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пр. Независимости, 65, корп. 2, комн. 327
220013, г. Минск, Республика Беларусь

Тел. +375 17 292-65-14

E-mail: sat@bntu.by
http://sat.bntu.by

Address

Belarusian National Technical University
Nezavisimosty Avenue, 65, Building 2, Room 327
220013, Minsk, Republic of Belarus

Tel. +375 17 292-65-14

E-mail: sat@bntu.by
http://sat.bntu.by

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Design Features when Using an Effective Microturbine as a Range Extending Engine

G. Nadareishvili[1], A. Kostyukov[1], K. Karpukhin[1]

[1]NAMI Russian State Scientific Research Center (Moscow, Russian Federation)

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Belarusian National Technical University, 2019

Abstract. The rapid development of electric vehicles stimulates the development of structures related to their operation. Including the use of the range extending engine for electric vehicles. The use of gas turbine engines for vehicles has always been of interest. The microturbine in the range extending engine is relevant today. However, the possibility of using a microturbine as part of a range extending engine is possible under several conditions. Microturbine should be successfully mated with a high-speed generator, and the whole structure should have a high efficiency and be economically advantageous. To create such a design, it is necessary to develop a simple microturbine with a design, equipped with a highly efficient heat exchanger, which allows to obtain high fuel and operational efficiency. Microturbine should have low temperatures on the turbine wheel to maintain high environmental parameters. The use of composite materials is necessary. The results of the development and technical characteristics of a single shaft microturbine of this class for use with a high-boring generator are presented, and its applicability as a range extending engine is justified. The main problems solved in the design of microturbines are shown: issues of thermal conditions, optimization of blade machines, flow in gas-air pipes. Power plants, based on the microturbine and high-speed generator, can be widely adopted on the basis of their simple and high operating characteristics, including the range extending engine as a range extending engine.

Keywords: microturbine, range extending engine, high-speed generator, energy efficiency

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Особенности конструкции при использовании эффективной микротурбины в качестве двигателя с расширенным диапазоном

Г. Надареишвили[1], А. Костюков[1], К. Карпухин[1]

[1]Государственный научный центр Российской Федерации ФГУП «НАМИ» (Москва, Российская Федерация)

Реферат. Бурное развитие электромобилей стимулирует развитие конструкций, применяемых при их эксплуатации. Это подразумевает и растущий ассортимент двигателей для электромобилей. Использование газотурбинных двигателей для транспортных средств всегда вызывало определенный интерес. Применение микротурбины в качестве

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ФГУП «НАМИ»
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125438, г. Москва, Российская Федерация
Тел.: +7 495 456-57-00
K.Karpukhin@nami.ru

Address for correspondence
Karpukhin Kirill
NAMI Russian State Scientific
Research Center
2 Avtomotornaya str.,
125438, Moscow, Russian Federation
Tel.: +7 495 456-57-00
K.Karpukhin@nami.ru

двигателя с расширенным диапазоном сегодня весьма актуальная проблема. Однако такая возможность имеется при соблюдении ряда условий. Микротурбина должна быть сопряжена с высокоскоростным генератором, а вся конструкция должна быть эффективной и экономически выгодной. Чтобы создать такую конструкцию, нужно разработать микротурбину, оснащенную эффективным теплообменником, который позволяет получить высокую топливную и эксплуатационную эффективность. Микротурбина должна иметь низкие температуры на колесе, чтобы поддерживать необходимые параметры окружающей среды. При этом следует использовать композитные материалы. Представлены результаты разработки и технические характеристики одновальной микротурбины данного класса для применения с высокопроизводительным генератором. Обосновано ее использование в качестве двигателя с расширенным диапазоном. Отмечены основные проблемы, решаемые при проектировании микротурбины: тепловой режим, оптимизация лопастных машин, потоки в газовоздушных трубах. Электростанции с микротурбиной и высокоскоростным генератором могут найти широкое применение в качестве двигателя с расширенным диапазоном на основе их простых и высоких эксплуатационных характеристик.

Ключевые слова: микротурбина, двигатель с расширенным диапазоном, высокоскоростной генератор, энергоэффективность

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Introduction

At this stage of development of vehicles with combined engines, one of the development directions is the possibility of introducing a low-power gas turbine engine, or microturbine, as a converter of thermal energy into mechanical energy. This solution has a large number of positive aspects, such as fuel consumption, small size, high-energy efficiency and a number of performance indicators. In this case, the vehicle is also equipped with a high-speed generator for converting the microturbine's mechanical energy into electrical energy. That ensures the microturbine operation in a given range on the characteristic of optimal fuel consumption.

The structure of such vehicle generally includes: generating unit based on high-speed power generator and microturbines, the storage system and electric power storage, microturbine's fuel system and a traction electric drive.

More than ten developments of motor vehicles using the microturbine as an additional source of energy for vehicles with traction electric drives are already known in the world, which was called MiTRE (Microturbine Range Extender) [1, 2]. As an example, among the vehicles there are Trolza (Ekobus) buses, Delta Hypercar supercar, trucks such as Isuzu NPR, Mack Truck and Kenworth.

P. L. Klimov and E. A. Razumets [3] give the definition of the term "microturbine". The appearance of microturbines in the energy sector of the economy is also described. An overview analysis of the benefits of using distributed microtube generation in distribution networks has been made. For information, the technological process of a single-axis microturbine is given. Thus, the term "microturbine" used in this report can be clearly defined. It is an autonomous low-capacity thermal power plant that has an electrical capacity of up to 1000 kW. At the same time, the microturbine is part of an electric generator that produces an extremely low level of NO_x emissions of –15 ppm, which allows them to be installed even in housing estate. The minimum electric power microturbines starts at 30 kW. Microturbines easily combined to a cluster, that is, a common energy system to produce large amounts of electrical power. Also in the cogeneration mode, the microturbine is able to solve the problems of heat supply of various objects. Trigeneration, applied to a microturbine, makes it possible to convert excess heat energy into cold, produced by absorption refrigerator.

Practically any kind of liquid or gaseous fuel can serve as a fuel for microturbines:

- natural gas with any pressure;
- biogas;
- associated petroleum gas with high sulfur content;
- diesel fuel;
- liquefied gas – propane;
- other fuels.

The conclusions of the article means that the main advantages of the distributed generation system based on microturbines are the following advantages:

- low noise level;
- low vibrations;
- small overall dimensions;
- a small number of moving parts;
- long maintenance intervals;

• ability to work on various fuels (natural gas, gasoline, kerosene, naphtha, alcohol, hydrogen, propane, methane and diesel fuel).

However, it is worth noting that most microturbines used on an industrial scale use natural gas as a priority fuel.

As part of the work, a microturbine heat exchanger is being developed, so it was important to investigate work on improving the characteristics of this microturbine part. One of the aggressive phenomena in the operation of the microturbine is the thermal load on the heat exchanger. In the work [4] on reducing the thermal intensity of a vehicle microturbine heat exchanger, the authors A. A. Andreenkov and A. A. Dementiev consider a power plant based on a microturbine as part of a vehicle.

The authors have considered the advantages of motor vehicles with combined power plants, which include an electric generator based on a gas microturbine. The article widely identifies microturbine issues and solutions that positively affect performance. It was highlighted that priorities were identified and formulated in the automotive turbine industry and the ways of their solution were outlined, which, with a favorable policy, would allow transport microturbines to compete with piston engines, microturbines are especially attractive for use on heavy vehicles. The effective efficiency of the microturbine is a function of the ratio of air pressure behind the compressor and the temperature of the working gases to the corresponding parameters at the engine inlet, the efficiency of the compressor and the turbine, and the thermal efficiency (degree of regeneration) of the heat exchanger.

It is noted that the development of microturbines designed for vehicles is impossible without their operation together with a reliable, highly efficient, lightweight and compact heat exchanger. Using the example of Capstone microturbines, which heat the air behind the compressor from 205 to 510 °C, it is stated that the specific fuel consumption has been improved almost 2 times compared to the cycle without regeneration; the heat efficiency of the heat exchanger is 0.86, which for heat exchangers with overall mass parameters satisfying the layout of the microturbine is a high value, but far from limiting, when considering work in the specified conditions of heat exchangers of other schemes. Therefore, obtaining higher performance is also the goal of this applied scientific research.

An overview of current trends in the development of high-speed turbogenerators with permanent magnets is given in the study by E. Kachalina and others [5]. The materials provide an overview of both microgenerators (with a capacity of 1 kW) and generators with a capacity of 1 to 10 MW.

The analytical review of microgenerators for our work is the most relevant. It discusses publications about turbogenerators with a capacity of less than 1 MW. It is indicated that microturbine generators are called machines with a capacity from 25 to 250 kW, while at the same time, intensive development and research of microturbine generators in the range from a few watts to kilowatts rotating at ultra-high speeds is underway. They are also called microturbine generators, possibly due to the fact that they are being developed directly for installation in a combined microturbine engine.

The design features are as follows: the rotor of the electric machine, the compressor and the turbine are located on the same shaft of the microturbine generator. When starting the turbine, the electric machine operates in the engine mode, then switching to generator mode. As a generator, as a rule, a permanent magnet synchronous motor is used. Microturbine generators with a synchronous motor with permanent magnets produces: Capstone Turbine Corp., Elliott Energy (Calnetix), Honeywell, Bowman Power Systems, Northern Research and Eng. Corp., Allison Engine Corp., Williams International (USA), Turbec (Sweden), Siemens (Germany), Toyota, Nissan, Hitachi, Kawasaki (Japan) and others. The attention of such a large number of different manufacturers demonstrates the obvious promise of developing high-speed low-power synchronous motors with permanent magnets.

As permanent magnets in synchronous motors with permanent magnets, as a rule, intermetallic compounds based on rare-earth metals – NdFeB and SmCo are used. Advantages of NdFeB – higher energy than SmCo, low price; disadvantages – low temperature demagnetization (Curie temperature), a tendency to corrosion.

The conclusions are as follows.

1. With powers not exceeding 200–250 kW, high-speed turbo-generators should be carried out on the basis of synchronous electric machines with magnetoelectric excitation.

2. The experience of using contactless high-speed supports shows that of the three known types: gas-dynamic, gas-static and electromagnetic, petal-type gas-dynamic mount, which are a type of gas-dynamic mounts, have found primary use.

3. The use of rare earth magnets (NdFeB, SmCo) provides acceptable magnetic properties of composite rotors with their low weight and dimensions, which is especially important for high-speed electric machines.

4. When designing permanent-magnet synchronous motors, considerable attention should be paid to the configuration of the rotor and the method of placing the magnets, taking into account the circumferential linear velocity. Preferred is the option with surface magnets and bandage.

5. To ensure maximum mechanical strength with acceptable eddy current losses, it is advisable to use bandages made of carbon-fiber composites to hold the magnets.

According to these conclusions, some nuances can be noted: the use of gas-dynamic petal mounts does not need an external source of compressed gas, which is necessary for conventional gas-static mounts, and, accordingly, does not need an electric power source that supplies electromagnetic supports.

The article by A. C. Maia Thales and others [6] presents the experience of developing an electromechanical design of a high-speed generator driven directly by a turbine, which is made on a turbocharger.

The paper [7] presents the results of the design of the output axial diffuser of a power turbine of an automobile gas turbine installation and presents the results of mathematical modeling of the gas flow. As a result, the diffuser geometry has been optimized in order to reduce losses in it, which improves the power efficiency of the power turbine stage, contributing to the achievement of high effective microturbine efficiency.

The author of the work identifies two aspects in the development of the output diffuser of an automobile microturbine.

1) The diffuser is characterized by hydraulic resistance, the value of which must be reduced so that the high energy dissipation does not level the positive effect of the recovery of static pressure. Increasing the pressure loss in the diffuser requires a higher total gas pressure at the inlet to the turbine stage, which reduces the efficiency of the traction turbine and ultimately reduces the effective efficiency of the microturbine.

2) Creating efficient diffuser nozzles implies the freedom to build axially and radially; in the case of an automobile microturbine, the possibilities are significantly limited by the layout conditions and installation factors.

It is concluded that the output diffuser of an automobile microturbine should combine compactness and high work efficiency [7].

System description

One of the main reasons hindering the development of the market of power plants with microturbines is their lower electrical efficiency as compared with piston engines. For example, the electrical efficiency (multiplication of the effective efficiency of the microturbine by the efficiency of the electric generator) of one of the best microturbine power plants Capstone is 29 %, whereas for a gas piston engine this parameter is in the range 34–35 % (for a power of 50 kW).

There are several ways to increase the efficiency of gas turbine engines. This increase in the efficiency of its main elements (compressor, turbine, heat exchanger), the implementation of the vapor-gas cycle, increasing the maximum cycle temperature of the gas turbine engine and carotene cycle through the introduction of intermediate air cooling between the compression steps in the compressor and the additional combustion chamber between the expansion steps in the turbine.

Fig. 1 shows that increasing the maximum gas temperature from 960 °C for turbines made of metals to 1500 °C leads to an increase in the effective efficiency of the microturbine to 38.4 % (at an acceptable value of the degree of pressure increase in the compressor π_k = 3.5 for microturbines with a power of 50 kW), which is 4–5 % more than that of reciprocating internal combustion engines with a power of 50 kW. Nevertheless, this way of increasing efficiency still continues to be only promising. To date, in none of the commercially available microturbines (including the Ingersoll Rand and microturbine with a ceramic turbine wheel [8]), the gas temperature is not increased relative to the level used in metal microturbines ((900–950) °C).

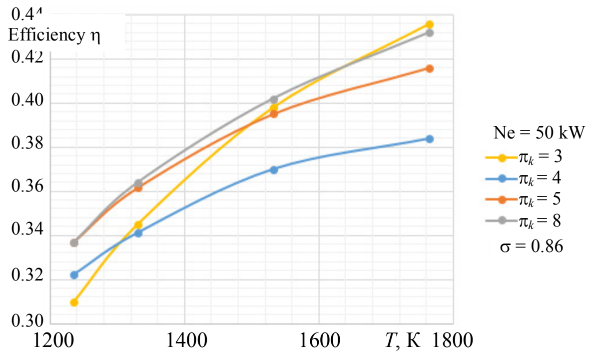

Fig. 1. Influence on the effective efficiency of the microturbine of increasing the temperature of the gas behind the microturbine combustion chamber with the degree of regeneration of the heat exchanger 86 % (π_k – pressure ratio)

Components. Bearing unit

Analysis of the review of the scientific and technical literature showed that centrifugal compressors and radial-axial turbines are most often used in microturbines (Fig. 2). At low powers of gas turbine engines, they have unattainably high efficiency for axial blade machines at high revolutions. Well known for their high strength properties. The layout of the turbocharger in microturbines is implemented in the cantilever arrangement of the thrust bearing.

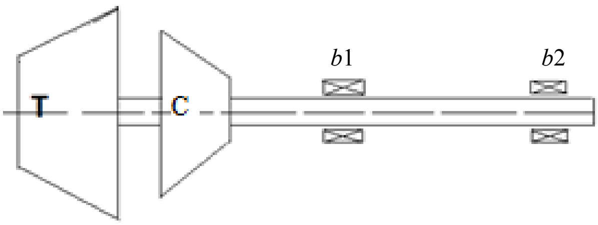

Fig. 2. Console arrangement of the turbine (T) and compressor (C)

Components. Heat exchanger

Rotary heat exchangers (regenerators) are superior to fixed heat exchangers (recuperators) in terms of efficiency and overall mass indicators (Fig. 3). The main problem of regenerators is their seals. Minimal leakages in seals have disc frame regenerators (1.5–2.0 %) [9].

To reduce the thermal deformations of the frame and, accordingly, to reduce leaks, as well as to allow the use of graphite seals (maximum temperature (450–470) °C), the frame is cooled.

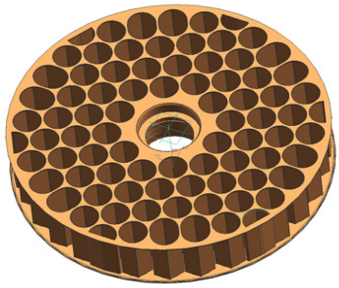

Fig. 3. Rotor frame heat exchanger

Components. Combustion chamber

The most promising for the microturbine, which is being developed, with a rotary heat exchanger will be a tubular low-toxic combustion chamber with enriched-lean combustion.

Layouts

The microturbine design (layout 1), made according to the scheme of cantilever placement of blade machines on the turbo-compressor shaft and with two rotating disk heat exchangers, is shown in Fig. 4.

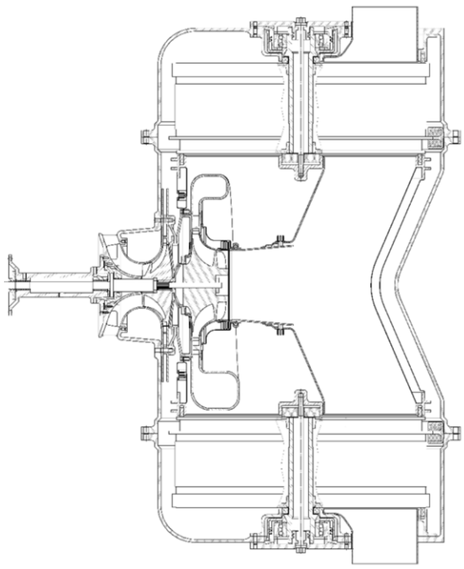

Fig. 4. Layout 1. Microturbine with two rotating heat exchangers, the axis of which is located normally to the axis of the turbocharger

The microturbine design (layout 2) is made according to the cantilever arrangement of blade machines on the turbo-compressor shaft and with one rotating disk heat exchanger, the axis of which is located normally to the axis of the turbo-compressor shown in Fig. 5.

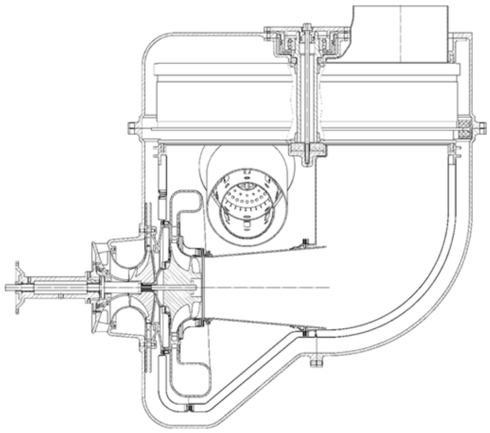

Fig. 5. Layout 2. Microturbine with one rotating heat exchanger, the axis of which is located normally to the axis of the turbocharger and with a conical diffuser behind the turbine

The microturbine design (layout 3), made according to the scheme of cantilever placement of blade machines on the turbo-compressor shaft and with one rotating disk heat exchanger, the axis of which is located parallel to the axis of the turbocompressor is shown in Fig. 6.

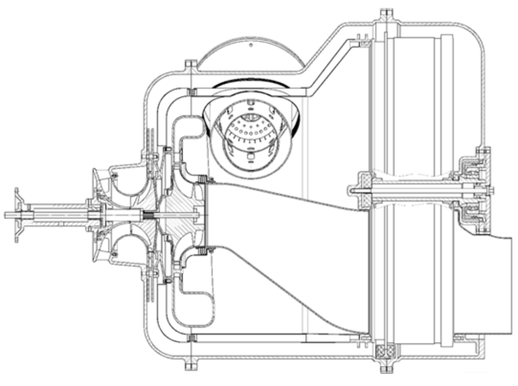

Fig. 6. Layout 3. Microturbine with one rotating heat exchanger, the axis of which is located parallel to the axis of the turbocharger and with a diffuser behind the turbine of complex shape

Fig. 7 shows the layout 4. The layout has one rotating heat exchanger, the axis of rotation of which is parallel to the axis of the turbocharger. Compared to arrangement 3, this arrangement has an elongated turbine diffuser and is made up of separate modules. The turbocharger module, the combustion chamber module and the heat exchanger module have their own bodies, which allows to reduce the dimensions of the chambers with high pressure and, accordingly, reduce the mass of their bodies and the mass of all microturbine, unload the diffuser behind the turbine and the turbine cover disk from the gas forces and thermal deformation forces, simplify assembly and disassembly and, accordingly, reduce the cost of overhaul. In addition, the calculated analysis of the efficiency of the diffuser behind the turbine of various lengths of the inlet gas manifold showed a significant advantage in terms of the efficiency of the microturbine with an elongated diffuser behind the turbine.

