes, reducing operating loads and stresses by assigning surplus stocks by criteria of strength, rigidity, vibration resistance, durability etc.
- *Structured and parametric redundancy* by reducing the number of failure sources at the same time.

Objective functional effectiveness of the known designs of *PWG* and existence of reserves for further perfecting of electromechanical *TT* design on the system indexes of reliability, taking into account posterior statistics of service data, historical maintenance records, which contain information about failures and performed repairs is confirmed [1, 6, 8, 18, 23, 34 and 35].
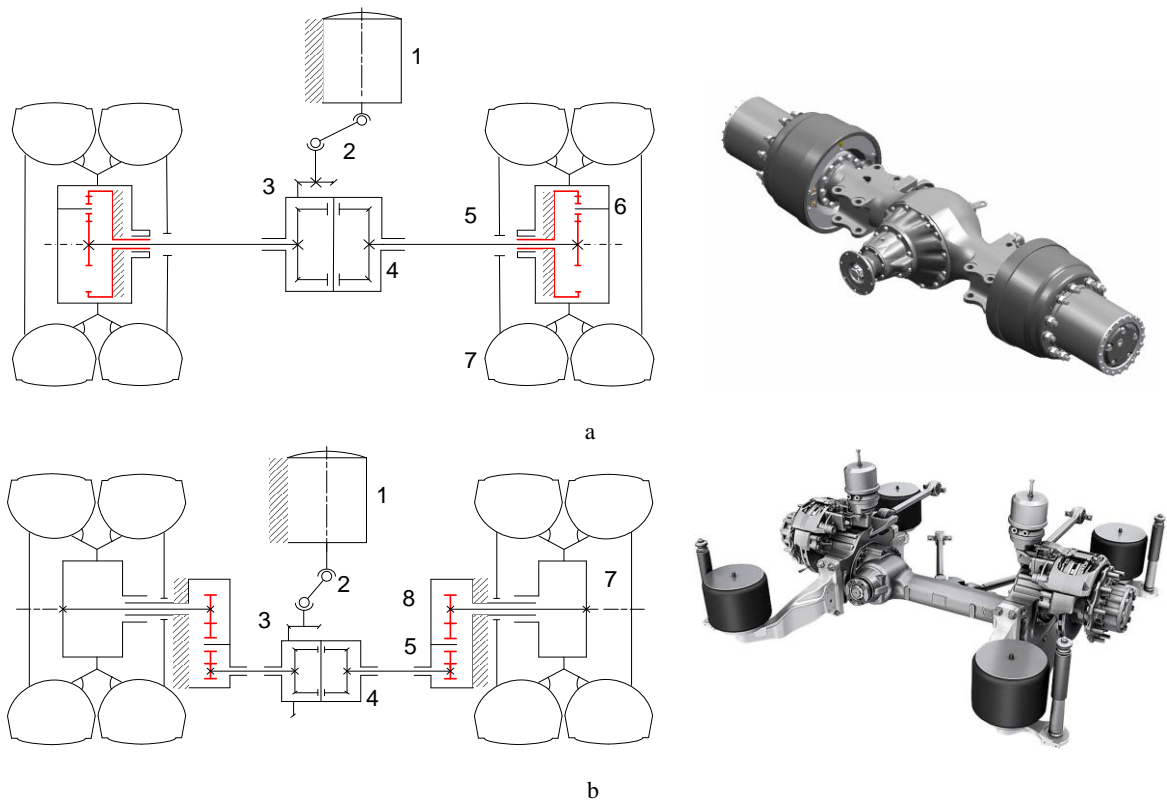
a

b

Fig. 8. *TT* schemes and examples of *DA* the 1st (a) and the 2nd (b) generations,
produced by firms *Raba*, Hungary (types 118.77, 318.78) [12] and *ZF*, Germany (type *AV*-133) [14]:
1 – *TEM*; 2 – cardan shaft; 3 – main gear; 4 – *MD*; 5 – semi-axle; 6 – *PWG*; 7 – driving wheel; 8 – *IHG*
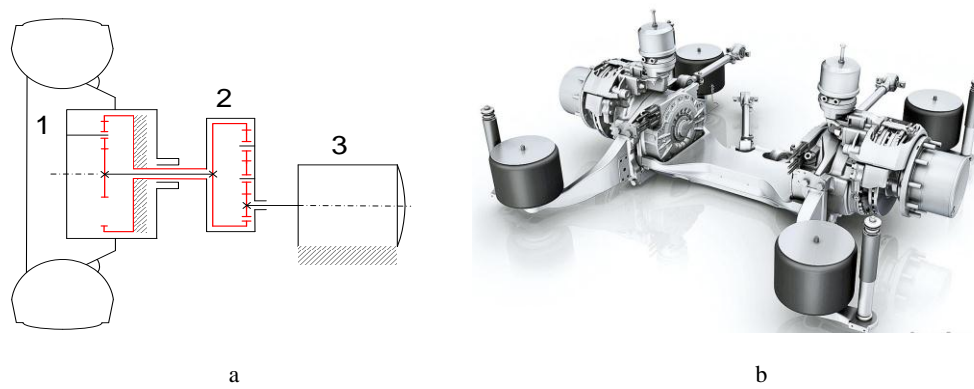