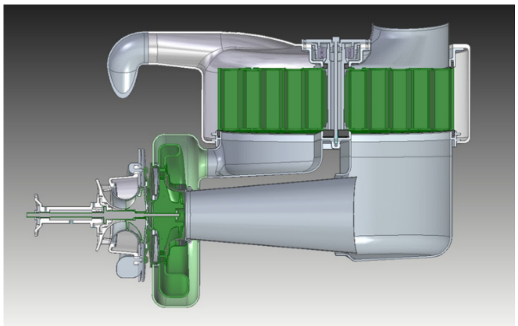

Fig. 7. Layout 4. Microturbine with one rotating heat exchanger, the axis of which is located parallel to the axis of the turbocharger and with an elongated turbine diffuser

Calculations

To confirm the parameters of the selected scheme (table 1), the calculation of the thermal state of the rotor of the designed microturbine was carried out. Such a calculation is decisive for the performance of the CCD and the efficiency value. The temperature state of the rotor was calculated as a result of solving the heat conduction problem in a stationary two-dimensional axisymmetric formulation. The solution of the problem can be divided into 3 main stages:

1) determination of boundary conditions;
2) simulation of the thermal state of the rotor;
3) analysis of the temperature field obtained.

Table 1

Presents the comparative indicators of the design schemes of the microturbine

Parameter	Layout 1	Layout 2	Layout 3	Layout 4
Heat exchanger seal length	–	+	+	+
Symmetrical body elements	+ –	–	–	–
Simplicity of design	–	+ –	+ –	+
Efficiency of the diffuser behind turbine	+	+	–	+ +
Modularity design	+ –	+ –	+ –	+ +

The results obtained were used to determine and localize the maximum rotor temperature. The temperature field was used as a PG for the subsequent calculations of the strength of parts and critical rotations of the microturbine.

Boundary conditions of thermal calculation

The calculation was performed by simulating thermal conductivity in the rotor assembly in a non-conjugate formulation, i. e. without conducting a related flow simulation with heat exchange in the cavities and on the surfaces of the rotor. This approach was chosen because of the significantly lower resource intensity of the mathematical model and the absence of the need for its complexity, since for most cavities and rotor surfaces (including wheel surfaces), there are well-studied experimentally criterial dependences in the literature for calculating heat transfer coefficients. Also available were data on changes in temperature and heat transfer coefficients of the working medium in the flow parts of the wheels and in the secondary cavities, obtained from aerodynamic modeling using CFD. It also contributed to the formulation of sufficiently detailed PG on the surfaces of the flow parts of the wheels, the rear surfaces of the wheel disks and secondary cavities. It should also be noted that this approach made it possible to implement a model with low computational resource-intensiveness, which allows for rapid estimates of the rotor temperature, which is undoubtedly extremely important during the design iterative work on engine design.

Fig. 8 shows a sketch of the rotor assembly in section. The sketch shows the dependencies for which heat transfer coefficients were calculated on the external surfaces and surfaces of the internal cavities of the rotor. Heat transfer on the surfaces of the rotor was set with the help of 3 type boundary conditions, which represent the heat transfer coefficient and the reference temperature of the external environment. The heat transfer coefficients were set by empirical dependencies on the characteristic geometrical dimensions, speeds and properties of the working medium, type dependences $\alpha = f(L, W, \lambda, ...)$. For a number of rotor surfaces, heat transfer coefficients were calculated by empirical dependencies through similarity criteria such as the Nusselt number, Reynolds number, Prandtl number and characteristic geometric dimensions. These are dependencies like Nu = f(Re, Pr, L, ...) and $\alpha = (\mathrm{Nu} \cdot \lambda)/L$. Below boundary conditions are described in more detail.

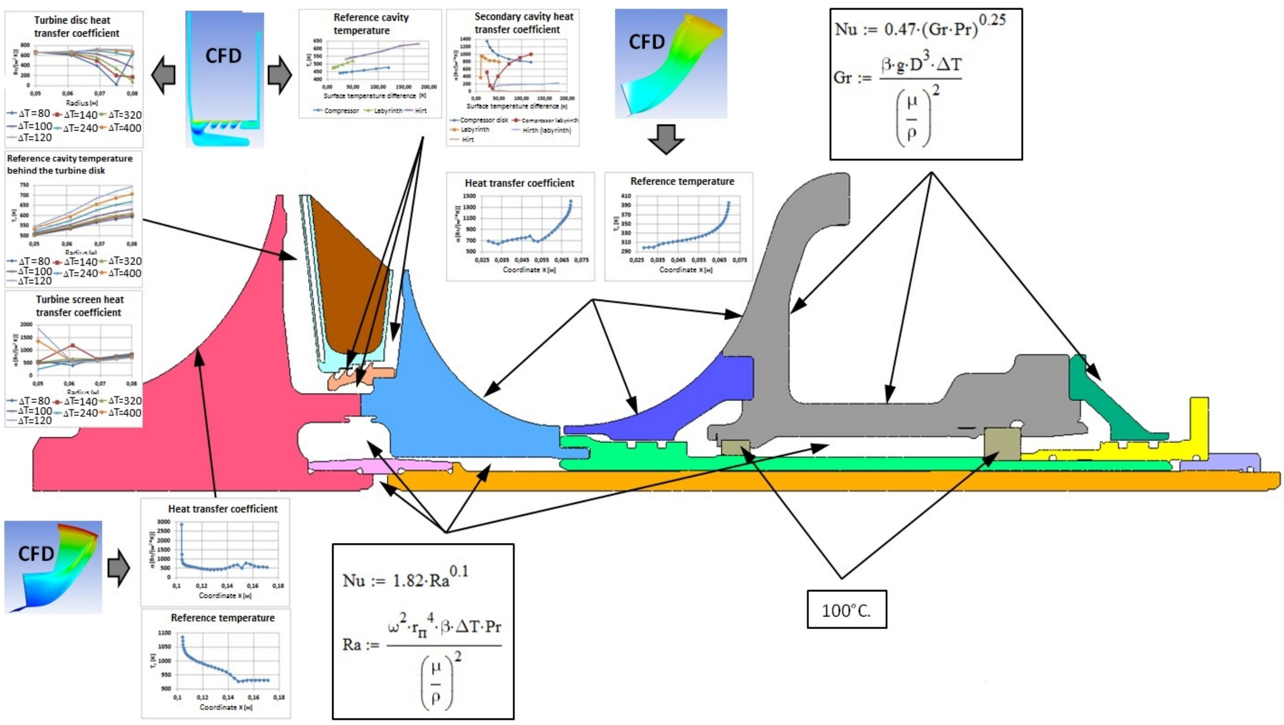

Fig. 8. Calculation scheme of the thermal state of the rotor assembly microturbine

Compressor

The heat transfer coefficients and the reference temperature of the flow path of the compressor were also determined from aerodynamic (CFD) calculations (Fig. 9). The reference temperature in the flow part of the compressor is also practically independent of the temperature of the wheel and has a small gradient in the circumferential direction. Therefore, the results for the reference temperature and heat transfer coefficient were also averaged around the circumference, and in the thermal model of the rotor were set as a function of the length of the flow part.

Fig. 10 shows the profiles of the heat transfer coefficient and the reference temperature along the length of the flow path of the compressor, calculated from the aerodynamic calculation.

Secondary cavities

By secondary cavities we mean the cavity of the labyrinth seal and the cavity behind the disk of the turbine and compressor.

The flow in the secondary cavities is characterized by significantly lower costs compared to the main engine path and is mainly determined by the pressure drop between the leak gaps from the compressor and turbine sides and the labyrinth seal. Due to the relatively small consumption and sufficiently developed areas of the surfaces of these cavities, the temperature of the air flowing through them varies considerably as it moves, namely, it increases as it flows from the compressor disk to the turbine disk due to intensive heat exchange with hot parts. Such a character of the flow requires the determination of PG in some cavities varying along the channel length and depending on temperature. Simulation of flow in the secondary path showed that such a channel is the cavity behind the turbine disk.

To determine the GI from heat transfer, in the secondary cavities, flow simulation was also used using a numerical model used to calculate leakage through labyrinth seals. This approach is more preferable for these cavities in comparison with the use of empirical dependencies, since allows much more accurately take into account the complex nature of the flow described above.

Thus, by calculating the flow, it was determined that in the cavities behind the compressor disk, in the labyrinth seal, and in the cavity between the labyrinth and the end spline connection (Hirt connection), the reference temperature and heat transfer coefficient vary slightly along the channel length and depend mainly on the temperature difference between the channel walls . In the cavity behind the turbine disk, as noted earlier, the reference temperature and heat transfer coefficient depend both on the channel length (disk radius) and on the temperature difference between the walls.

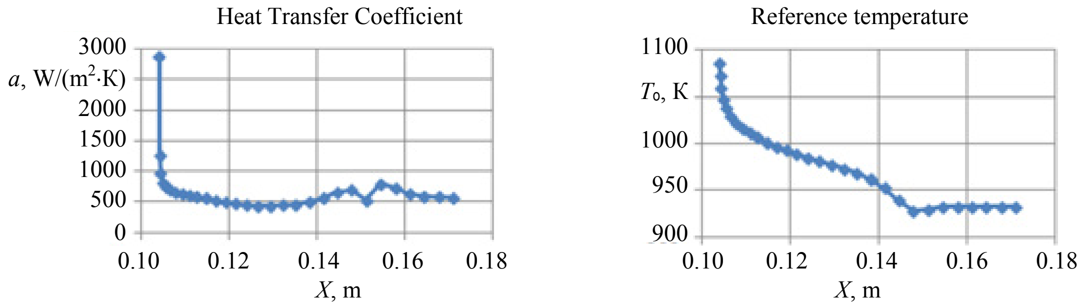

Fig. 9. The distribution of heat transfer coefficient and the reference temperature in the flow part of the turbine

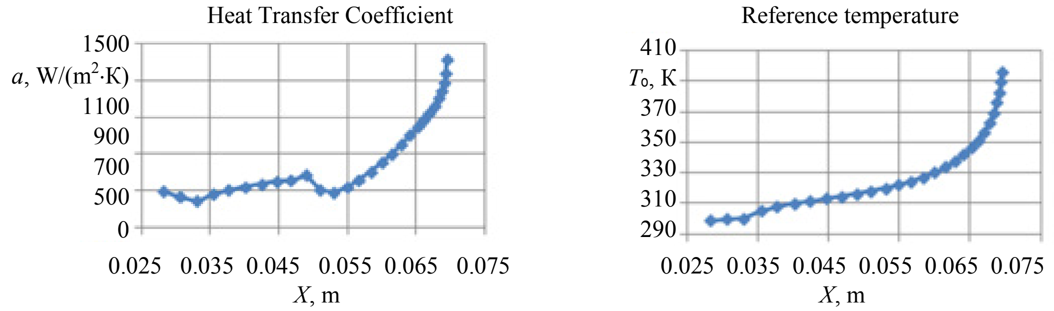

Fig. 10. The distribution of heat transfer coefficient and the reference temperature in the flow part of the compressor

Fig. 11 shows the calculated heat transfer coefficients and the reference temperatures of the cavity behind the compressor disk, the labyrinth seal cavity, the cavity between the labyrinth and the front splines (Hirt connection) depending on the temperature difference between the surfaces.

Fig. 12 illustrates the calculated heat transfer coefficients for the back surface of the disk and the turbine screen, as well as the reference temperature of the cavity behind the turbine disk, depending on the radius and on the temperature difference between the walls.

Internal weakly ventilated rotor cavities

The internal cavities of the rotor include the following cavities:

– the cavity under the end spline connection (Hirt compound) α;

– the cavity between the turbine disk, coupling pin and the turbine nut;

– the cavity between the supports, the shaft and the bearing housing.

Heat transfer in such cavities has been studied quite well and is described by the empirical dependence of the form [6–10]

$$\mathrm{Nu} := 1.82\mathrm{Ra}^{0.1},$$

where Nu – Nusselt number; Ra – Rayleigh number,

$$\mathrm{Ra} := \frac{\omega^2 r_p^4 \beta \Delta T \,\mathrm{Pr}}{\left(\dfrac{\mu}{\rho}\right)^2};$$

ω – angular frequency; r_p – radius at the periphery; β – coefficient of thermal expansion; ΔT – temperature difference between the walls; Pr – Prandtl number; μ – dynamic viscosity; ρ – density.

The reference temperature in the cavities was calculated iteratively in the process of calculating the thermal model of the rotor, as the average temperature of the cavity walls. The thermophysical properties of air were also calculated by the average temperature in the cavity [6–10].

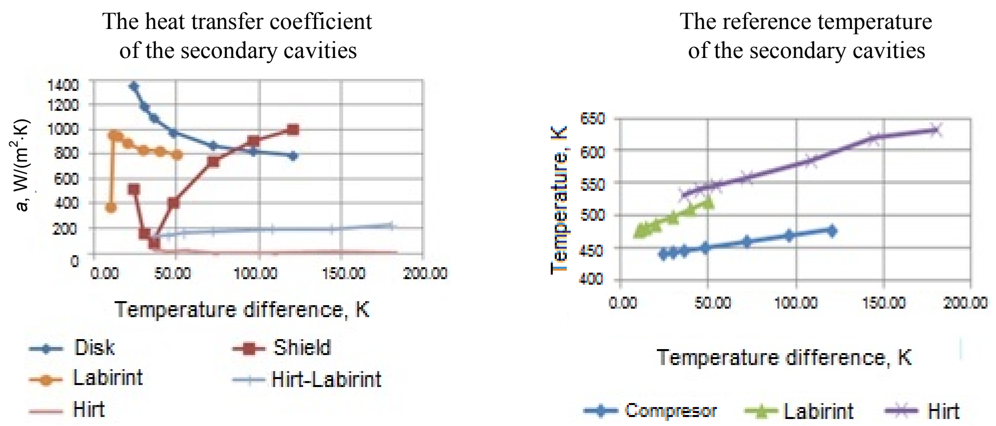

Fig. 11. Heat transfer coefficients and reference temperatures of secondary cavities depending on the temperature difference between the walls

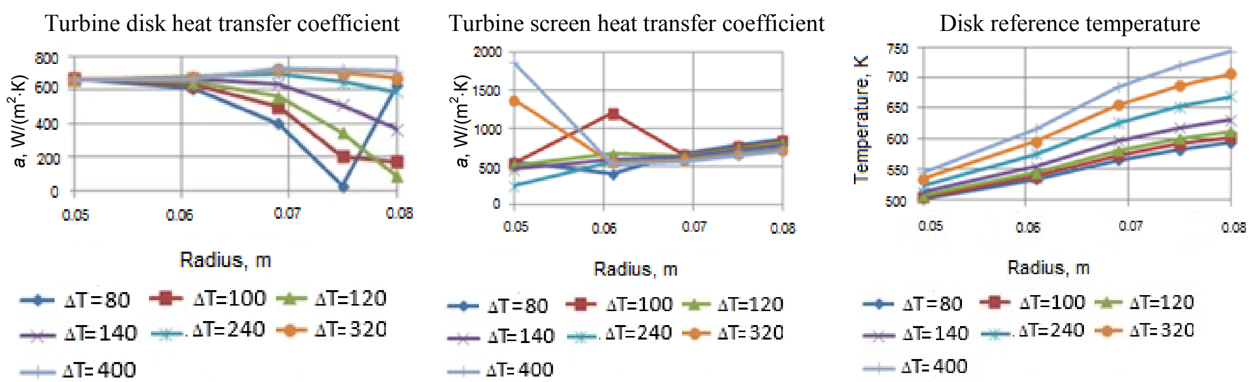

Fig. 12. Heat transfer coefficients and the reference temperature of the cavity behind the turbine disk, depending on the temperature difference between the walls

External surfaces of the bearing housing

The heat exchange of the outer walls of the bearing housing with the external environment is carried out by natural convection caused by the temperature difference between the walls and the surrounding air. This type of heat transfer is well studied, and for cylindrical and inclined walls there are empirical dependencies of the form [7–11]

$$\mathrm{Nu} := 0.47(\mathrm{Gr}\cdot\mathrm{Pr})^{0.25},$$

where Gr – Grashof number,

$$\mathrm{Gr} := \frac{\beta g D^3 \Delta T}{\left(\dfrac{\mu}{\rho}\right)^2};$$

D – diameter; g – gravitational acceleration.

As the reference temperature, the ambient air temperature was set at 250 °C.

Rotor bearings

On the rotor bearings, volumetric heat emission sources were specified in accordance with the calculations of heat generation in sliding bearings and experimental data from the SKF supplier for rolling bearings. In the slide support, heat dissipation from friction of 2 kW was set; in the rolling support, heat dissipation from friction of 700 W was set. Also in the supports were asked volumetric heat sinks that simulate oil cooling of bearings. The set power of the heat sinks was selected in such a way that the temperature of the supports did not exceed 1000 °C, which is determined by the allowable working temperature range of the oil and the material of the supports.

It should be noted that in order to avoid overheating of the supports and keeping their temperature below 1000 °C, practically all the heat (~98 %) emitted by the bearings during operation should be removed due to oil cooling.

Thus, the boundary conditions for the thermal calculation of the rotor assembly were determined. The heat exchange similarity criteria described above and the temperature difference between the walls, depending on which they are calculated, were calculated iteratively in the process of solving the thermal model of the rotor.

Thermal resistance of contacts

Contact surfaces in various types of connections, such as connections with tension, bolted connections, etc., are not ideal due to the presence of asperities. As a result, at the contact point of such surfaces the temperature field has a characteristic jump, i. e. imperfect thermal contact takes place. Thus, for correct modeling of the temperature field of the rotor assembly, it is necessary to determine the thermal resistances of non-ideal contacts (Fig. 13).

The thermal resistance of the contact depends on the degree of roughness of the contacting surfaces, the materials from which they are made, and the contact pressure, i. e. force of compression of surfaces.

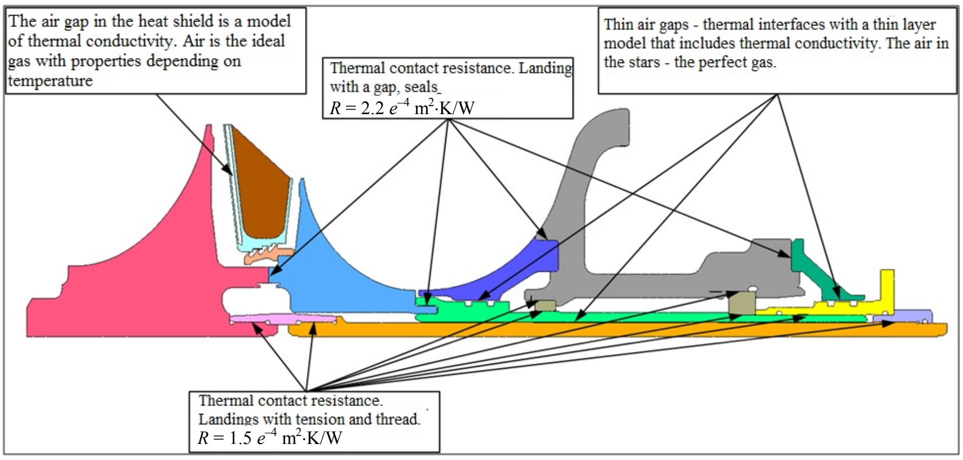

Fig. 13. Thermal resistances of rotor assembly contacts of microturbine

The thermal resistance of the contact was calculated from empirical dependencies, and also compared with experimental data available in the literature [8–13]

$$R_k := \frac{1}{\left[\frac{2\lambda\left(\frac{p_k}{3\sigma_b}\right)^n}{\pi r_m} + \frac{\lambda_c K}{\delta_e}\right]},$$

where λ – reduced thermal conductivity coefficient,

$$\lambda := \frac{2\lambda_1\lambda_2}{\lambda_1 + \lambda_2};$$

p_k – contact pressure; σ_b – ultimate strength of softer material at the temperature of the contact zone T_k; n – exponent; λ_c – air thermal conductivity; K – experimental coefficient; r_m – radius of the contact patch; δ_e – equivalent thickness of the gap.

Some parts of the rotor are not in direct contact, but are separated by a thin air gap. Due to the small size of these gaps, the absence of the difference in the velocities of the walls and the high-pressure flow in them, the convective component of heat exchange can be neglected and only thermal conductivity can be taken into account. Especially for this kind of "contacts" there are models of interfaces with a thin layer, imitating a heat-conducting medium separating parts. This model was used to simulate thin air gaps. The air in the gaps was set as an ideal gas with temperature dependent properties.

The thermal resistances calculated by the given expression, as well as thermal models of the gaps are shown in Fig. 13.

Simulation of the thermal state of the rotor

Fig. 14 shows a view of the calculated region of the assembly and the grid of the thermal model of the rotor assembly. The heat conduction problem was simulated in a two-dimensional axisymmetric formulation. Convective sources and heat sinks are set by PG of the 3rd kind (heat transfer coefficient and reference temperature), heat dissipation in the supports are set by means of volumetric energy sources, contact details are set using thermal interfaces (direct conjugation) taking into account the contact thermal resistance, and also taking into account the thermal resistance of thin air gaps, which are taken into account through thermal interfaces with a thin layer model.

The rotor assembly model consists of several design areas that describe the details of the rotor and are combined into an assembly through boundary conditions and thermal interfaces.

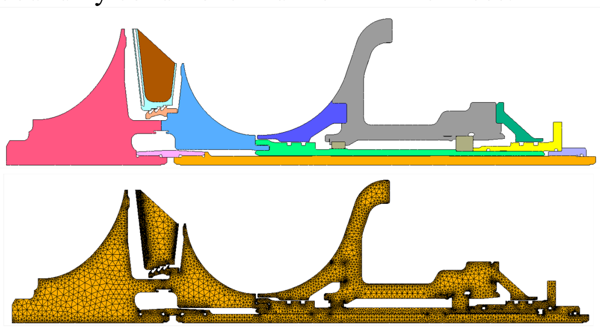

Fig. 14. View of the calculated grid of the rotor model

A computational grid with elements of the tetrahedral topology was used. The mesh size of the two-dimensional axisymmetric model was ~20.000 elements.

The results of the simulation of the thermal state of the rotor. Heat flow in the rotor

Fig. 15 shows the scalar and vector fields of the density of heat flows in the rotor. The vector field shows in detail the local distribution of heat fluxes in the rotor and the direction of heat flow through the parts in the assembly.

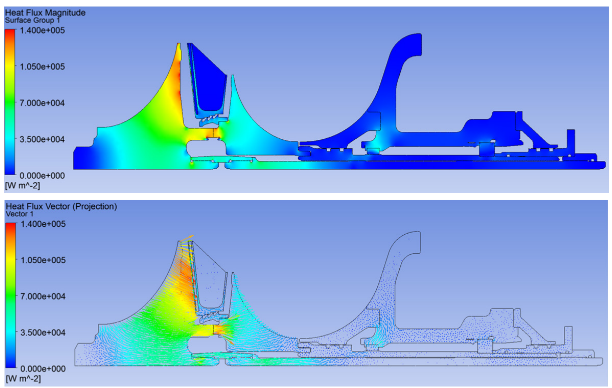

Fig. 15. Scalar and vector density fields of heat flows in the rotor

The results show that the main heat load falls on the turbine wheel from the hot gas in the flow part. The turbine wheel, being the hot part of the rotor, causes the main thermal load on the rotor coupling pin, which in turn, along with the compressor, transfers the heat flux to the rotor shaft.

The main part of the heat from the turbine wheel is removed by intensive convection in the cavity behind the turbine disk. Cold air from a compressor degree leak passes through the labyrinth seal and enters the cavity behind the turbine disk. Passing through these secondary channels, air takes heat from hot parts, including from the turbine wheel, heating up along the direction of travel, and then through the leakage of the turbine stage enters its flow part, mixing with the gas of the turbine path. Also the heat flux field shows the proper the operation of the heat shield of the turbine, through which there is a fairly small heat flux. This prevents the compressor wheel from heating up, which in turn improves the strength characteristics and efficiency of the compressor stage. A significant part of the heat from the hot gas in the flow section of the turbine passes through the turbine disk into the end splines (Hirt connection) and through the thermal resistance of the contact due to heat conduction enters the compressor wheel. Also, part of the heat from the flow part passes through the wheel and the turbine nut into the rotor coupling pin due to thermal conductivity, also passing through the thermal resistance of the contact.

The heat flux entering the compressor wheel is removed from it by intensive convection in the flow part of the wheel due to significant consumption and the developed heat exchange surface. Also, a portion of the heat load of the rotor coupling pin is retracted through the air cavity to the compressor wheel due to convection and then also carried away by the main current in the flow part of the compressor. The rest of the heat is removed from the coupling studs into the rotor shaft through the resistance of the air gaps and further from the rotor shaft is dissipated from the developed surfaces of the casing of the input cavity of the compressor and the bearing casing, which are in an environment of cold outside air.

It is also clearly seen in the figure that, despite the sufficient oil cooling of the supports taken into account in the thermal model, a rather significant thermal load falls on the bearing housing and to some extent on the rotor shaft from the hydrodynamic support. This again indicates the need for effective cooling of the supports.

In general, the heat fluxes from the hot part of the rotor are sufficiently efficiently discharged and do not reach to a great extent the rotor shaft and its supports, which indicates a fairly successful rotor design in terms of thermal state. Significant heat flow comes to the compressor wheel and the rotor coupling pin in the hot part, however, how critical this circumstance can be given only by analyzing the temperature field of the rotor, carried out below.

Temperature field

Fig. 16 shows the calculated temperature field of the rotor assembly.

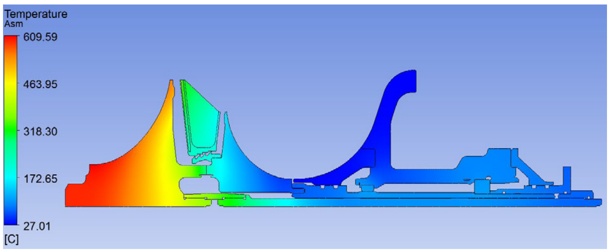

Fig. 16. Temperature field of the rotor assembly of microturbine

It can be seen that the maximum temperature is localized at the periphery of the turbine wheel, in the output part of the wheel, and also over the entire contact surface of the hot gas with the flow part of the turbine wheel. The rear part of the turbine disk turns out to be cooler due to the significant heat removal by cold compressor air of leakage into the cavities behind the turbine disk. It should be noted that this nature of heat transfer in the turbine wheel causes a significant temperature gradient over the wheel in the axial direction. However, the maximum temperature of the turbine wheel does not exceed 610 °C (Fig. 17), which is a valid value for the heat-resistant alloy used.

Fig. 18 shows the temperature field of the compressor wheel. The figure clearly shows that, despite the significant heat flux coming from the turbine wheel through the Hirt connection, the temperature of the compressor wheel does not exceed 250 °C and is localized in the zone of connection with the turbine wheel. The main part of the compressor wheel body does not exceed 200 °C. These temperatures are also acceptable for the titanium alloy used. It should be noted that a significant role in the heat flow insulation in the Hirt compound, the thermal resistance of the contact plays, which, in addition to the non-ideal contact of parts, is also due to the presence of an air gap between the teeth of the joint. The thermal resistances of the contacts, taken into account in the thermal model, are noticeable by gaps in the temperature field at the interface of the assembly parts.

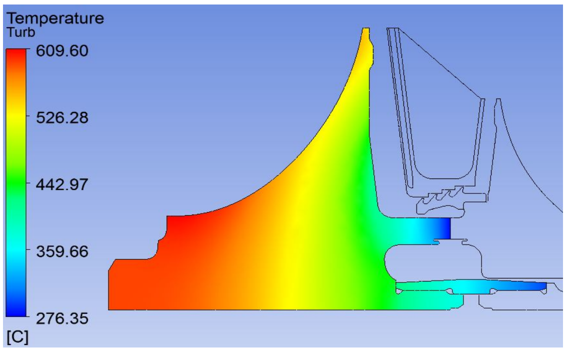

Fig. 17. Field temperature turbine wheels

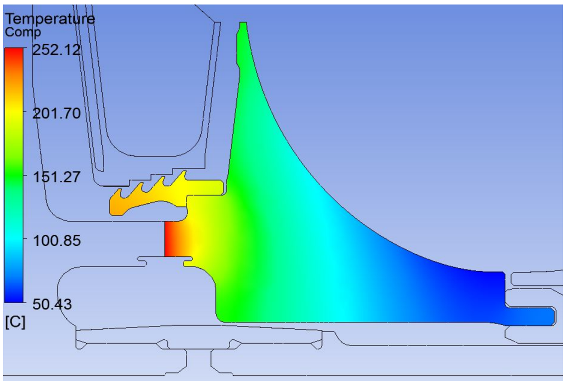

Fig. 18. Compressor wheel temperature field

Fig. 19 shows the temperature of the rotor pin. As described above, the heat flow is quite efficiently removed from the studs partially into the compressor through the air gap, partially into the rotor shaft and body parts.

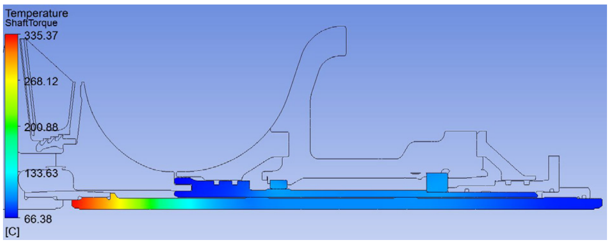

Fig. 19. Temperature field of the rotor coupling pin

In this regard, the heat coming from the turbine wheel through the turbine nut heats only a part of the stud located directly under the turbocharger. The rest of the studs remain cold, which increases the strength and resource characteristics of the rotor. The maximum temperature of the stud does not exceed 335 °C, which is quite satisfactory for the alloy steel used.

Fig. 20 shows the temperature distribution over the shaft and rotor bearings. As can be seen from the figure, the temperature of the supports practically does not exceed 100 °C, due to the account in the model of oil cooling of the supports. Due to the fact that no significant heat comes into the rotor pin, and the incoming heat is quite efficiently removed, the rotor shaft practically does not perceive the heat load of the hot part. Therefore, the thermal state of the shaft is caused by heat flows coming from the supports, and the shaft remains sufficiently cold. The temperature of the supports, in turn, is due only to heat generation of friction and the efficiency of oil cooling. In other words, the supports also do not perceive the heat load of the hot part. It must be said that this is a rather important positive aspect of the developed structure, which undoubtedly contributes to improving the strength characteristics of the rotor and its resource.

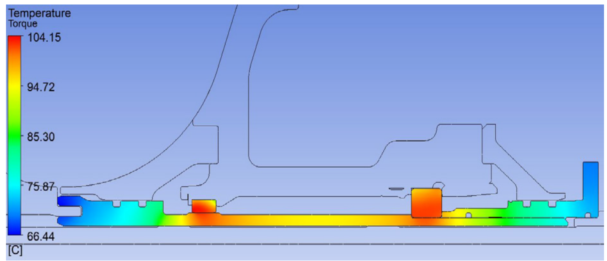

Fig. 20. Temperature field of the shaft and rotor bearings

The temperature of the bearing housing is shown in Fig. 21. As can be seen from the figure, the maximum body temperature is localized at the landing sites. The temperature of the body in these places does not exceed 100 °C. The external temperature of the body does not exceed 80 °C in the area above the rolling support and remains fairly low over the rest of the surface. It can be concluded that the bearing housing remains sufficiently cold, effectively dissipating the residual heat generated by the supports into the external environment.

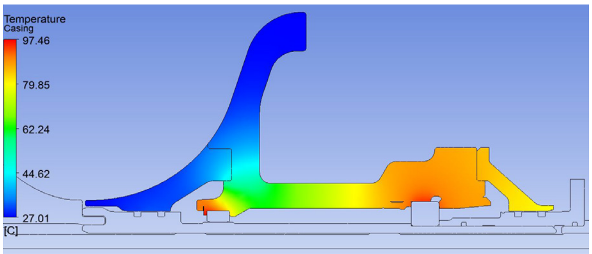

Fig. 21. Temperature field of the bearing housing

CONCLUSIONS

1. Based on the analysis performed, the fourth layout of the microturbine appears to be the most promising design. In general, the temperature field

of the turbine qualitatively corresponds to the analysis of the integral heat fluxes described above.

2. A quantitative assessment of microturbine rotor temperatures shows that the maximum temperature of the turbine wheel is 610 °C, the maximum temperature of the compressor wheel is 252 °C, the maximum temperature of the coupling pin on the turbine side is 335 °C, and the temperature of the rotor shaft and bearing assembly does not exceed 100 °C.

3. Based on the calculated maximum temperatures of the turbine, compressor and shaft, it can be concluded that the temperature state of the main parts of the rotor is satisfactory, since at these temperatures, there is no significant reduction in the strength limits for the respective materials of the parts. So for the material of the VZhL-12 turbine, the strength and fluidity limits are significantly reduced at temperatures above 900 °C; for the material of the VT6 compressor, a significant decrease in mechanical properties is observed at temperatures above 300 °C [14].

4. The resulting temperature field was used further as boundary conditions for calculating the strength and critical frequencies of the rotor. The use of a microturbine with an electric machine makes it possible to realize the advantages of a microturbine and the ability to use the installation as a Range Extender.

5. Optimum parameters and layout allow for high efficiency 38.4 % and a miniature microturbine volume.

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Electric Propulsion Systems Design Supported by Multi-Objective Optimization Strategies

M. Hirz[1], M. Hofstetter[1], D. Lechleitner[1]

[1]Institute of Automotive Engineering, Graz University of Technology (Graz, Republic of Austria)

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Abstract. Electric drive systems consisting of battery, inverter, electric motor and gearbox are applied in hybrid- or purely electric vehicles. The layout process of such propulsion systems is performed on system level under consideration of various component properties and their interfering characteristics. In addition, different boundary conditions are taken under account, e. g. performance, efficiency, packaging, costs. In this way, the development process of the power train involves a broad range of influencing parameters and periphery conditions and thus represents a multi-dimensional optimization problem. State-of-the-art development processes of mechatronic systems are usually executed according to the V-model, which represents a fundamental basis for handling the complex interactions of the different disciplines involved. In addition, stage-gate processes and spiral models are applied to deal with the high level of complexity during conception, design and testing. Involving a large number of technical and economic factors, these sequential, recursive processes may lead to suboptimal solutions since the system design processes do not sufficiently consider the complex relations between the different, partially conflicting domains. In this context, the present publication introduces an integrated multi-objective optimization strategy for the effective conception of electric propulsion systems, which involves a holistic consideration of all components and requirements in a multi-objective manner. The system design synthesis is based on component-specific Pareto-optimal designs to handle performance, efficiency, package and costs for given system requirements. The results are displayed as Pareto-fronts of electric power train system designs variants, from which decision makers are able to choose the best suitable solution. In this way, the presented system design approach for the development of electrically driven axles enables a multi-objective optimization considering efficiency, performance, costs and package. It is capable to reduce development time and to improve overall system quality at the same time.

Keywords: automotive engineering, electric powertrain, mechatronics system, development process, system design, multi-objective optimization

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Проектирование электрических силовых установок при поддержке многоцелевыми стратегиями оптимизации

М. Хирц[1], М. Хофштеттер[1], Д. Лехляйтнер[1]

[1]Институт автомобилестроения, Грацкий технический университет (Грац, Австрийская Республика)

Реферат. Системы электропривода, состоящие из аккумулятора, инвертора, электродвигателя и коробки передач, применяются в гибридных или чисто электрических транспортных средствах. Процесс компоновки таких движительных систем осуществляется на системном уровне с учетом различных свойств компонентов и их интерферирующих характеристик. Кроме того, учитываются разные граничные условия, например технические характеристики, эффективность, комплектование, стоимость. Таким образом, процесс разработки силовой передачи включает в себя широкий диапазон влияющих параметров и периферических условий и тем самым представляет собой проблему многомерной

Адрес для переписки
Хирц Марио
Институт автомобилестроения,
Грацкий технический университет
ул. Инффельдгассе, 11/2
8010, г. Грац, Австрийская Республика
Тел.: +43 316 873-352-20
mario.hirz@tugraz.at

Address for correspondence
Hirz Mario
Institute of Automotive Engineering,
Graz University of Technology
11/2 Inffeldgasse, str.,
8010, Graz, Republic of Austria
Tel.: +43 316 873-352-20
mario.hirz@tugraz.at

оптимизации. Современные процессы разработки мехатронных систем обычно выполняются в соответствии с V-моделью, которая представляет собой фундаментальную основу для управления сложными взаимодействиями различных дисциплин. Кроме того, применяются этапные процессы и спиральные модели, чтобы справиться с высоким уровнем сложности при разработке, проектировании и тестировании. Вовлекая большое количество технических и экономических факторов, эти последовательные рекурсивные процессы могут привести к неоптимальным решениям, поскольку процессы проектирования системы недостаточно учитывают сложные отношения между различными, частично конфликтующими областями. В этом контексте настоящая публикация представляет интегрированную многоцелевую стратегию оптимизации для эффективной концепции электрических силовых установок, включающую комплексное рассмотрение всех компонентов и требований на многоцелевой основе. Синтез системного дизайна основан на Парето-оптимальных конструкциях со специфическими компонентами с целью обеспечения работы, эффективности, комплектации и затрат, предусмотренных для данной системы. Результаты отображаются в виде Парето-фронтов вариантов систем электрических трансмиссий, из которых лица, принимающие решения, могут выбрать наиболее подходящее из них. Таким образом, представленный подход к проектированию системы для разработки осей с электрическим приводом обеспечивает многоцелевую оптимизацию с учетом эффективности, функционирования, стоимости и комплектации. Данный подход позволяет сократить время разработки и одновременно обеспечить улучшение качества системы.

Ключевые слова: автомобилестроение, электрическая трансмиссия, мехатронная система, процесс разработки, системное проектирование, многоцелевая оптимизация

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Automotive development processes and integration of propulsion systems design

Car development processes are composed of a number of steps and require complex interaction of car manufacturer, system- and components supplier as well as engineering provider. During past decades, an increasing application of virtual engineering provided great potential for reduction of development time and increasingly supported collaboration of the different involved parties. Nowadays, a typical full-vehicle development project has a duration of about 4 years (in case of derivate development less than 3 years) and the trend is moving towards further decrease [1]. As one main module, the drivetrain system plays an important role in the development of new cars – especially in case that new, electrified propulsion systems are going to be designed and integrated into the full-vehicle architecture. Fig. 1 shows the sequence of sections of a typical automotive development process. In addition to the main process phases, selected development disciplines are added, which are relevant for the development of propulsion systems.

In the beginning, the *Definition Phase* includes a compilation of characteristics of the new car to be developed, which comprises market research of future trends under consideration of customer demands and legislative boundary conditions. In addition, manufacturer-related strategic aspects are considered, e. g. integration of the planned model into existing model ranges or the development of new vehicle architectures, e. g. electric car platforms. At the end of the *Definition Phase*, product specifications are defined, which involves a definition of requirements for the subsequently performed vehicle development, containing a long list of prescribed product characteristics. In view of the propulsion system, this includes performance parameters, energy/fuel consumption, different types of boundary conditions, e. g. packaging- and space requirements, costs and others. In addition, technological specifications are pre-defined in this phase, e. g. type, layout and configuration of the powertrain to be developed.