a

b

Fig. 9. *TT* scheme of the *AM-W* (a) and example of *DA* the 3rd generation (b),
produced by firm *ZF*, Germany (type *AVE*-130) [14]: 1 – *PWG*; 2 – *IHG*; 3 – *TEM*; 4 – driving wheel

Fig. 10. Example of *DA* the 4th generation, produced by firm *ZIEHL-ABEGG*, Germany (type *ZAwheel SM* 530) [13]

Table 3. Circuit-logical reliability of the *TT*

Wheel formula, the *DA* generation	Block-diagram of the *TT* structure	Calculation formulas	P_{ST}
4×2, 6×2, the 1st or the 2nd		$P_{ST} = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_5^2$ $P_{ST} = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_6^2$	0.735
6×4, 8×4, the 1st or the 2nd		$P_{ST} = P_7 \cdot \left[1 - \left(1 - P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_5^2 \right)^2 \right]$ $P_{ST} = P_7 \cdot \left[1 - \left(1 - P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_6^2 \right)^2 \right]$	0.883
4×2, 6×2, the 3rd		$P_{ST} = P_8 \cdot P_1^2 \cdot P_9^2$	0.773
6×4, the 3rd		$P_{ST} = P_8 \cdot \left[1 - \left(1 - P_1^2 \cdot P_5^2 \cdot P_6^2 \right)^2 \right]$	0.883
4×2, the 4th		$P_{ST} = P_8 \cdot P_{10}^2$	0.857
4×4, the 4th		$P_{ST} = P_8 \cdot \left[1 - \left(1 - P_{10}^2 \right)^2 \right]$	0.94

Note. The following designations are accepted: 1 – *TEM*; 2 – cardan shaft; 3 – main gear; 4 – *MD*; 5 – *PWG*; 6 – *IHG*; 7 – *EMD*; 8 – *ATVS*; 9 – *AM-W*; 10 – *IM-W*.

The main features of electromechanical *TT* structures designing for given conditions of arrangement and interface of all components in restricted space, also preferred application of the reference, unified details and modules, leads that many elements of system have the dimensions exceeding durability, necessary by criteria of strength, rigidity, stability of oscillations, i.e. are *obviously reliable*.

At the same time on design there are details and modules, which dimensions owing to external restrictions cannot increase. Examples of such "weak" elements of the *TT* systems based on the *PWG* and *IM-W* modules the thin walled epicycles and satellite' pinion bearings are [8, 16 and 34]. According to established trends of indicator N_Σ / J_Σ (fig. 4) the operating loads on low-speed tooth gearings during 2010-2016 in 35...40% increased, that causes the need of modernization of the known designs taking into account stochastic and alternating nature of heavy mode loads and elastic fluctuations in the *T*-bus' electromechanical *TT* structures.

High power density in narrow installation spaces in special requirements for leading away power losses resulting. As a rule such elements in reliability theory, known as *"weak links"* or "*criteria elements*", the all system reliability limited.

Most efficient ways of *parametrical redundancy* the *T*-buses *TT* systems based on the *DA* the 1st, the 2nd and the 3rd generations are:

- Watching diagnostics as a function of technical systems reliability and protection of gear transmissions from harmful effects – shock loads, vibrations, the parametric resonance phenomena in non-stationary operation mode [8, 16 and 34].
- Application the hierarchical model based on *n*

rated dimensionless indicators of perfection for the *CAE*-design of multi-stages *PWG* and *IHG* with internal spur or bevel gears, each of which provides the overlap factor of more than 3,0 [10].
- Development of roller bearings designs with increased load capacity and minimum friction losses for its application in high-loaded *PWG* and *IHG* with narrow installation space [9].
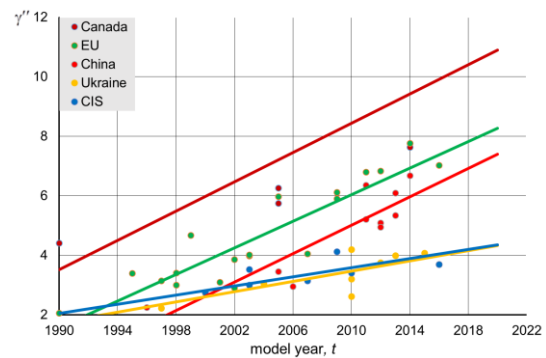-

Fig. 11. Trends of the index γ in the second approach – γ″ (R^2=0.57…0.82)

5. CONCLUSION

Today the process of designing and organizing the serial production of urban passenger transport is associated with significant capital expenditures, and the full cycle of manufacturing a new model, including scientific research, design development and testing, reaches three and more years. Therefore, it is very important correctly estimate the intensity of expected functional and consumer properties at the early stages of vehicle' design, that has consequently an impact to the decision-making.

In this work the main trends of the *T*-bus and its main loaded systems and modules – the *TT* and *DA*,

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evolution trends established and in number reflected. As a result of the executed research existence of demand in the world market and objective technical reserves for updating and expansion of the *T*-bus' technology is confirmed.

The open access dataset for further development directly by designers and customers in order to precision and extrapolation accordingly with the *T*- and *E*-buses evolution trends presented.

The technique of taking note of the *TT* system aprioristic reliability at express diagnostics of certain vehicle' model perfection level developed.

The relevance of scientific research, development of innovative technologies for *T*- bus' designing and serially production, for which the advancing values of perfection level index well-founded theoretically and confirmed statistically, accented.

Accented also, that open access to objective dataset of the vehicle' models perfection' indicators is one of the foremost challenges in methodology of the *CAE*-methods machine optimal design and have practical significance to improve the accuracy of the decisions, which influence on the reliability' diagnostics, safety and maintenance costs on this basis made [5].

The relevance of offered models, methods and techniques, datasets and perfection' indicators evolution trends for consumers, designers and manufacturers from Ukraine and Belarus is due not only to renew the fleet of urban passenger transport, but also to establish relations of scientific and technological multilateral mutually beneficial cooperation, to search for suppliers of components for own production the new models to EU market oriented and the world technical/technological level corresponded.

The offered results and recommendations do not apply for completeness of coverage of all the factors influencing the rates of evolutionary development and updating of the urban transport in various countries, often incomparable on their economic potential, tactical and strategic priorities. However, there is also a considerable amount of uncertainty in the market share of the *E*-drive urban transport that must be taken into account in further researches.

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APPENDIX

Table A – Parameters, characteristics and indicators of the *T*-bus' models perfection

№	Model, manufacturer, country	Basic technical parameters and characteristics							Specific indicators			
		Model year	Loaded mass, m_Σ, t	Quantity of passengers / seats J_Σ/J_S	Max. speed V_{max}, km/h	Power of *TEM* N_Σ, kW	Noise level in inside L_{pA}, dBA	Wheel formula	Relative power of *TEM* N_Σ/J_Σ, kW/pass	Relative seat' capacity J_S/J_Σ	Relative noise level L_{pA}/N_Σ, dBA/kW	Relative full mass m_Σ/N_Σ, kg/kW
1	Tatra T400, Czechoslovakia [1,4]	1955	17.7	80/26	60	2×65	82	6×4	1.62	.33	.62	136.2
2	ZiU-5, USSR [1,4]	1958	17.6	90/35	60	95	84	4×2	1.06	.39	.88	185.3
3	ZiU-9, USSR [1,4]	1966	18.4	91/30	60	110	84	4×2	1.21	.33	.76	167.3
4	Skoda 14Tr, "Skoda Ostrov", Czechoslovakia [1,4]	1982	17.6	100/29	60	120	83	4×2	1.20	.29	.69	146.5
5	MAN NGE 152M17, "Graf & Stiff", Austria [2,5,7]	1989	27.9	142/48	65	149	75	6×2	1.10	.34	.50	187.3
6	E902, "New Flyer", Canada [1,4]	1990	18.7	96/32	60	180	74	4×2	1.46	.33	.41	103.9
7	ZiU-682 GM, Russia [1,4]	1990	18.1	114/26	60	120	84	4×2	1.05	.23	.70	150.8
8	DAC-217E, "ROCAR-DAC", Romania [2,4]	1990	25.7	156/39	60	175	84	6×2	1.12	.25	.48	146.9
9	AG 300T, "Van Hool", Belgium [2,5]	1995	30.0	152/45	60	250	74	6×2	1.65	.21	.30	120.0
10	BJD-WG120A, "Huaya", China [1,5,7]	1996	11,9	91/30	60	60	75	4×2	.66	.33	1.25	197.5
11	UMZ-T2, Dnipro, Ukraine [1,4]	1997	18.7	102/27	65	130	83	4×2	1.27	.26	.64	143.8
12	Jelcz M121E, Poland [1,5,7]	1997	17.5	109/32	65	149	75	4×2	1.35	.29	.50	117.5
13	Berkhof Premier AT18, "VDL Berkhof", Belgium [2,5,7]	1998	26.6	140/45	60	170	74	6×2	1.37	.37	.44	154.6