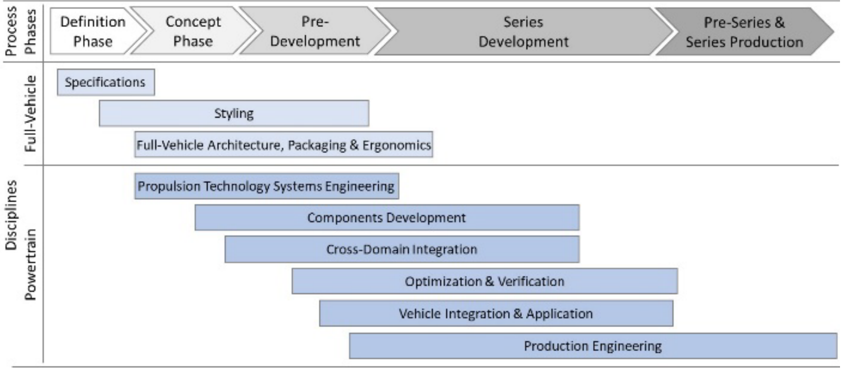

Fig. 1. Process phases and development disciplines in typical state-of-the-art car development

The development process itself starts with the *Concept Phase*, which includes conceptual design of the complete vehicle layout including styling, vehicle packaging and ergonomics, body and component development, and of course the propulsion system. Beginning with initial styling works, the vehicle architecture is built up and all components are integrated [2]. Drivetrain modules are taken over from existing platforms or newly developed, including new technologies, e.g. electric or hybrid propulsion systems. Here, it has to be distinguished between so-called conversion design and specifically developed electric vehicle platforms. In conversion design, hybrid- or electric drivetrain technology is implemented into traditional vehicle architecture. In many cases, the car to be developed is built on an existing vehicle platform that enables the integration of different types of drive train systems, e. g. combustion engine, hybrid-concepts and purely electric drive.

Fig. 2 shows such a vehicle architecture by an example of the Volkswagen Golf. As a difference, special-purpose design enables the optimized development of vehicle architecture according to the requirements of a specific propulsion technology. In this way, the result is optimized regarding the demands of electric drive architecture, but the flexibility concerning an implementation of different propulsion technologies is reduced. Fig. 3 exemplary shows a modern electric platform design, which is modular in view of variable wheelbase and configuration of the driven axles.

The *Pre-Development Phase* includes a continuation of concept development under consideration of detailed technological and economical aspects. This covers finalization of styling works, engineering of all components and modules, as well as far reaching verification and validation. In addition to virtual development, prototypes of modules and even vehicles are tested and investigated on test beds and on road. In this phase, engineering-, component- and module suppliers are increasingly involved in the development process.

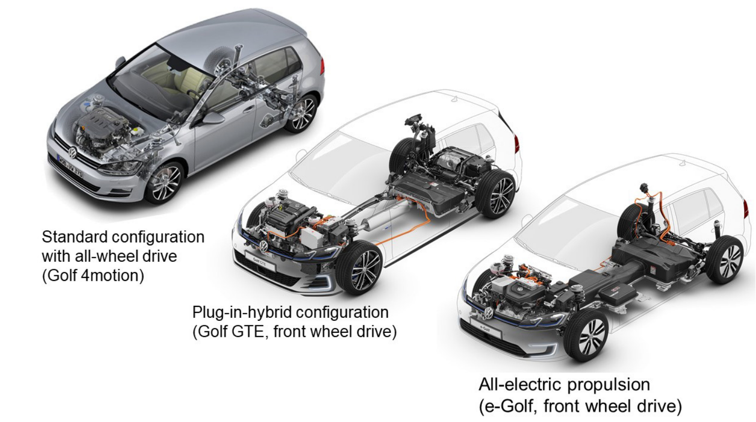

Fig. 2. Different drive train configurations of the Volkswagen Golf [3]

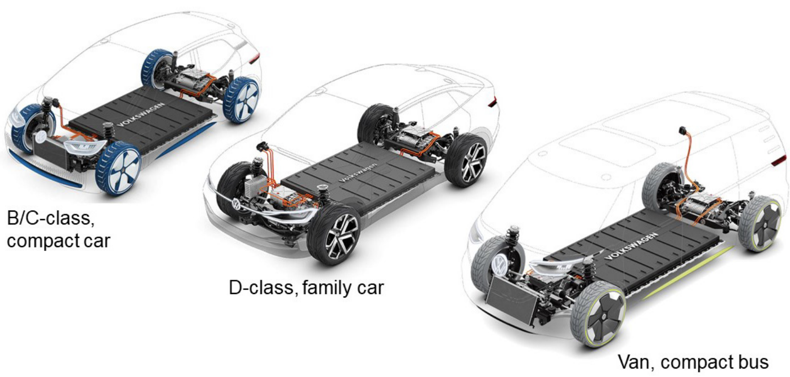

Fig. 3. Modular electric car platform from Volkswagen [4]

The *Series Development Phase* has a strong relation to production development and supplier integration including logistics, assembling processes and quality engineering. In this phase, a comprehensive virtual vehicle model serves as a basis for far reaching investigations of manufacturing-related procedures. At the end of this phase, both the new car model and its production are completely developed and all interactions with manufacturing facilities and suppliers are defined.

The final phase of car development includes *Pre-Series & Series Production*. Final settings of the assembly line and in the logistics management are done during the production of initial pre-series models. This includes final adjustments of machines and robots as well as quality related investigations, e. g. in the paint shop or optimizations in view of tolerances. After homologation of the new car in target markets, series production phase starts.

Electric propulsion systems are increasingly applied in both hybrid- and purely electric driven cars today.

In case of hybrid drivetrain technologies, there are different topologies available, e. g. parallel, serial and combined hybrids. Some of these topologies directly connect the electric motor(s) to the combustion engine or integrate them into the gearbox; others use electric driven axles. In case of purely electric propulsion, electric axles come to use. In this way, electric axle drives represent central components in a wide range of applications of hybrid- and electric driven cars. Fig. 4 shows an exemplary design of an integrated electric axle drive, consisting of power electronics (inverter), electric motor and a gearbox unit, which also contains the differential gear and drive shaft joints. Not shown in the figure, but essential is the drivetrain control system that is typically part of the inverter, consisting of a powerful microcontroller and embedded software.

The design process of electric axle drive systems is of high complexity because of the required integration of inverter, electric motor and mechanical gear, which covers three technological domains: mechanical, electrical and software engineering. In this way, a development process for mechatronics systems is presented, which supports an effective integration of cross-domain development. Initially, the so-called V-model stems from software development, and was taken over into other industries during the past decades. Today, it represents a standardized development process for mechatronics systems [6].

Fig. 5 shows a typical development process of automotive mechatronics systems according to the V-model [6, 7], which represents a special case of a waterfall model that describes sequential steps of product development [8, 9].

The process starts at the top end of the left branch with product specifications that result from a list of requirements. The entire left branch focusses on product design and is divided into a sequential chronology with increasing levels of detail. The *System level* includes product main level-related development, e. g. vehicle architecture, packaging, technology integration. After having defined main characteristics on *System level*, the *Module level* includes a breakdown of complex systems into several modules, e. g. vehicle body, drivetrain, chassis, comfort and driving assistance modules.

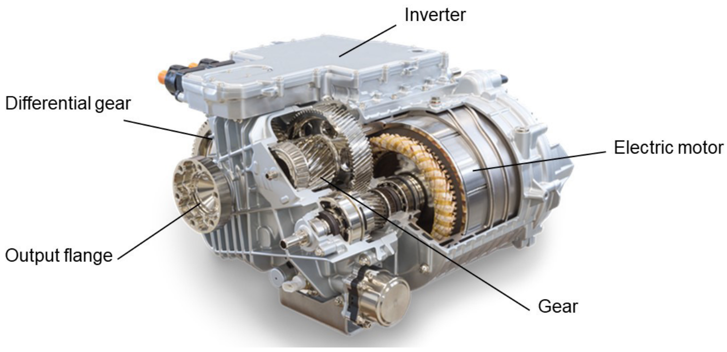

Fig. 4. Exemplary electric axle drive configuration [5]

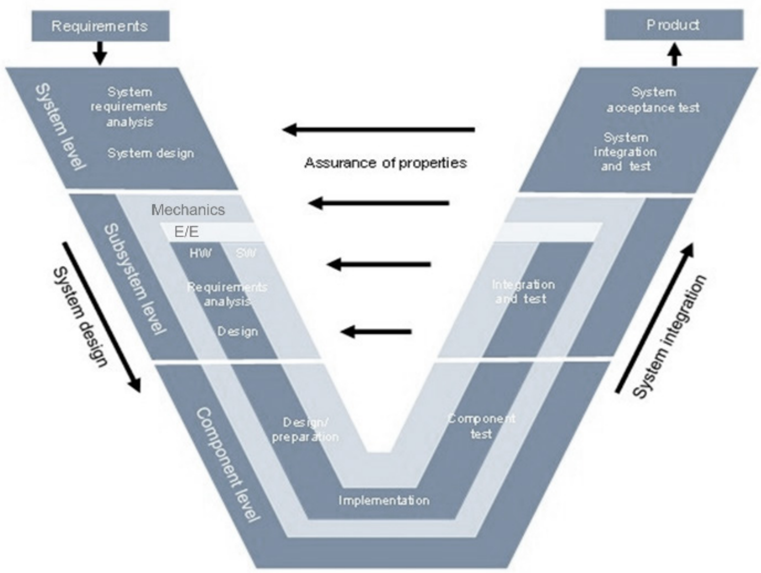

Fig. 5. Development process according to the V-model, according to [6, 7]

The different modules are designed under consideration of their interaction with other modules and in accordance with full-vehicle related specifications. Finally, modules are divided into their components, which are developed in the *Component level*. Cross-domain implementation is performed at the bottom level of the V-model in the course of component integration. Today, this is mainly done by product-oriented processes, which focus on product characteristics and functionalities.

The right branch of the V-model includes integration, testing and optimization at *Component-Module-* and *System level*. After being tested, components are built together into modules, which are integrated and tested according to their specific functionalities. In the final *System level* at the top end of the right branch, all elements are assembled to a full-vehicle prototype and tested for product compliance with the initially defined specifications. Typically for development according to the V-model is a close interaction of design and testing. In this way, data and information exchange between product design (left branch) and integration & testing (right branch) supports efficient improvements and optimization.

Fig. 5 also points to the different domains that occur in the development of mechatronics systems: mechanics, and electrics/electronics (*E*/*E*). *E*/*E* is divided into hardware and software development. One key of success lies in the introduction of flexible, interdisciplinary processes, which are able to consider different domain-specific methodologycal, functional and development-cycle-time related characteristics with the target of providing all product- and process-related information for effective cross-domain development of the mechatronics systems. Besides geometrical, structural, functional and production-related information of mechanics and hardware, this also includes software-related requirements, structural and functional information.

In case of highly complex products, e. g. electric axle drives, the development process is run through several times, especially on module and component level. Both duration and complexity of these development cycles differ significantly in the three domains, which leads to varying levels of maturity levels throughout mechanic, hardware and software development. The different domain-specific development procedures in combination with varying cycle frequency lead to a considerable increase of complexity in the development processes. This complexity can be handled by use of so-called spiral models. The spiral model stems initially from software industry, where it was developed to support handling of the complex (purely virtual) development processes during design and testing of control algorithms, programs and IT-applications, [10]. Fig. 6 displays an exemplary spiral model of mechatronics systems development processes following the V-model that highlights the separation of the development processes into *System* design as well as *Mechanics-Electrics* and *Software* development. In the example, the subsequently performed process phases are shown in more detail for the *System* level. The processes of the three development domains are not shown in detail but follow the same principle, considering the specific procedures of mechanics, electrics and software development. In practical applications, the V-model is run through repeatedly at the different levels and domains.

The phase of systems engineering plays an essential role in the development of complex mechatronics products, because it includes the general functional and structural layout. Out of knowledge gathered in the systems engineering phase, the subsequently performed domain-specific processes are supplied with required data and information for successful product development. In this way, the systems engineering phase has to fulfill the task of cross-domain conceptual design of mechanical, electrics and software components as well as their integration into the product to be developed.

In the development of electric propulsion systems, e. g. electric axle drives, the systems engineering phase includes the conceptual layout, optimization and integration of all involved components. Besides functional development, which focuses on performance characteristics, energy efficiency, controller design and embedded software, the proper selection and layout of electrical and mechanical components plays a crucial role. According to the introduced development process of mechatronics systems (Fig. 5, 6), system design is placed at the beginning of the V-model, respectively in the center of the spiral model. Considering the general automotive development process as stated in Figure 1, the focus of the presented approach is put on the initial phases, e. g. *Definition Phase* and *Concept Phase*. During these early layout and design procedures of electric axle drives, a number of boundary conditions, parameters and influencing factors have to be considered. These factors are partially uncertain because of early development stages and in addition often conflicting in terms of system optimization. In this context, the layout of electric axle drives represents a multi-objective, multi-criterial task that requires enhanced optimization methods.

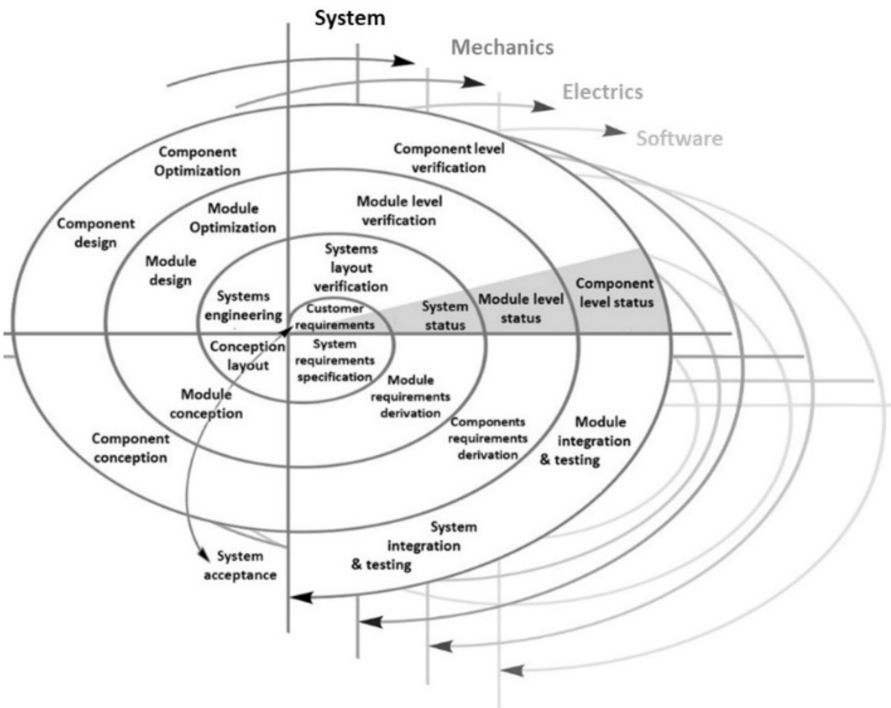

Fig. 6. Spiral model of mechatronics systems development processes following the V-model

Multi-objective design optimization of electric axle drives

Multi-objective design optimization of electric axle drives comprises the components electric motor, gearbox including differential gear, and the power electronics (inverter). The power supply system (battery, a combination of combustion engine and battery, or a combination of battery and fuel cell) is an additional important area of development, but this topic is not considered in the present work in more detail.

Today, there are two major topologies for electric axles available, which are basically set by the gearbox design: offset configuration and concentric configuration (Fig. 7). The offset design is the most common topology in the market, which is characterized by an axial offset between helical gearbox input and output shaft [12]. The concentric design often uses planetary gears and is more compact in general – but axial length restrictions and ground clearance are more critical, e. g. [13].

Typically applied electric machines are induction motors (IM, also called asynchronous machines, ASM) or permanent magnet synchronous machines (PSM). Both technologies are used as traction motors and should be considered in the systems engineering phase. Due to the introduced drivetrain configurations (Fig. 7), most of the gearbox solutions have an offset helical gear design (single-gear, two stage) or concentric designs with planetary gears.

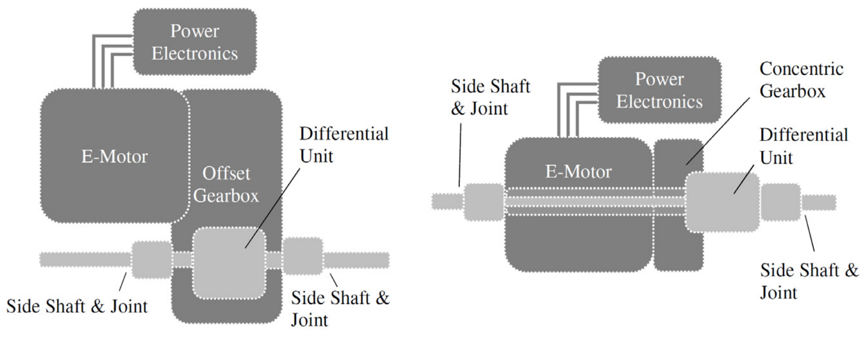

Fig. 7. Exemplary axle drive designs in offset (left) and concentric (right) configuration [11]

The gearbox design is adjusted to the mechanical loads induced by the electric motor under consideration of different load conditions. The integrated differential unit is usually a common part for all variants. Non-shiftable gearbox design is well established, since the speed range and torque characteristic provided by the electric motors is sufficient to cover the vehicle speed and torque requirements with one fixed transmission ratio. However, there are also some electric cars with two-speed gearboxes to enlarge the vehicle speed range and to improve the longitudinal vehicle dynamics behavior.

A power electronics (inverter) unit supplies the electric machine with corresponding voltage and current and consists of semiconductor technology and controller area. There are two variants of inverter placement, remote and attached. Remote inverters are placed remotely from the electric machine and connected by phase cables, whereas attached inverters are directly mounted on the electric machine. For the latter, there are variants with a single flat circuit board as well as with a segmented circuit board, e. g. [14], to achieve a better package integration into the electric machine.

Due to the fact, that in electric drivetrain development the phase of systems engineering plays a major role, several works have dealt with multi-objective optimization of electric propulsion systems. Eghtessad [15] investigates different powertrain topologies, component technologies and component parameters of battery-electric vehicles. Schulte-Cörne [16] describes the dimensioning of a hybrid architecture including electric axle drives with an integrated consideration of the hybrid operation strategy. Meier [17] uses a statistical design of experiments (DOE) as a means of establishing optimal hybrid powertrains. A major contribution has been developed by Hofstetter, who integrates packaging-related aspects of the vehicle, building-block system-related considerations of the drivetrain components as well as cost-related factors into the optimization approach [18, 19]. This approach is elaborated more detailed in the following section.

In general, systems design optimization targets the best fulfillment of requirements, which are defined in accordance to related evaluation criteria. For an axle drive layout, this includes *performance*, *package* and *costs* aspects. In this context, a multi-objective optimization process has to handle the trade-offs between different objectives, respectively evaluation criteria. The evaluation criteria themselves are derived from vehicle-related system requirements (Fig. 5).

Performance-related criteria include the required axle torque, power and efficiency at different operating points under specified power supply conditions. These requirements can be derived by analyses of vehicle dynamics and operation conditions, e. g. by use of longitudinal vehicle simulation, while also considering influences of the electric energy supply. In this way, torque, power and efficiency characteristics are derived by expert software tools for a specific motor type, based on analytical motor theory [20]. These information servers as a basis for conceptual layout of the electric machine. More demanding requirements, such as continuous power ratings and thermal management, are derived by use of 1*D*- or 3*D*-thermal simulation tools, e. g. [21]. The generated parameter sets can be used for more detailed electric machine design, e. g. by use of specified electric simulation software, e. g. [22].

Package criteria include the installation space provided by the vehicle architecture. They are developed in correlation with geometrical full-vehicle design and include geometrical restrictions caused by different aspects, e. g. wheelbase, track width, ground clearance, rear seats, trunk size or exhaust system. In conceptual development, the installation space available for electric axle drives is described as geometrical model. Evaluation of the axle model packaging is enabled by use of volume models created within computer-aided design (CAD) environment considering the main geometrical extensions, e. g. [23]. Besides the extensions of the main volume elements, also specific shapes, such as the corridors for the two side shafts, can be included. Fig. 8 shows the conceptual volume model of an exemplary electric axle drive, including inverter model (orange), electric motor model (yellow) and gearbox model (grey). The provided installation space, which is derived from the vehicle packaging model, is displayed in turquoise color. During geometrical optimization, the perfect positioning of all involved components within the pre-defined available volume is determined. This process also includes variable geometrical extensions of the components, e. g. variable length and diameter of the electric motor, variable gearbox configurations and dimensions.

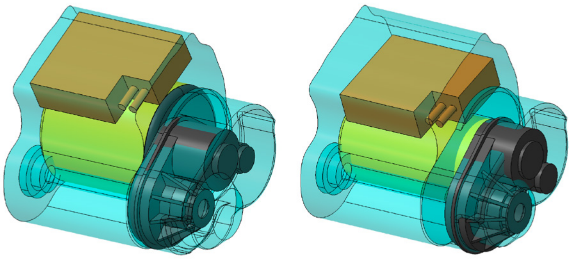

Fig. 8. Conceptual volume model variations of an axle drive system in offset-configuration [19]

Costs-related criteria consider material, supplied components, production effort and expenses of development. The material costs are calculated based on object lists in combination with CAD data. The production effort is assigned to specific component technologies and their manufacturing processes. Development costs are considered by favoring carry-over-parts over new product development if beneficial. In a more general approach, common parts of different electric axle configurations may also be taken into account, as proposed by [24]. All these influences are considered in cost estimation models covering the most important cost drivers. A maximum cost requirement may be set for the axle drive to allow only solutions below a certain cost level. Another example is to assess the best solutions achievable with limited development costs, which implies the existence of a higher carry-over-parts level, but might also come along with compromises in performance or package.

The electric axle layout is evaluated in the three criteria domains, whereby in each domain multiple objectives have to be defined, which are measured by metrics. The objectives define if a higher or lower metric is beneficial. In addition, pre-defined requirements are set, demanding a specific minimum or maximum value of an objective (which corresponds to a metric). The intersection of the requirements on the three domains (performance, package, costs) sets up the feasible design space, as illustrated in Fig. 9.

Numerous solutions may exist within the previously described design space. Every solution is evaluated with respect to the pre-defined objectives. It is thus not possible to determine a unique best solution in general terms, since these objectives may be conflicting. The outcome of the multi-objective optimization are the Pareto-fronts, which show the trade-offs between multiple and possibly conflicting objectives. For each criteria domain (performance, package, costs) numerous metrics are used to quantify the degree of compliance. For example, there are three different kinds of performance domain metrics (power, torque, efficiency) for several operating points. For each of these metrics, a compliance measure is applied to quantify the degree of compliance.

The proposed computer-aided optimization process is based on a library of available component technologies, which can contain parametric as well as non-parametric component models. The underlying models describe the component properties regarding performance, package and cost (Fig. 9). First, a preselection process is applied to cut down the number of possible component candidates. In this process, all those components are discarded, which obviously do not meet the axle drive requirements in any arrangement (component filter). For example, the peak power requirement eliminates all components that are not capable of providing or transmitting this peak power. The remaining components are combined to functional axle drive assemblies in a fully factorial way and those assemblies, which are obviously not capable of meeting the performance or cost requirements are discarded (performance/cost assembly filter).

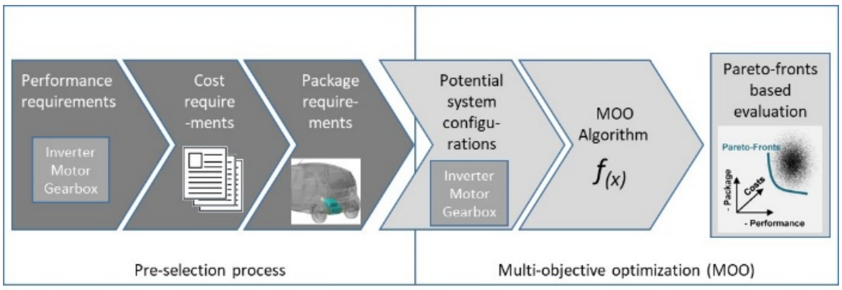

Fig. 9. Optimization process

The remaining configurations are tested against the package restrictions, also considering degrees of freedom in the package assembly (package assembly filter). Finally, the remaining assembly candidates contain the component candidates including all parameters that are used to determine the package-related parameter search ranges for the multi-objective optimization. The multi-objective optimization explores these parameter ranges as well as additional internal parameters, which are not essential for the package check, but do affect other properties (for example the number of turns per notch in an electric motor do not affect the outer dimensions, but change the torque-over-speed characteristics). The component parameters are applied to expert software tools, which generate the resulting component characteristics for the electric motor, the gearbox and the inverter. The assemblies of these components are then evaluated on system level to generate the performance and cost metrics, while the package metric can be obtained from the pre-processing evaluations by use of the pre-defined CAD models.

The system synthesis concept is based on a sequential optimization of the three main components *Power electronics*, *Electric machine* and *Gearbox* (Fig. 10). Finally, the computation results represent the trade-offs between the multiple objectives, which are depicted as Pareto-fronts and computed according to the pre-defined evaluation criteria.

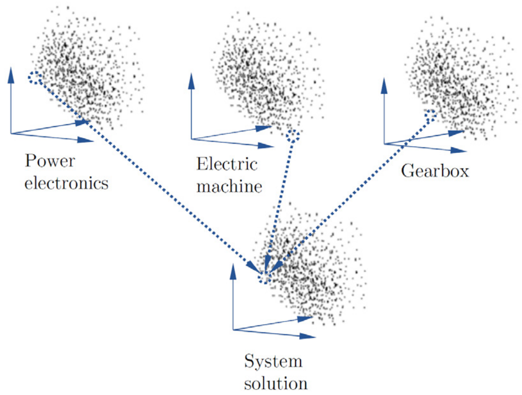

Fig. 10. System synthesis concept of the optimization approach [19]

In this way, the Pareto-fronts provide a multidimensional representation of the result of the multiobjective optimization process. As known from Pareto-fronts, the optimal result is not unambiguously defined, but depends on a trade-off as a function of the evaluation criteria [25]. In this way, it is up to the involved engineers and experts to select the final system configuration. The introduced approach supports decision making by provision of suggested, optimal design solutions considering the main criteria efficiency, performance, costs and package. Fig. 11 shows an exemplary optimization result, displayed as 3*D*-Pareto front, which contains the evaluation criteria *Package metric*, *Relative costs* and *Losses*, respectively drivetrain efficiency. Each dot in the diagram represents one found optimal solution. The best possible trade-offs between package metric and costs are displayed as circles.

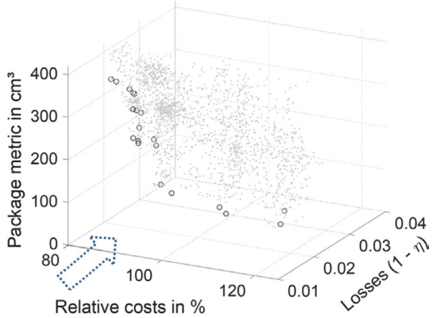

Fig. 11. Exemplary optimization result: 3*D*-Pareto front showing the evaluation criteria package metric, relative costs and efficiency [18]

CONCLUSIONS

1. The layout process of electric axle drives is performed on system level by involvement of component characteristics and their integration under consideration of pre-defined development targets, e. g. performance, efficiency, packaging and costs. In addition, various boundary conditions have to be incorporated, e. g. customer demands, legislative aspects and vehicle-related factors. In this way, the development process involves a broad range of influencing parameters and periphery conditions and thus includes a multi-dimensional optimization problem.

2. The present work introduces a systematic implementation of electric axle drive development into state-of-the-art development processes in the automotive industry and points to the importance of the early design phases in propulsion system layout and optimization. Integrated into the standardized processes of mechatronics systems development, an approach for multi-objective optimiza-

tion is introduced, that supports the handling of the occurring complex interactions of various design-related parameters. The introduced systems engineering synthesis is based on component-specific Pareto-optimal designs with the target to optimally handle performance, efficiency, package and costs for given system requirements. The results are displayed as Pareto-fronts of electric axle drive system designs variants, from which decision makers are able to choose the best suitable solution.

3. In this way, the introduced approach provides a methodological procedure to support decision making starting in the early layout phase with the target to improve effective systems engineering in electric axle drive development processes.

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Contactless Automated Express Evaluation of Damages to a Car Body by Visual Parameters

M. Tarasova[1], N. Filkin[1], R. Yurtikov[1]

[1]Kalashnikov Izhevsk State Technical University (Izhevsk, Russian Federation)

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Abstract. Explosive development of computer technologies and their availability made it possible to extensively focus nowadays on emerging state-of-the-art technologies, digitalization, artificial intelligence, and automated systems, including in the field of road safety. It would be reasonable to implement some technical devices in this respect to remove human factor and automate some procedures completed at the scene of a road accident. Automatically filled up road accident inspection records and, mainly, diagrams of the accident will reduce time required for the examining inspector and remove human factor. Ultimately, an automated road accident data sheet is suggested to be established. To tackle the issues above requires a technique to determine whether the produced damages to the car body result from the same road accident. The fact remains that there are circumstances when even vehicle trace examination would not do the job, in case of multiple corrosive damage to the body. In view of the above, a technique designed to determine whether the damages produced are caused at the same point of time gains its ground. A technique for a time-related corrosion examination is offered herein to cut expenditures for diagnostics and expert examination of road accidents. That will also eliminate the matters of argument with respect to the road accident evaluation in court. Among added benefits of the technique are that it is simple, quick to implement, and requires no human involvement. It is a well-established fact that each chemical element or a mixture of substances has its own time-invariant color attributes which allows to determine availability of one or another substance during corrosion of metal surfaces, by emission from the surface in question.

Keywords: road accident expert examination, artificial intelligence, color, corrosion, deformation of car body, RGB, car, vehicle, road safety

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Бесконтактная автоматизированная экспресс-оценка повреждений кузова автомобиля по визуальным параметрам

М. Тарасова[1], Н. Филькин[1], Р. Юртиков[1]

[1]Ижевский государственный технический университет имени М. Т. Калашникова (Ижевск, Российская Федерация)

Реферат. Благодаря бурному развитию вычислительной техники и ее доступности большое внимание в наше время уделяется новым современным технологиям, цифровизации, искусственному интеллекту и автоматизированным системам, в том числе и в сфере организации безопасности дорожного движения. В рассматриваемом аспекте было бы уместно внедрение технических средств, позволяющих исключить человеческий фактор и автоматизировать некоторые процессы на месте осмотра дорожно-транспортного происшествия (ДТП). Автоматизация процесса заполнения бланка протокола осмотра места ДТП и главным образом схемы ДТП позволит снизить затраты времени лица, проводящего осмотр, а также исключить человеческий фактор. По сути, представляется создание некого

Адрес для переписки
Тарасова Мария
Ижевский государственный технический университет имени М. Т. Калашникова
ул. Удмуртская, 139,
426069, г. Ижевск, Российская Федерация
Тел.: +7 912 454-49-59
tarasovamariya@yandex.ru

Address for correspondence
Tarasova Maria
Kalashnikov Izhevsk State Technical University
139 Udmurtskaya str.,
426069, Izhevsk, Russian Federation
Tel.: +7 912 454-49-59
tarasovamariya@yandex.ru

автоматизированного паспорта ДТП. Для решения таких вопросов просто необходимо создание методики, которая поможет определить, являются ли представленные повреждения кузова результатом одного ДТП. Ведь даже проведение транспортно-трасологической экспертизы не поможет в случае множественных повреждений кузова коррозией. Исходя из этого приобретает актуальность разработка методики, которая будет определять одновременность возникновения повреждений. Предлагается методика временной оценки процесса коррозии, что позволит сэкономить на диагностике и экспертизе дорожно-транспортного происшествия. При этом снимутся спорные вопросы оценки ДТП в судебных инстанциях. Дополнительными преимуществами данной методики можем считать простоту и скорость проведения экспертизы, отсутствие участия человека. Не секрет, что каждый химический элемент или смесь веществ имеет свои цветовые особенности, не изменяющиеся во времени. Наличие тех или иных веществ в процессе коррозии металлических поверхностей определяется по излучению от рассматриваемой поверхности.

Ключевые слова: экспертиза ДТП, искусственный интеллект, цвет, коррозия, деформация кузова автомобиля, RGB, автомобиль, транспортное средство, безопасность дорожного движения

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Introduction

All road safety-related challenges are covered by the Federal Targeted Program "Enhanced Road Safety in the Years of 2013–2020" [1] aimed at provision of the measures to reduce number of road accidents and used for comprehensive approach thereto.

However, it is too early to suggest that the issue can be settled to the fullest extent. Prompt visit to the scene of road accident and immediate actions taken by a group of highway patrolmen allow to clear the traffic way quickly and efficiently, which in its turn directly contributes to recovery of the road traffic capacity. The key element in this case is to capture the scene of accident. Well-established inspection of the scene as performed by the officials improves efficiency of investigative activities. However, it might be difficult to inspect the scene of road accident to the highest standard due to a number of factors, including traffic flow density, road conditions, the fact that the scene may take a large portion of the traffic way, climatic conditions, time of day, availability of technical devices for comprehensive inspection and study of the traffic way, and, mainly, human factor. Performance of inspectors at the scene of road accident impacts investigation findings and defines the need to call for one or another technical vehicle expert examination.

Given the global development of state-of-the-art technologies, an increasing attention is paid nowadays to emerging technologies, as well as artificial intelligence and automated systems. Road safety ranks high as well. That is the area where use of technical devices for automation of certain procedures completed at the scene of road accident is as relevant as ever and allows to remove human factor from the chain. This requires development of so called automated road accident data sheet, including automatically filled up road accident inspection records, which saves time of the examining inspector and gives an objective account of the situation.

There is a lot of techniques that can be used to determine whether a number of damages to the car body pertain to the same accident or there is a deceit under way. Alternatively, a vehicle trace expert examination might be considered. However, some factors, such as rust, might make the exert examination difficult. In view of the above, a technique designed to determine whether the damages produced are caused at the same point of time gains its ground.

The theoretical groundwork for the article is based on a number of studies dealing with road safety and technical expert examination of a car body [2–6], as well as atmospheric corrosion processes that take place therein [7, 8]. The studies that deal with color reproduction and image analysis [9], as well as color of rust spots and conversion of color channel vector for digital photos [10–12] can also be highlighted.

Having analyzed all available scientific literature and periodicals, it can be safely assumed that the evaluation as to whether corrosive damage to the car body is caused at the same point of time is poorly covered.

Body

Moisture sets corrosion of metal surfaces in motion. As soon as condensate contacts with a metal surface, its rusting begins. Its color and structure in the points where the metal surface is exposed to water change. A spongy rough red or even brown film appears which means that hydrated ferric oxide or, in common terms, rust has formed.

It is atmospheric corrosion that is the primary cause of damage to protective coating of a car body. The corroded surface is subjected to some processes that occur with time, resulting in change of ratio between hydrated iron compounds and oxides. Herewith, the layer corroded through and through changes its color which contributes to defining the corrosion stage and, therefore, time of the car damage.

Typical color changes in corrosion spots are covered in [13]. Comparing the color code of initial and corroded surfaces allows to find corrosion spots. As time passes, corrosion expands, additional spots appear, and the surface gains on color of corrosion products. To determine start-of-corrosion time, it is required to find a pattern in the way the color code changes between the initial and corroded surfaces.

Fig. 1 shows main corrosion products that are formed on surface of a car body. The additive color model RGB used illustrates that each chemical element has its own color.

Corrosion results in such substances formed on the surface, which combination is responsible for final color of the corroded surface. The color spectrum has a wide range, from yellow and orange to brown and even black. That poses a problem of finding a relation between the chemical substances formed on the surface, their concentration, and color of the corroded surface.

Among main corrosion chemical components are FeO(OH), $Fe(OH)_3$, Fe_2O_3 and Fe_3O_4. There is no point to discuss others due to their high chemical reaction rate.

The above mentioned RGB color model is based on additive color mixing, meaning that it describes color synthesis. There are only three channels (red, blue, and green) that are used to obtain a wide range of color shades.

The technique is as follows. An image sensor of a camera device, having a form of a grid made of individual pixels, acts as a sensing element. Each pixel has three separate elements (channels) to capture amount of light that strikes it and passes through red, green, and blue filters. Each channel features monochromatic perception, whereas its state varies from zero light perceived (0 %) to complete exposure (100 %). In particular, depth of the color perceived has 8-bit gradient, from black (0) to white (255). Therefore, color of an individual pixel can be defined based on combination of primary color gradients.

The sources [14, 15] suggest that color of the corroded surface of a car body changes with time. It means that different color of two spots of rust that is taken from the same metal surface but occurred at different times will bear evidence that different corrosion spots appeared in different circumstances, and it would be correct to say that the damages are caused under different conditions.

Accuracy of the system used is such that it will easily determine difference in time of the inflicted damages. It might be several days or even several years. The technique for processing the images of damaged elements of a car body is provided in [14]. Fig. 2 shows image expansion in color channels.

As can be seen from the above, establishing the time dependency of corrosion color may be used to determine time when the surface got damaged. The following technique will be quite of use. Let's carry out an experiment which will help define dependency of change in color of chemical elements and their mixtures on their concentration. Having provided identical illumination, main corrosion products with different concentrations are captured with a digital camera. A color mark with 18 % of grey is used as a marker. This is so called grey card that will be used to provide the conditions required for exposure during taking photos in specific circumstances, involving setting of corrected white color balance under the conditions of mixed lighting so that the image will be further used as a white-grey color standard.

Now, let's distribute the obtained density values between three main channels of the objects under study (red, blue, and green).

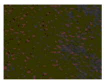
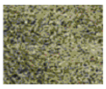
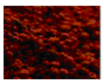
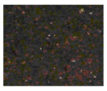
Chemical element	Color	R	G	B		Chemical element	Color	R	G	B	
FeO		0	0	0		FeO(OH)		148	158	56	
$Fe(OH)_2$		218	216	113		Fe_2O_3		141	104	63	
$Fe(OH)_3$		165	138	109		Fe_3O_4		0	0	0	

Fig. 1. Main corrosion products

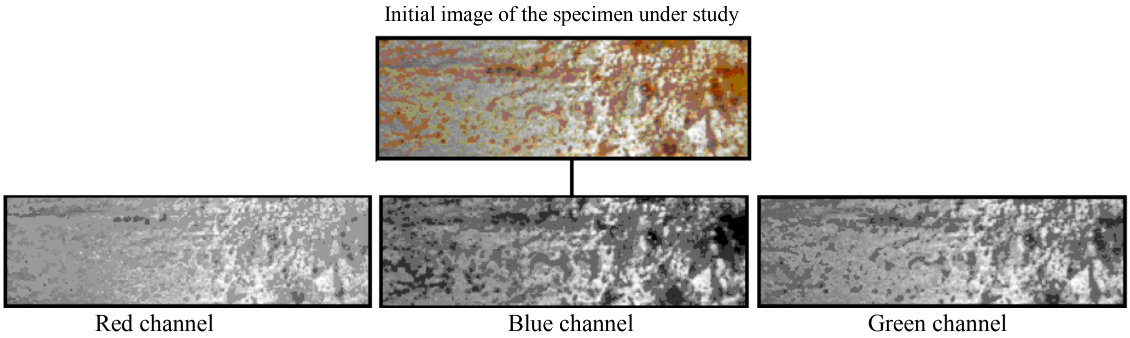


Fig. 2. Image expansion in three color channels

It can be concluded that color of corrosion products incrementally changes with time, which is accompanied by the change in density of color shades and, consequently, light reflected from corrosion products. This suggests that the damages inflicted are caused at the same point of time provided that color shades of corrosion spots and color density of rust in the damaged areas are identical.