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14	Ikarus 415.80 T, "Astra Bus", Romania [1, 4, 7]	1998	18.2	106/26	60	176	75	4×2	1.66	.25	.43	103.4
15	MAZ-103T, Belarus [1, 4, 7]	2000	18.0|	108/25	65	170	75	4×2	1.57	.23	.44	105.9
16	BKM-32100D, Belarus [1, 4, 7]	2000	18.0	90/22	60	150	75	4×2	1.66	.24	.50	120.0
17	Hess SwissTrolley 2, "Carrosserie Hess", Switzerland [2, 5, 7]	1999	28.0	121/42	65	240	73	6×4	1.98	.35	.30	116.7
18	Bogdan T601.12, Lutsk, Ukraine [1, 5]	2000	17.7	100/23	55	140	74	4×2	1.40	.23	.52	126.4
19	Solaris Trollino 18, "Solaris Bus&Coach", Poland [2, 5]	2001	28.0	160/49	65	240	75	6×2	1.41	.31	.31	116.7
20	Solaris Trollino 15, "Solaris Bus&Coach", Poland [1, 5, 7]	2002	24.0	150/37	70	240	74	6×2	1.60	.25	.31	100.0
21	Irisbus Civis ETB 18, France-Italy [2, 5, 7]	2002	30.0	133/33	70	4×80	72	6×4	2.41	.25	.23	93.8
22	BKM-321, Belarus [1, 4, 7]	2003	18.0	101/26	60	180	75	4×2	1.78	.26	.42	100.0
23	Trolza-5275.03, Russia [1, 5]	2003	18.4	120/27	60	180	74	4×2	1.50	.23	.41	102.2
24	Irisbus Sitelis (Skoda 25Tr), France-Czech Republic [2, 5, 8]	2003	22.35	155/45	65	240	73	6×2	1.55	.29	.30	93.1
25	O405NE, "Mercedes-Benz", Germany [1, 4]	2003	17.2	105/35	60	149	74	4×2	1.46	.33	.50	115.4
26	UMZ-E186, Dnipro, Ukraine [1, 5]	2004	18.3	116/26	60	180	74	4×2	1.55	.23	.41	101.7
27	WG68U, "Yang Zi Jiang", China [1, 5]	2005	16.5	82/32	69	96	74	4×2	1.17	.39	.77	171.9
28	E40LFR, "New Flyer", Canada [1, 5, 7]	2005	19.6	77/31	65	240	74	4×2	3.11	.40	.31	81.70
29	E60LFR, "New Flyer", Canada [2, 5, 7]	2005	29.0	130/47	60	2×140	74	6×4	2.15	.36	.26	103.6
30	Hess SwissTrolley 3, "Carrosserie Hess", Switzerland [2, 5, 7]	2005	28.7	142/46	60	2×160	74	6×4	2.25	.32	.23	89.7
31	WGD61U, "Yang Zi Jiang", China [1, 5, 8]	2006	16.5	80/30	69	96	74	4×2	1.20	.37	.77	171.8
32	MAZ-SVARZ 6235, Belarus-Russia [1, 4]	2007	18.0	100/25	65	180	75	4×2	1.80	.25	.42	100.0
33	Skoda 28Tr Solaris, "Skoda Electric", Czech Republic [1, 5, 7]	2007	24.0	135/43	65	240	74	6×2	1.78	.32	.31	100.0
34	AKSM-420, Belarus [1, 5, 8]	2009	18.0	97/29	60	180	74	4×2	1.85	.29	.41	100.0
35	ExquiCity 24, "Van Hool", Belgium [3, 5, 7]	2009	34.2	145/61	67,5	2×160	73	8×4	2.21	.39	.23	106.9
36	Hess lighTram 4, "Carrosserie Hess", Switzerland [3, 5, 8]	2009	37.4	200/68	65	2×160	72	8×4	1.6	.34	.23	116.9
37	Dnipro-T103, UMZ, Dnipro, Ukraine [1, 5, 8]	2010	18.0	100/25	65	170	74	4×2	1.70	.25	.44	105.9