Summing it up, a set of the evidences above can confirm whether damages to the car body are caused at the same point of time. This set can also be called a general population.

If corrosive damages to the car body pertain at least to two general populations, it can be said that rust did occur at the same time.

Now, let's discuss the case when two samples pertain only to one general population in more details. To do so, it is required to compare their mean values. Let's assume that both samples are independent and take the variant from among all admissible and possible ones where both variances are unknown but supposedly equal to each other. The selected variances of the first and the second populations will be used as an evaluation criterion. $S^2_{1\delta}$ and $S^2_{2\delta}$ are sample variances that are estimates of the same variance of the population σ^2.

There are good reasons to take critical values of the Student's distribution equal to 0.975 to ensure reliable results. Therefore, all damages to the car body, having such reliability will be confirmed to be inflicted as a result of the same road accident.

The procedure for determination as to whether damages to the car body are inflicted at the same point of time is provided below.

The areas of interest of the car body are captured with a digital camera. Their density gradient of primary colors is determined and added up. These resultant four color density samples (general populations) are processed so that sample mean values and sample variances are found for each general population. Two samples are formed for each general population, the first containing the values lower and the second containing the values higher than that of the respective general sample mean value. Then, sample mean values and sample variances are determined for all the samples obtained. A Student-Fischer test is used to check equality of sample mean values for each pair and that of sample variances. If the condition that the critical values corresponding to Student and Fisher distributions, determined from size of each sample and evaluation reliability, are higher for all respective pairs of sample populations is fulfilled, it can be concluded that the damages are caused at the same point of time.

Taking the proposed hypothesis and the technique as a basis, an express evaluation as to whether the damages are inflicted at the same time is developed.

Fig. 3 shows a flow chart for the express evaluation under discussion [16]. This method considers a car as a physical object, meaning that both damage spot and car model are taken into account. So are weather conditions (climate) and technical features of the vehicle.

During the examination, the object is captured with a camera, the corroded area is isolated with the use of software, and its color attributes are studied. After all color attributes are subjected to analysis, a conclusion as to whether the damages to the car body are caused at the same time is made, which allows to reveal deceit as a result of the expert examination and analysis of the road accident.

The technique is implemented with the special-purpose software intended for identification of time of damages. The result is taken as a basis of the judgment as to whether the damages pertain to the road accident under examination.

This software evaluates color shades of the damaged surface, which contributes to identification of corrosion spots and concluding about time of the damages (whether they are caused at the same point of time).

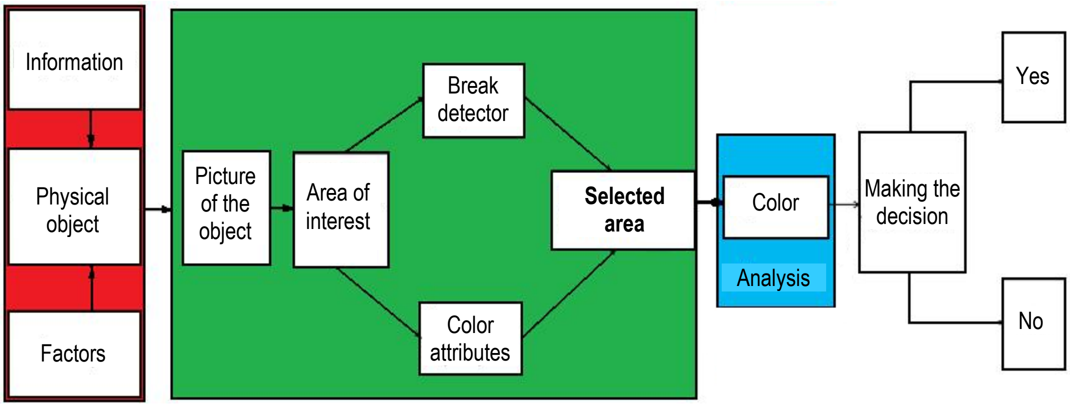


Fig. 3. Flow chart for express evaluation of corrosive damages to the car body

CONCLUSIONS

1. A technique for express evaluation is developed to be used during technical analysis of a car to determine whether the damages to the car body subject to corrosion are caused at the same point of time. This technique allows to define whether corrosion started at the same time, based on change in color of corrosion products. It may be used to reveal deceit during evaluation of consequences of road accidents.

2. An experiment was carried out to check efficiency of the technique for determination as to whether corrosion spots appeared on a car body at the same point of time. Herewith, experimental analysis shows that its accuracy reaches 95 %.

3. The key advantages of the technique are that it is simple, quick to implement, and requires no human involvement. Neither steel grade, atmospheric composition, nor other similar factors that would reduce accuracy of other corrosion evaluation methods impact investigation results.

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Skills and Training Requirements for the Future Transportation Sector of Europe

E. Bekiaris[1], M. Loukea[1]

[1]Centre for Research and Technology Hellas, Hellenic Institute of Transport (Thessaloniki, Greek Republic)

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Abstract. More than 10 million people are directly employed by the transport industry in Europe, accounting for 4.5 % of total employment and representing 4.6 % of Gross Domestic Product (GDP). This fact, combined with the rapid developments and changes of the sector, makes imperative the need to create, attract and retain appropriate staff. As the overall trend is to increase automation, the sector will depend more and more on specialised equipment and products. Future jobs will therefore require new and advanced skills in engineering as well as in back office operations, but at the same time, the growing interdisciplinary elements of transport activities will also require transport professionals with developed skills in safety, security, logistics, IT, behavioural sciences, marketing and economics. The European Research project SKILLFUL has developed a structured foresight into the vocational and academic qualifications in the Transportation sector of the future and has proposed training schemes and their supportive business models that could ideally be adopted European-wide, to enhance employability and sustainable industrial development in the transportation sector in Europe. The identification of future requirements constituted the basis of the project. The impact of new technologies and game changers, as well as emphasis on intermodality and interdisciplinarity on employability and future worker skills, have led to the development of relevant scenarios on future jobs knowledge and skills requirements, regarding the road transport in Europe. This has led to the identification and design of proper and specific curricula for training (with emphasis on middle-skilled professionals and lifelong learning), while also to the introduction of six novel concepts of business actors, expected to facilitate the training process and enhance the transport-education chain. The project goes a step beyond by addressing also critical issues towards a Pan-European master curriculum on transport.

Keywords: European transportation sector, future skill requirements, training, employability, business roles

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Навыки и требования к обучению с целью обеспечения будущего транспортного сектора Европы

Э. Бекиарис[1], М. Лукеа[1]

[1]Греческий центр исследований и технологий, Греческий институт транспорта (Салоники, Греческая Республика)

Реферат. В Европе более 10 миллионов человек заняты непосредственно в транспортной отрасли, что составляет 4,5 % от общей занятости (4,6 % валового внутреннего продукта (ВВП)). Эта статистика в сочетании с быстрым развитием и изменениями в данном секторе экономики предполагает необходимость обучения, привлечения и сохранения квалифицированного персонала. Поскольку общая тенденция заключается в увеличении процесса автоматизации, данное направление экономики будет все больше зависеть от специализированного оборудования и приспособлений. Поэтому на новых рабочих местах потребуются новые квалификации и навыки, передовые технологии в осуществлении инженерно-технических работ, а также в ведении технической документации; в то же время усиление роли междисциплинарных элементов транспортной деятельности также потребует привлечения профессионалов в области транспорта, обладающих высоким уровнем знаний и навыков в сфере безопасности, охраны, логистики, информационных технологий, бихевиористики, маркетинга и экономики. В рамках реализации Европейского научно-исследовательского проекта SKILLFUL был выработан структурированный прогноз будущих профессиональных и академических квалификаций

Адрес для переписки
Бекиарис Эвангелос
Греческий центр исследований и технологий,
Греческий институт транспорта
6-й км Карилау-Терми Роуд,
57001, г. Салоники, Греческая Республика
Тел.: +30 2310 49-84-53
abek@certh.gr

Address for correspondence
Bekiaris Evangelos
Centre for Research and Technology Hellas,
Hellenic Institute of Transport
6th km Charilaou-Thermi Road,
57001, Thessaloniki, Greek Republic
Tel.: +30 2310 49-84-53
abek@certh.gr

в секторе транспорта, а также предложены схемы обучения и поддерживающие их бизнес-модели, которые идеально подходят и могут быть приняты в масштабе всей Европы. Это должно повысить возможности трудоустройства и обеспечить устойчивое развитие транспортного сектора в Европе. Определение новых требований и легло в основу данного проекта. Влияние новых технологий и наличие решающих факторов, которые кардинально меняют ситуацию в сфере транспорта, выдвижение в категорию приоритетных интермодальности и междисциплинарности в вопросах трудоустройства и развития в будущем новых навыков привели к разработке соответствующих сценариев с целью формирования новых знаний и навыков для новых рабочих мест в сфере автомобильного транспорта в Европе. В связи с этим определены и разработаны надлежащие специальные учебные программы (особое внимание уделено подготовке специалистов среднего звена, вопросам организации образования через всю жизнь), а также внедрению шести новых концепций бизнес-акторов, что должно способствовать организации учебного процесса и продвижению транспортно-образовательной сети. Рассматриваемый проект выходит за рамки своих специфических задач, решая при этом и важнейшие вопросы, которые связаны с общеевропейской основной учебной программой по транспорту.

Ключевые слова: Европейский транспортный сектор, перспективные требования к навыкам, обучение, трудоустройство, роль бизнеса

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Introduction

Labour markets around the world are experiencing significant changes, within the transport sector having a leading role due to the constant technological development and the new business schemes. Moreover, social and demographic changes affect the field, as in ageing societies workers are retiring later, while labour mobility, immigration, and labour market integration contribute significantly to economic growth in many countries, causing, however, challenges that need to be addressed.

The specific challenge occurring from this, concerns the identification and assessment of future requirements for skills and training tools/methods across transport modes and systems, in order to improve the potential of the workforce but also improve the gender balance in the field of transport (as only a rate of 22 % represent women working in the transport sector) [1]. This creates particular challenges for those working in the transport sector, now and in the future, in terms of upskilling, training and qualifications.

Attracting and retaining skilled professionals in the transportation sector will require significant investment in training to address existing skill shortages and further adapt to the evolution of the sector and its developments. Training investments can be provided by different sides of the transport sector. Companies may decide to invest in training to address the specific needs of their activity. However, they would do so only if they are able to seize the return of this investment, by retaining their workers and offering them opportunities to be promoted. Where this is not possible, the skill shortage requires government intervention.

Across the different transport modes, the labour issue plays out in different ways. For example, a shortage of pilots exists in most regions of the world, while in the rail sector, skill requirements were traditionally of a technical nature, but are becoming more and more service-oriented, implying a shift in focus towards commercial and business competencies. Another important challenge for all sectors is also to acquire the necessary skills demanded by the integration of information technologies.

Within this context, and with regard to the transport sector, SKILLFUL identifies the needs and requirements for the user groups, which range from low to high skilled workers, across transportation modes and for multimodal chains and for all levels/types of works (blue collar, white collar, managers, operators, researchers, etc.).

The SKILLFUL project

The SKILLFUL project (http://skillfulproject.eu/) is a European funded Research project that aims to identify and present the necessary skills and competences for the transportation workforce of the future, in three different horizons (short-term in 2020, medium term in 2030 and long term in 2050), and to suggest the appropriate training schemes that will be required to address these needs. More specifically, the aim of the project is threefold:

- to critically review the existing, emerging and future skills requirements of the transportation sector professionals;
- to structure the key specifications and components of the curricula and training courses, in order to meet these challenges;

• to identify and propose new business roles in the transport and education chain, in order to achieve European wide competence development and take-up in a sustainable way.

The project analyses the emerging and foreseen trends in future transport, considering the whole transportation chain in Europe (including all transportation modes) and all different levels and types of transport professions (blue collar, white collar, managers, operators, researchers, etc.). The project also assesses existing training and education programmes of transport across Europe and suggests a number of University and Vocational training schemes the future transport needs, defining also the competences of their trainers and trainees.

Furthermore, six novel business roles are introduced and suggested for the education and training chain related to the transportation sector that are considered necessary for the effective future training provision throughout the European transportation sector.

Overview of SKILLFUL methodology

The whole project process can be divided into three major categories/steps:

➢ **Step 1.** Identification of Future Trends/ Needs & Best Practices;

➢ **Step 2.** Development of Training Schemes & Definition of Profiles and Competences;

➢ **Step 3.** Verification and Optimization of training schemes.

In a nutshell, the first step lays the necessary foundations for the implementation of the appropriate educational/training programs and relevant curricula, methodologies and tools and for configuring also their wider context, while also includes the identification of future trends and the impact on jobs that are likely to affect the European Transportation system (WP1). Following on from this, training methodologies and approaches have been identified and developed to meet the emerging and future needs of transportation professionals (WP2). This first part of the project is the one that has identified the needs existing in the whole chain system of Transport and education, with the identification of: a) the factors that will affect the transport system over the next years and in different time frames (short-term until 2020, mid-term until 2030 and long-term until 2050), whereas game changes, new and evolving technologies, new services and business schemes etc.; b) how this is going to be done (i. e. what factors will bring what changes); c) which professions jobs is foreseen to be mostly affected and what news ones are expected to emerge, resulting to lists with 28 specific professions and/or positions.

This prioritisation has acted as a "feeder" for the next SKILLFUL activities and main outcomes of the project; indicatively the following ones:

• connection of emerging training needs to the existing educational systems, noting and tackling further educational needs and gaps;

• suggestion and development of new training schemes in order to address the aforementioned training needs and gaps;

• identification of requirements and competences both for trainers and trainees and for each training module/scheme developed within SKILLFUL;

• identification and description of the six new business roles, proposed for the education and training chain related to the Transportation sector, expected to change the future training provision of the transportation sector and become the catalyst for its sustainability.

Expected changes in the human capital of the transportation system in Europe and suggested training schemes

The analysis made within the SKILLFUL project, as described above, provided some interesting outcomes about the technological and business trends that are already affecting or are expected to affect the European transportation system in the near and long future. The main trends that are expected to influence transport in Europe and its employability, as identified by the project are listed below:

• globalisation;

• digitalisation and connectivity;

• greening of transport (electrification, alternative fuels, propulsion systems);

• automation (robotics, autonomous and unmanned transport systems);

• smart transport (tracking, predictions, big data, efficient logistic and transport chains);

• mobility as a service, sharing/combined transport systems, multimodality;

• new transport vehicle systems adopting future needs of the customers regarding on demographic and climate change and needs;

- safe and secure transport;
- employability and sustainable employment.

During the interviews that have been conducted within the first phase of SKILLFUL, participants have been asked to highlight the professions, jobs and occupations that they foresee to be most affected or may disappear by also defining the timeframe of these changes, while also suggest the new occupations that are expected to arise in the same timeframes, in order to cover the emerging and future needs of the transport system in Europe and worldwide. For the justification of all these estimations, direct correspondence between each one of the future changes in the occupational sector with specific driving forces has been made, while also a description of the responsibilities and competences for the altered and emerging jobs has been provided. Thus, according to the outcomes of SKILLFUL, 28 occupational fields of the transportation sector have been defined, concerning the professions that are expected to be mostly affected by the present and future changes and developments of the European transportation system (13 professional fields for jobs/positions to be changed or eliminated and 12 groups for jobs/positions to be emerged) [2].

Development of the training courses and schemes

One of the project objectives was to propose and develop future training curricula and schemes both for the university education and the vocational training of the transport sector's workforce, as well as to identify critical issues to be addressed in order to meet the future needs of the field. Proposed future training curricula and courses included information on course content, objectives and learning outcomes. At the same time, the trainees' minimum requirements together with trainer's competences for each course have been defined and described by their developers. The trainer's competence was understood as a capability including knowledge, skills, attitudes and experiences to perform or carry out defined tasks in a particular context of training. It was set in the wider context of the EU's work in transport field to be able for future development and flexible to the needs of practice. A full list of requirements for trainer's competences for each training scheme was based upon a conceptual framework and on relevant outputs of previous project work, including literature review and a wide consultation of stakeholders (internal and external to the Consortium of the project), who have been identified as experts either in the field of transport or education/training or both.

In addition, a detailed analysis was performed for each course, in order to identify the correlations between the emerging and future trends in the transport sector to be covered on the one side and with the most promising training methodologies of the future. These correlations were retrieved in for each course in order to ease readability and interpretation of the identified expected changes and additional needs for the future. The most relevant training methodologies and tools that have been identified are listed below:

➢ **Training methodologies**

- E-learning.
- Virtual/augmented reality.
- Gaming environment.
- Human led individualized training.
- Blended learning.
- Peer led/ mentoring learning programme.
- Traditional lecture.
- Networked learning (e.g. social media networking).
- Smart learning technologies: personalised learning processes and schemes based, for example on big data, machine learning and AI.
- Scenario/story based learning.
- Training on the job/experiential learning.
- Informal learning.

➢ **Training tools and technologies**

- Portfolio.
- Smart learning technologies.
- Virtual Learning Environment.
- Educational robotics.
- Podcasting.
- Game-based learning.
- Virtual/augmented reality.

➢ **Settings**

- Distance (D-)/Mobile (M-)/Ubiquitous (U-) – Learning.
- Flipped/inverted Classroom.
- Work-based learning.

- Collaborative/team-based learning.
- Informal learning.
- Networked learning (social network technologies).
- Pedagogical model.
- Heutagogy/E-heutagogy.
- Active/Authentic learning.
- Observation/Discovery-based learning.

Within SKILLFUL 34 training courses have been suggested and described and 17 of them have been also fully developed and evaluated through the realisation of pilots, including real users. SKILLFUL courses have been clustered in the following categories.

- Courses for **transport infrastructure operators** addressing the requirements for new skills and competences to catch up with emerging technologies.
- **Lifelong training schemes for low – to middle-skilled** segments of transport professionals.
- **Interdisciplinary thematic courses** on key technologies, services, and trends that focus on issues proven to have a transferable character among modes.
- The **Young Researchers Seminar,** which is a joint initiative of ECTRI, FERSI and FEHRL organised every 2 years in a different European city. Within SKILFLUL two seminars have been organised focusing on the issues and trades identified by the project and with the participation all researchers from all modes.

SKILLFUL has also suggested and designed a first core syllabus towards a Pan-European Transport Engineering master, together with the development of several modules, in accordance again to the requirements that have emerged by the outcomes of the SKILLFUL project.

New business roles in Transport Education and Training chain

During the second phase of the SKILLFUL project new business roles have been identified and proposed for the education and training chain related to the Transportation sector. The promotion and adoption of these business roles could dramatically change the future training provision of the transportation sector and ensure in a great extend its sustainability. For example, as energy aggregators have paved the way for new and more efficient schemes for the reduction of energy consumption Europewide; "knowledge aggregators" may equally become the catalyst for a sustainable and advanced VET/CVET quality in the transportation area. Furthermore, some of the suggested roles, such as the ones of "training certifiers" and "training promoters" could also help the expansion of training schemes from local/national level to European and, thus, strongly facilitate the mobility of the European workforce

Based upon the outcomes of the SKILLFUL project, as indicatively described above, six new roles of business actors have been identified and suggested (Tab. 1).

Table 1

Suggested business roles by SKILLFUL project [3]

Transport Knowledge Aggregators	Transport Knowledge Aggregators are entities that collect and analyse information on emerging technologies and services in the transport domain from different sources. Their mission is to aggregate them, connect them and produce training courses to offer to the greater Transport Education and Training Ecosystem
Transport Lifelong Training Promoters	Lifelong learning promoters in Transport are actors that support financially, institutionally or by other means the continuous re-skilling (usually upskilling) of Transport workforce , in order to keep on pace with emerging job needs and enhance employability of the existing workforce
Transport Training Certifiers	Transport training certifiers are entities that have the authority of de jure or de facto certifying key knowledge and skills in the Transportation sector that are then acknowledged across the sector Europewide
Transport Training Infrastructure Providers	Transport Training infrastructure providers are entities that open to third parties (with various business models) big infrastructures for the purpose of training and skills creation of transport professionals
Collaborative passion arenas in Transport	Collaborative passion arenas in Transport refer to the equivalent of open source development communities for skills' creation. It concerns signified communities that create and share knowledge in Transport, collaboratively developing alternative knowledge and self-organising/recognising it between them; through Hacathlon or equivalent competitions. They are based on social communities and co-creation spaces
In vivo Altschool social networks in Transport	In vivo Altschool social networks in Transport can be defined as training/skills development environments on Transportation issues within the living society, with emphasis on mutual training and real life skills creation

Business roles and professional titles like "aggregators", "promoters", "certifiers", "infrastructure providers" and "collaborative arenas", have been already met in different business domains. The Information and Communication Technology (ICT) sector has largely contributed to new ways of conducting business through the forms that services have taken, i. e. products or services are not sold as used before, but are rather "rented" or paid for during their use by the customer. Within SKILLFUL, such roles are transformed and instantiated for promoting future skills in the Transport sector.

CONCLUSIONS

1. The transport sector is going through major changes, as global challenges and megatrends like automation and digitalization, together also with safety and security concerns, are affecting the future of the whole transport system and its human capital. These constant technological and business developments and the growth of the transport sector also make the need for continuous education, training and qualification of transport professionals imperative. In this context, one of the main challenges for the European transport sector is also whether it would be able to attract but also maintain that are properly skilled and able to cope with the new needs of the sector.

2. Considering the importance of such employability and education/ training issues for the whole Europe, the EU funded research project SKILLFUL has been working on the identification of the leading relevant scenarios on employability enhancement in the future, as well as towards the identification of key educational and training schemes for all levels and types of transport occupations, training approaches, and transport modes, in order to meet the future needs of the sector. The SKILLFUL project aims to generate a structured foresight into the vocational and academic qualifications in the transportation sector of the future that could be adopted European-wide, and to enhance the future employability of the European transport sector.

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Analysis of the State of the Road Traffic Safety in the Republic of Kazakhstan

K. Ibrayev[1], A. Ibrayev[1], D. Kapskiy[2], Y. Kot[2], A. Rybinskiy[3], S. Bogdanovich[3]

[1]GOLD PRODUCTS LLP (Nur-Sultan, Republic of Kazakhstan),
[2]Belarusian National Technical University (Minsk, Republic of Belarus),
[3]Belarusian Road Scientific-Research Institute “BeldorNII” (Minsk, Republic of Belarus)

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Abstract. The article presents the results of the study of the road traffic safety on the automobile roads of the Republic of Kazakhstan. We performed the analysis of the main indicators, specifying the state of the road traffic safety on the automobile roads of the republican significance of the Republic of Kazakhstan. In many regulatory acts, such as “The Priority Action Plan for Improving the Road Traffic Safety of the Republic of Kazakhstan for 2017–2020”, developed with the support of the Asian Development Bank, and in the “National Concept of Road Traffic Safety” project as well , developed by the Interdepartmental Research Institute called “The Academy of Law Enforcement Agencies” of the General Prosecutor’s Office of the Republic of Kazakhstan, the urgent need to improve road traffic safety is clearly pointed. At the same time, it is necessary to have the information about the extent of the existing problem in the field of road traffic safety, which is ensured by the constant consideration and analysis of the statistical indicators, as well as by planning appropriate measures aimed at correcting the situation and achieving planned indicators in the framework of, for example, the national concept of road traffic safety. Currently, statistics on road traffic accidents, occurring in Kazakhstan, are published by the Committee on Statistics of the Republic of Kazakhstan and the Committee on Legal Statistics and Special Accounting. However in the current situation, this is not enough, especially since the ARC MIID of the Republic of Kazakhstan outlined the program of actions aimed at eliminating the existing shortcomings in the field of the road traffic safety and significant improving its indicators. The analytical investigation of the status of the road traffic safety on the roads of the Republic of Kazakhstan was carried out. This will become a kind of starting point in the consistent work in this direction, which will provide the interested parties, first of all the experts, with the high-quality and reliable information about the main figures, characterizing the state of safety of the road users. Based on objective accident data, it is possible to take the effective measures aimed at improving the situation on the roads of the Republic of Kazakhstan.

Keywords: road traffic safety, road traffic accident, actual state, statistics, indicators of the state of the road safety

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Анализ состояния безопасности дорожного движения в Республике Казахстан

К. Ибраев[1], А. Ибраев[1], Д. Капский[2], Е. Кот[2], А. Рубинский[3], С. Богданович[3]

[1]Компания «Голд Продактс» (Нур-Султан, Республика Казахстан),
[2]Белорусский национальный технический университет (Минск, Республика Беларусь),
[3]Белорусский дорожный научно-исследовательский институт «БелдорНИИ» (Минск, Республика Беларусь)

Реферат. В статье представлены результаты исследования безопасности дорожного движения и проведен анализ основных показателей, определяющих состояние безопасности дорожного движения на автомобильных дорогах республиканского значения Казахстана. Во многих распорядительных документах, таких, например, как «Приоритетный план действий по повышению безопасности дорожного движения в Республике Казахстан на 2017–2020 годы»,

Адрес для переписки
Ибраев Кензат
Компания «Голд Продактс»
ул. Туркестан, 30/224,
010000, г. Нур-Султан, Республика Казахстан
Тел.: +7 701 614-42-40
goldproducts.kz@gmail.com

Address for correspondence
Ibrayev Kenzat
GOLD PRODUCTS LLP
30/224 Turkistan str.,
010000, Nur-Sultan, Republic of Kazakhstan
Tel.: +7 701 614-42-40
goldproducts.kz@gmail.com

разработанном при поддержке Азиатского банка развития, а также в проекте «Национальная концепция безопасности дорожного движения», подготовленном Межведомственным научно-исследовательским институтом «Академия правоохранительных органов» Генеральной прокуратуры Республики Казахстан, четко указана острая необходимость повышения безопасности дорожного движения. В то же время необходимо иметь информацию о масштабах существующей проблемы в области безопасности дорожного движения, что обеспечивается постоянным изучением и анализом статистических показателей, а также планированием соответствующих мер, направленных на исправление ситуации и достижение запланированных показателей в рамках, например, Национальной концепции безопасности дорожного движения. В настоящее время статистика дорожно-транспортных происшествий, происходящих в стране, публикуется Комитетом по статистике Республики Казахстан и Комитетом по правовой статистике и специальному учету. Однако в сложившейся ситуации этого недостаточно, тем более что Министерство индустрии и инфраструктурного развития Республики Казахстан наметило программу действий, направленную на устранение существующих недостатков в области безопасности дорожного движения и значительное улучшение ее показателей. Проведено аналитическое исследование состояния безопасности дорожного движения. Это станет своего рода отправной точкой в последовательной работе в данном направлении, которая предоставит заинтересованным сторонам, в первую очередь экспертам, качественную и достоверную информацию об основных показателях, характеризующих состояние безопасности участников дорожного движения. Исходя из объективных данных о ДТП, можно принять эффективные меры, направленные на улучшение ситуации на дорогах Республики Казахстан.

Ключевые слова: безопасность дорожного движения, дорожно-транспортное происшествие, реальное положение, статистика, показатели состояния дорожной безопасности

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Introduction

Various international organizations collect, analyze and publish statistics on the road traffic safety on roads. These are, for example, WHO, the World Bank, the European Commission, the OECD, and others. Some countries also publish their national reports on the road safety, including the world leaders in improving the road safety such as Australia, Great Britain, Sweden [1–3] and some others. This, once again, testifies to the importance and seriousness of the problem of improving the road traffic safety on auto roads. This applies to the Republic of Kazakhstan as well.

The most scaling statistical analysis of the road traffic accidents in the context of various countries of the world is carried out by WHO. Currently, two such studies are known that were carried out in 2009 [4] and 2013 [5]. The main indicator of the road safety according to WHO is the number of deaths in the road accidents per 100.000 people of the country. So, the average world indicator (as of 2013) is 18.0 deaths in the road accidents / 100 thousand people, while in Europe – 8.7 deaths in the road accidents / 100 thousand people, in Kazakhstan 24.2 deaths in accident / 100 thousand people [5].

The experience of compiling and analyzing of such summarized information about the accidents on the road network shows that such periodic reports not only hold up-to-date information, but also capture the relevant trends, which in its turn, helps to make reasonable management decisions, allowing, to some extent, to control the overall situation in the field of the road traffic safety.

The WHO data for 2009 [4] and 2013 [5] show that there are countries that are better than others in solving the task of minimizing the consequences of the road accidents, which allows us to hope to improve the situation at the national level. For this, first of all, it is worth to turn to the analysis of the foreign experience.

According to the indicator called as “the traffic fatalities per 100.000 people”, Sweden is the safest country with an indicator of 2.8 people per year (as of 2013), the UK – 2.9 people who died in road accidents / 100 thousand people, Germany – 4.3 deaths in traffic accidents / 100 thousand people, the USA – 10.6 deaths in traffic accidents / 100 thousand people, Australia – 5.4 deaths in traffic accidents / 100 thousand people, Canada – 6.0 fatalities in road accident / 100 thousand people [5]. This indicator for Belarus is 13.7 deaths in traffic accidents / 100 thousand people, for the Russian Federation – 18.9 deaths in traffic accidents / 100 thousand people [5].

In relation to the Republic of Kazakhstan, we considered four groups of data, which include:

– general and detailed information about the nature, causes and consequences of road accidents as a phenomenon in the Republic of Kazakhstan as a whole and by regions over the past five-year period;

– the information characterizing the place and the time of the accident in the Republic of Kazakhstan for the previous year;

– the general and detailed information, quantitatively and qualitatively characterizing the participants of the accidents in the Republic for the last reporting period;

– the reference information characterizing the network of the republican highways and the fleet of vehicles required for the comparative analysis.

For the analysis we used the information from the official website of the Committee on Statistics of the Ministry of National Economy of the Republic of Kazakhstan. The graphs below are based on the information contained therein.

The road traffic safety of the National auto roads

According to the statistics, the peak in the number of accidents in Kazakhstan falls on 2013. In subsequent years, there has been a significant improvement in the generalized indicators characterizing the road traffic safety (Fig. 1).

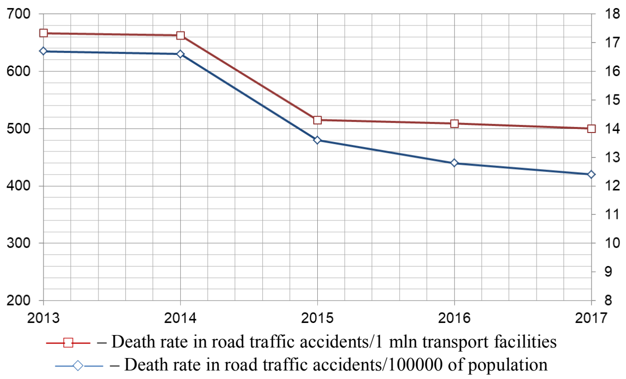

Fig. 1. Dynamics of the changes in the road traffic safety indices in Kazakhstan

Currently, this tendency is not so pronounced, in particular, on the network of the republican roads there was no significant improvement in indicators characterizing the state of safety in 2018. The positive tendencies in some areas are offset by negative dynamics in others. Only in one region of Kazakhstan – East Kazakhstan – in the last two years there has been a consistent decrease in both the total number of accidents and the severity of their consequences: in comparison with 2016, the number of accidents recorded in 2018 decreased by 31 %; the fatalities in road accidents decreased by 26 %; the number of injured was reduced by 30 %.

In absolute terms, the situation is least favorable in the Almaty region: the largest number of recorded accidents, fatalities and injuries – 802 accidents (+46 % by 2017), 206 fatalities (+20 %) and 1255 injured (+46 %), respectively. When considering the road traffic safety from the perspective of accident indices, the negative accents affect not only Almaty, but Zhambyl and Akmola regions as well. The accident rate in these regions had the greatest impact on the average value of the number of accidents per 100 thousand of the population of Kazakhstan, which in 2018 amounted to 18.1 for the republican roads (Fig. 2). Taking into account that in the remaining eleven regions this indicator is three to four times lower than the national average, the close attention should be paid to these regions when planning the work to improve the road traffic safety.

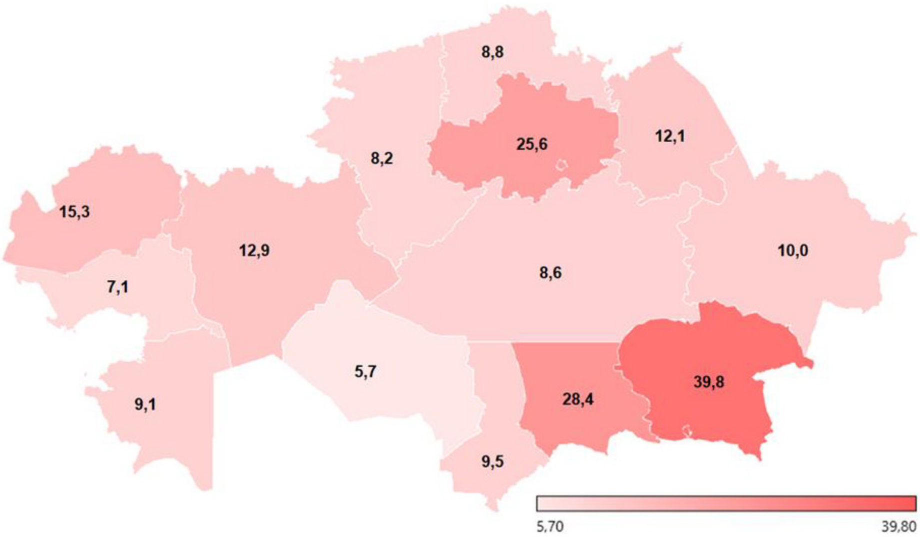

Fig. 2. The traffic fatalities in 2018 on the republican auto roads per 100 000 of the population

The reasons and the circumstances of the road accidents

The results of the numerous studies conducted around the world show that the non-compliance with the speed limit significantly increases the risk of the traffic accidents [6]. The relationship between the speed and the road traffic safety is not just statistical, but it is causal as well [7]. The continuous authoritative research only confirms these provisions [8].

In Kazakhstan, as well as in the whole world, the main cause of the accident is the non-compliance with the speed limit (Fig. 3), specified for this section of the road – 38 % of the total amount (923 accidents). At the same time the most adverse outcome is observed in an accident in which the vehicle enters an oncoming lane (head-on collision): in 71 out of 100 cases, this type of accident is fatal for one of the participants, while another 247 people are injured. Despite the fact that the total number of such accidents slightly exceeds 10 % of the total amount, the death rate in them is 20 % of the total, and almost every six wounded received injuries during the reporting period precisely when leaving for oncoming traffic.

Driving under the alcohol influence in the world practice [9] is recorded as the most malicious way of neglecting the public order, and at the same time, this way is the most dangerous from the point of view of social consequences. The statistics of the accidents on the republican roads of Kazakhstan indicate that drug intoxication (including alcohol) is not so common (Fig. 3), and mortality in such accidents is about 21 %, which is the eighth cause of death in road accidents. In Kazakhstan, in 2018, the legislation regulating the inspection of drivers and the procedure for determining their alcohol intoxication changed. Under the new rules, the blood alcohol content of the driver should be more than 0.5 per mille in order to record the fact of driving under the alcohol intoxication.

The minimum number of road traffic accidents in 2018 occurred in the shortest month of the year – February: 123 road accidents, one in three of which were fatal (Fig. 4). The maximum number of road accidents occurred in November – 259 road accidents. At that, the most negative month in this series was August, when more than 10 % of all road accidents were recorded, of which almost every second road accident ended with the death of one of its participants. It can be noted that such a breakdown of road accidents by months corresponds to data obtained in other countries [10], so this may indicate a possible existence of some regularity.

The most dangerous, and this should be remembered by all road users, is the evening time and the twilight period (Fig. 5). In total, almost half of all accidents occur during the day period with insufficient natural lighting for auto roads. At that, the greatest number of deaths occurred in the period from 18 to 24 hours – more than 30 %.

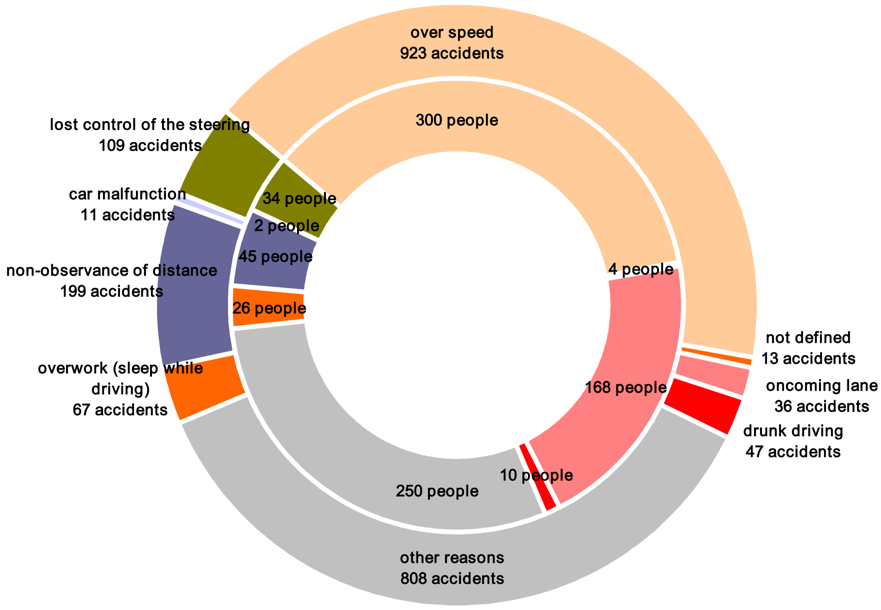

Fig. 3. The reasons of the road traffic accidents

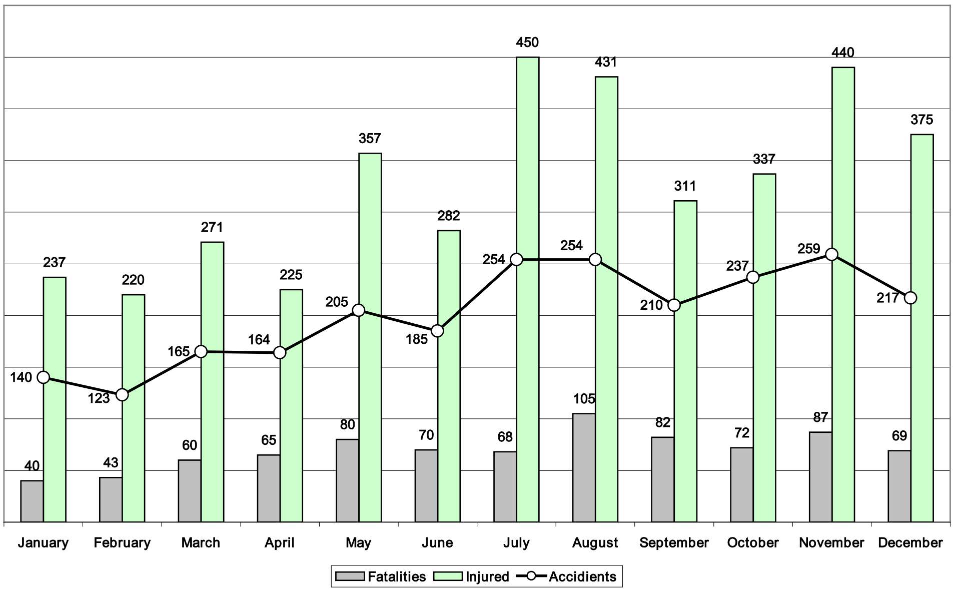

Fig. 4. Statistics of road accidents by months of 2018

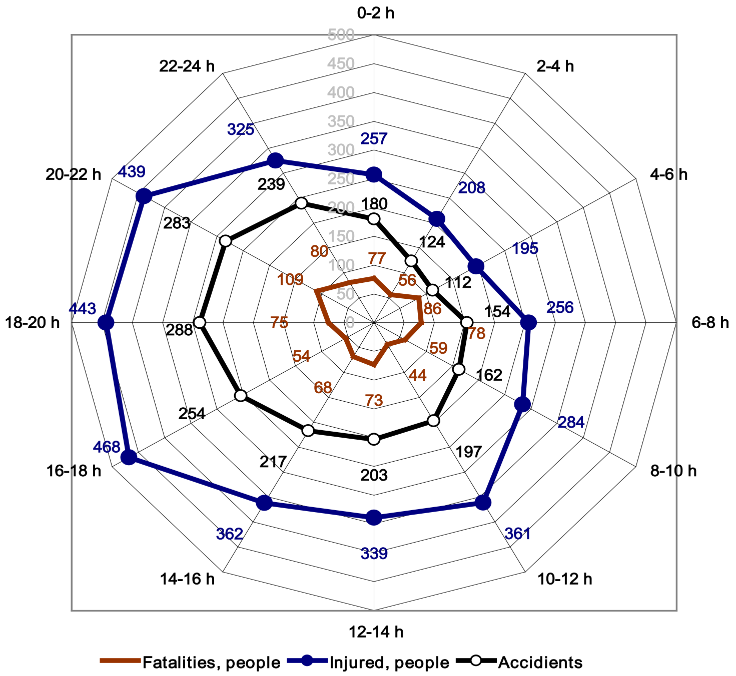

Fig. 5. Statistics of road accidents by the time of the day

The typical traffic violator , the culprit of every third accident, is a driver of 25–35 years (Fig. 6). In 2018, the drivers of 40–45 years posed the minimum danger to the life and health of road users. The highest index of injured is observed in the road accidents with participation of the young drivers under the age of 20: 271 people per every 100 road accidents. Novice drivers should be more attentive and responsible towards other road users, in particular towards their passengers and fellow travelers.