38	Bogdan T701.15, Lutsk, Ukraine [1, 5]	2010	18.9	116/32	65	175	74	4×2	1.67	.28	.42	108.0
39	Bogdan T901.10, Lutsk, Ukraine [2, 5]	2010	30.5	150/38	55	2×140	74	6×4	1.87	.25	.26	108.9
40	AKSM-43303A, Belarus [2, 5, 7]	2010	28.0	153/48	60	240	74	6×2	1.57	.31	.31	116.7
41	WG6120BEVHM4, "Yang Zi Jiang", China [1, 5]	2011	18.0	76/28	69	150	73	4×2	1.97	.39	.49	120.0
42	WG6100BEVH, "Yang Zi Jiang", China [1, 5, 8]	2011	16.5	72/30	69	165	73	4×2	2.29	.42	.44	100.0
43	ExquiCity 18, "Van Hool", Belgium [2, 5, 7]	2011	26.0	107/42	73	2×160	73	6×4	3.00	.39	.23	81.30
44	Hess SwissTrolley, "Carrosserie Hess", Switzerland [2, 5, 7]	2012	27.9	142/50	60	2×160	72	6×4	2.25	.35	.23	87.2
45	CK6122GEV1, "Zhong Tong Bus", China [1, 5, 8]	2012	18.0	96/38	69	150	73	4×2	1.56	.40	.49	120.0
46	CK6123GEV, "Zhong Tong Bus", China [1, 5, 8]	2012	18.0	107/44	69	150	73	4×2	1.40	.41	.49	120.0
47	Etalon T12110, Chernihiv, Ukraine [1, 5, 8]	2012	18.0	105/31	65	180	73	4×2	1.72	.30	.40	100.0
48	Bogdan T701.17, Lutsk, Ukraine [1, 5, 7]	2013	18.0	105/34	65	175	73	4×2	1.67	.32	.41	102.8
49	ZK6125BEVG5, "Yu Tong", China [1, 5, 8]	2013	18.0	86/38	69	150	73	4×2	1.74	.44	.49	120.0
50	WG6160DHMS, "Yang Zi Jiang", China [2, 5, 8]	2013	28.0	153/58	69	240	73	6×2	1.57	.38	.30	116.7
51	XT40, "New Flyer", Canada [1, 6, 9]	2014	20.3	85/40	65	240	72	4×2	2.82	.47	.30	84.60
52	XT60, "New Flyer", Canada [2, 6, 8]	2014	30.1	125/61	65	4×125	72	6×4	4.0	.49	.15	60.20
53	WG6120BEVHM2, "Yang Zi Jiang", China [1, 5, 8]	2014	18.0	92/40	69	200	73	4×2	2.17	.43	.37	90.00
54	Trollino Metrostyle, Solaris/Kiepe Electric, Poland-Germany [2, 5, 8, 9]	2014	28.0	110/44	60	2×160	72	6×4	2.91	.4	.23	87.5
55	EIektron T19101, Lviv, Ukraine-Germany [1, 5]	2015	18.6	106/34	65	180	73	4×2	1.70	.32	.40	103.3

56	Hess SwissTrolley 3/4, Kiepe/MAN, Germany [2, 5, 8]	2016	27.5	123/48	65	2×160	73	6×4	2.6	.39	.23	85.9
57	Trolza 5265.08 Megapolis, Russia [1, 6, 8, 9]	2016	18.0	100/28	60	180	73	6×2	1.8	.28	.41	100.0
58	Dnipro-T203, UMZ, Dnipro, Ukraine [1, 5, 8]	2016	18.0	107/31	65	180	73	4×2	1.68	.29	.40	100.0

Notes: [1] single-section body; [2] two-sections; [3] three-sections; [4] *DA* the 1st generation; [5] *DA* the 2nd generation; [6] *DA* the 3rd generation; [7] transmission with two *DA*; [8] *T*-hybrid with *D-G*; [9] *T*-hybrid with *TB* and *TSC*.

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