Assessing the situation on the republican roads in indices per 100 km of the road network in 2018 (Tab. 1) and in the previous years, we can note a positive tendency towards a decrease in the road accident rate and the severity of the consequences of the road accidents (Fig. 7).

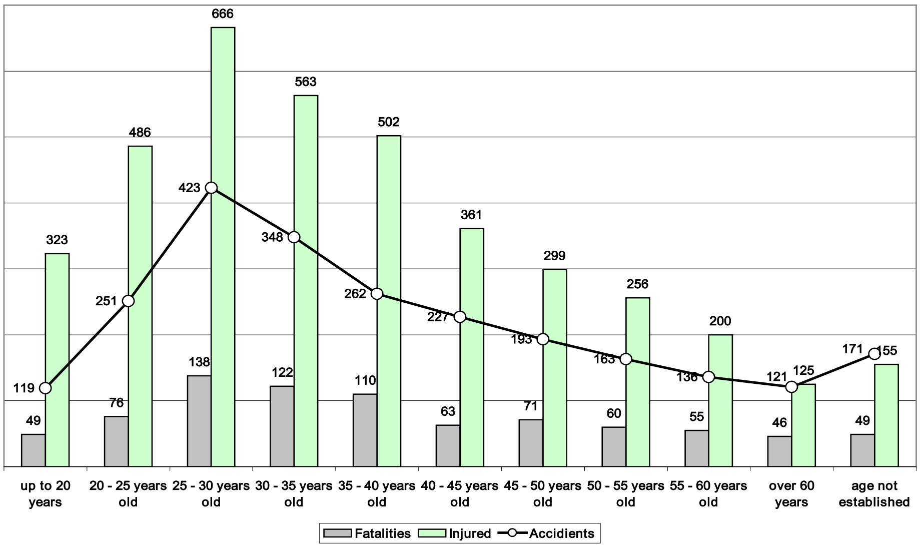

Fig. 6. The road accident statistics by the age category of the drivers

Table 1

Consolidated indices of the state of the road traffic safety on the republican roads of Kazakhstan in 2018

Region	RTA quantity/100 km	Fatality, people/100 km	Injured/100 km	Region	RTA quantity/100 km	Fatality, people/100 km	Injured/100 km
Almaty	28.4	7.3	44.5	Karaganda	4.3	3.5	7.6
Akmola	8.3	2.6	12.8	Kzyl-Orda	4.4	1.9	8.6
Aktobe	5.9	2.4	10.4	Kostanay	5.1	1.7	5.3
Atyrau	3.9	2.9	6.7	Mangistau	5.7	3.4	10.0
Eastern Kazakhstan	4.0	1.4	7.1	Pavlodar	5.5	2.4	8.1
Jambyl	27.5	6.1	54.1	Northern Kazakhstan	3.3	2.0	5.5
Western Kazakhstan	7.1	3.1	10.3	Turkestan	32.0	9.9	47.8

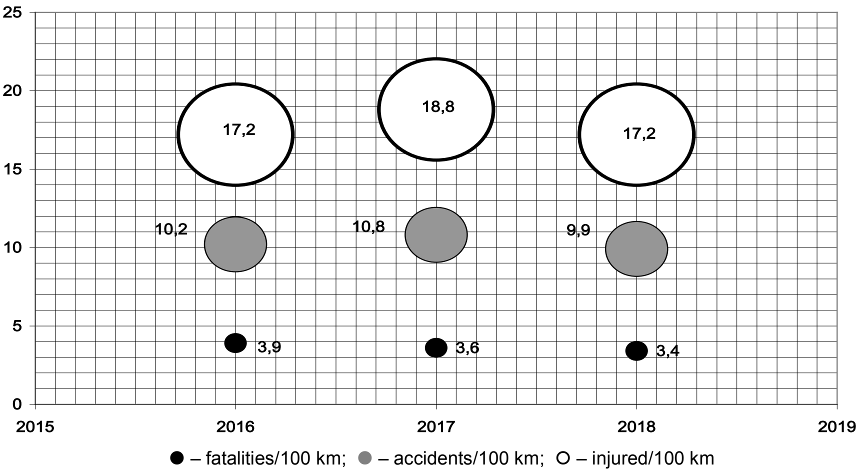

Fig. 7. Consolidated indices of the state of the road traffic safety per 100 km of the republican roads of Kazakhstan

Road accident tendencies in the Republic of Kazakhstan

The analysis of the absolute values associated with the road traffic accidents within a short period (1–3 years) does not provide a complete understanding of the tendencies in the accidents. The consideration of historical data, including the use of some relative data, is of significant interest [11].

Fig. 8 presents data on the number of road accidents and fatalities in them over 15 years, as well as the change in the number of cars over the same time. Studying the graphs in Fig. 8 allows to make some interesting observations. In the period from 2003 to 2007 there was a certain dependence of the growth in the number of deaths in the road accidents from the increase in the number of cars. At the same time, in the period of 2007–2013, there was no relationship between the number of the road accidents and the number of cars. However, after the number of cars exceeds 200 units per 1000 people (2011–2013), a gradual annual decrease in the number of the road accidents, as well as the deaths in them, is observed. This tendency, especially in relation to the number of road accidents continues to the present.

Fig. 8. Road accidence in the Republic of Kazakhstan in 2003–2018

Here we should recall the studies of R. Smeed, conducted in 1949. Smeed linked the road accident statistics with the level of motorization in the country and showed that the mortality rate in the road accidents per unit of the car fleet decreases as the motorization continue to grow [12, 13]. The dependencies proposed by him, called the "Law of Smeed", were subsequently specified and repeatedly tested in many countries. At that, in the developed countries, the actual road accident rates lie below the Smeed curve, in Africa, Brazil, India, China – above the curve. However, the general regularity of the model remains in all countries [12].

If we compare the transport risks in the Republic of Kazakhstan with the world trend according to Smeed, we get the following picture (Fig. 9). You can see that from the level of 200 cars/1000 people the transport risks situation in the Republic of Kazakhstan looks more like the situation typical for the developed countries.

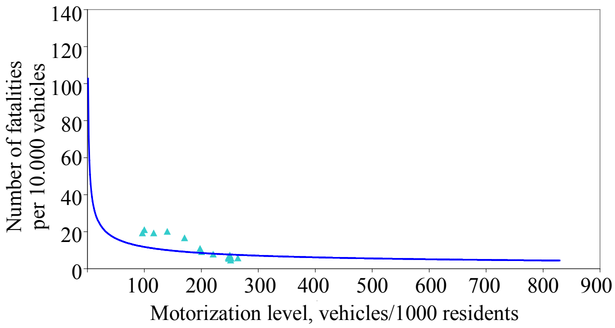

Fig. 9. Transport risks in the Republic of Kazakhstan and the world trend: ▲ – Republic of Kazakhstan, 2003–2017; —— – world trend according to R. Smeed

It is known together with the growth of the automobilization of the country, the nation's transport self-education process takes place, as a result of which the road accident rate may be decreased even without regard to specially taken measures. The process of self-education of the nation takes place simultaneously with the formation of the road network that meets the transport needs, as well as the continuous improvement of the parameters of active and passive car safety, as J. Adams spoke about in the 1980 [14].

In terms of the transport risks, the situation in the Republic of Kazakhstan is far from satisfactory. Fig. 10 shows the possible trend of this indicator in comparison with the average value in the developed countries. The figure shows that the transport risks are getting closer to the limit that is significantly higher than in the developed countries.

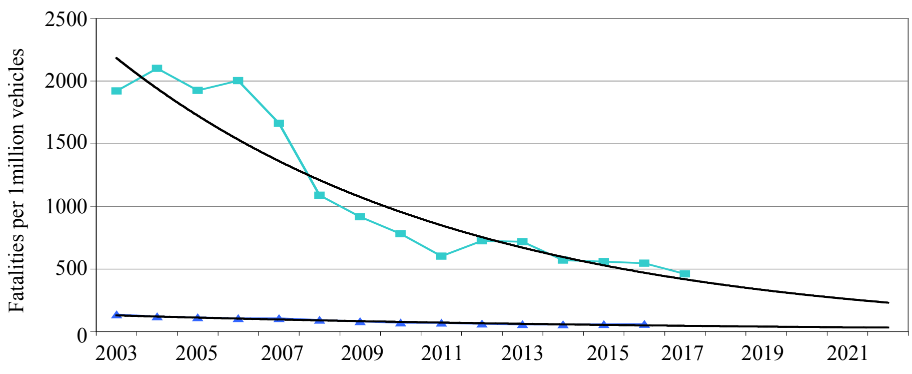

Fig. 10. Possible trend of the transport risks: —■— – Republic of Kazakhstan; —▲— – average value in developed countries

The significant improvement in the road accident situation requires the targeted systematic actions throughout the country. If we consider the immediate actions that can be taken at the level of the road authorities, then it makes sense to assess the risks of traffic on auto roads, for example, according to the IRAP method.

CONCLUSIONS

1. The foreign practice indicates that the preparation of the detailed reliable statistics on the road accidents is a good way for authorized bodies to demonstrate to the citizens their openness, responsibility and care for them in the field of exercising their powers.
2. For 12 months of 2018, we see that on the roads of the republican significance in Kazakhstan the long-term tendency of reduction of the number of road accidents and the number of injured persons remained.
3. In the period from 2016 to 2018 only three (East Kazakhstan, Kostanay and Turkestan) out of eleven regions of Kazakhstan show the rise of the main accident rates, in the remaining areas there was a downfall, which had a negative impact on the process of improving the road traffic safety in the country in whole.
4. The most dangerous time of the day in 2018 was the period from 20 to 22 hours, the most dangerous month was August. The most frequent reason for the accident in 2018 was the excess of the permissible speed of the vehicle, and the greatest danger to the life and health of road users was crossing into the oncoming lane (front collision of the vehicles).
5. In 2018, the number of dead and injured as a result of the traffic violations by drivers under the alcohol intoxication decreased. At the same time, the analysis shows the significant setback of the Republic of Kazakhstan from developed countries in terms of the road traffic safety. Improving the accident situation requires the targeted systemic actions throughout the country.

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Analysis of Trams' Consumption Depending on the Type of Traffic Light Used

A. Czerepicki[1], A. Górka[1], J. Szustek[2]

[1]Warsaw University of Technology (Warsaw, Republic of Poland),
[2]Tramwaje Warszawskie Sp. z o.o. (Warsaw Trams Ltd) (Warsaw, Republic of Poland)

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Abstract. In the XXI century, when environmental awareness is growing and the impact of human activity on the planet is more and more noticeable, striving to minimize energy consumption seems to be a necessary direction in the development of technology. This development cannot take place without an initial understanding and describing the relationships influencing specific technologies. It also needs empirical verification of assumed theories. Modern trams play an important role in the functioning of urban transport. Being one of the oldest modes of environmentally friendly transport, in European capitals they are currently perceived as one of the most convenient means of transport. This is due, among other things, to the high velocity of transport along the route. The energy consumed by trams indirectly depends on the driving characteristics, i. e. speed, acceleration and stops on the route, which are also caused by stopping at traffic light controlled junctions. This paper presents the results of an experiment showing the change in the level of electric energy consumption depending on the applied method of traffic light control. This article presents the conditions influencing the power consumption in trams, describes the possible strategies of traffic lights control and their consequences for other traffic participants. The research was carried out in real conditions in everyday traffic, measuring the level of electricity consumption in case of both fixed-time and actuated signaling with full priority for trams. On the examined section there were both modern asynchronous-drive as well as traditional resistor-drive vehicles. The conclusions drawn from the survey confirm the validity of introducing modern solutions and may be useful for estimating investment costs.

Keywords: tram, electricity consumption, traffic lights, tram priority

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Анализ расхода электрической энергии трамваем в зависимости от используемого типа световой сигнализации

А. Черепицкий[1], А. Гурка[1], Я. Шустек[2]

[1]Варшавский технический университет (Варшава, Республика Польша),
[2]ООО «Варшавские трамваи» (Варшава, Республика Польша)

Реферат. В XXI в., когда растет общественное осознание важности экологических проблем, а результаты деятельности человека на планете носят все более заметный характер, стремление к минимизации расходования энергии представляется единственно правильным и необходимым направлением развития технологий. Это развитие не может осуществляться без предположения и описания зависимостей, влияющих на конкретные технологии, а также без эмпирических исследований, которые данные предположения верифицируют. Современные трамваи как первый вид экологического транспорта сегодня во многих крупных европейских городах считаются одним из наиболее удобных средств передвижения. Причина популярности современного трамвая заключается в скорости его передвижения по выделенным путям. Расход энергии при этом зависит от профиля движения трамвая по трассе, который во многом

Адрес для переписки
Черепицкий Анджей
Варшавский технический университет
ул. Кошыкова, 75,
00-662, г. Варшава, Республика Польша
Тел.: +48 22 234-73-11
aczerepicki@gmail.com

Address for correspondence
Czerepicki Andrzej
Warsaw University of Technology
75 Koszykowa str,
00-662, Warsaw, Republic of Poland
Tel.: +48 22 234-73-11
aczerepicki@gmail.com

определяется количеством ускорений, торможений и остановок, в том числе на регулируемых перекрестках. В публикации представлены результаты эксперимента, целью которого был анализ изменения электрической мощности, требующейся трамваю для прохождения трассы, в зависимости от выбранного способа управления световой сигнализацией. Сформулированы условия, которые влияют на величину расхода энергии. Представлены возможные стратегии управления световой сигнализацией на перекрестках с участием трамваев и их последствия для прочих участников движения. Исследования выполнялись в режиме действующей транспортной сети в условиях рабочего дня. Была проведена регистрация количества расхода энергии для разных стратегий управления сигнализацией: с постоянным временем переключения, а также аккомодационной с максимальным приоритетом для трамваев. Исследования касались всех видов трамваев (как современных с асинхронным двигателем, так и с тяговым приводом), которые проследовали по выбранному участку трамвайных путей. Результаты исследований подтверждают обоснованность внедрения современных стратегий управления движением трамвая и могут найти применение в том числе при планировании новых инвестиций в развитие трамвайных маршрутов.

Ключевые слова: трамвай, расход электрической энергии, световая сигнализация, приоритет трамвая

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Introduction

In the XXI century, when environmental awareness is growing and the effects of human activity on the planet are more and more perceptible, striving to minimize energy consumption seems to be the only right and necessary direction in the development of technology. Modern trams play an important role in the functioning of urban transport. Being one of the oldest modes of environmentally friendly transport, today in European capitals they are often seen as one of the most convenient means of transport in metropolitan areas.

The highest velocity is achieved by trams on separate tracks, in tunnels or flyovers which do not collide with other infrastructure, so called fast trams. Unfortunately, this is not possible to create fast trams in a dense network of urban buildings, so the element of infrastructure, which is most often used is traffic lights allowing for temporary provision of a protected "tunnel" for the tram. The way of controlling this signaling has a significant impact on the efficiency of public transport.

The energy consumed by trams indirectly depends on the driving characteristics, i. e. speed, acceleration and stops on the route, which may be caused by the need to stop at traffic-light controlled intersections.

The aim of the research presented in this article was to examine the consumption of electricity depending on the type of traffic light control used.

Types of traffic light signaling

Crossroads controlled by traffic lights can be divided into fix-timed controlled and actuated, which means that they depend on the current traffic conditions. In such control it is possible to give priority to selected groups of participants, which is most often used for public transport. Following the Poznań idea [1], were can adopted three priority levels for trams: full, high and low, and they are distinguished by the criterion of average time loss. A full priority ensures lossless crossing at an intersection, a high priority ensures an average loss of time of up to 10 s and a low priority applies to other cases above 10 s. Moreover there are limits on the maximum duration of prohibitive signals for non-preferential traffic flows that may cause a short-term reduction in priority level. For this reason, an absolute tram priority similar to that of railways is not introduced, as this would be detrimental to the functioning of the city, causing long-term blockage of intersections without any respect for other road users. In addition, a lack of priority or negative priority can be distinguished, i. e. the deterioration of tram traffic conditions due to design errors – usually a detection deficit or incorrectly accepted coordination offsets.

In Warsaw (the capital of Poland), it was decided to introduce adaptive traffic lights ensuring priority for trams.

The main demonstrated benefit of the priority for trams is the increase in the speed of travel by this means of transport, which reduces the travel costs of passengers and contributes to the increased use of public transport. The experience of Warsaw Trams shows an increase in travel speed by 15–30 % for complex projects covering all intersections over a longer distance. Increasing the speed of the journey goes hand in hand with a reduction in the demand for rolling stock, which results from a reduction in the duration of full tramway brigade cycles. As a result, the same timetable can be achieved with fewer trains. The third benefit of the tram priority is the improvement of safety at junctions by eliminating the dilemma zone at entrances with no stops. The standard 3-second length of the yellow signal equivalent of the tram is not sufficient to guarantee safe stopping of the tramway. National regulations do not allow this signal to be extended [2], because such action could increase the risk of rear-end collision of the second train set and cause the dilemma zone phenomenon.

Another benefit of the priority is the impact on electricity consumption. Only the generally mentioned correlation [3, 4] has been found in the literature, but no studies carried out in real conditions have been reported. Therefore, it is possible to identify a certain research gap in this field. Additionally, in view of the increasingly frequent arguments concerning the need to increase energy efficiency and decarbonization of transport [5], it seems appropriate to determine the scale of the phenomenon.

Literature contains numerous references to the optimal driving style (theoretical acceleration curve) [6] and simulation tools modelled on railway solutions for determining the energy consumption during the tram ride [7, 4]. However, no studies presenting the scale of occurrence of the phenomenon in uncontrolled conditions have been found.

Obtaining the ideal runs for the electricity consumption postulated in the literature [6] is not achievable – at least until autonomous trams or cabin control systems are introduced, following the model of the ETCS level 3 system used on railways. Where the driver receives information about the speed at which he should go to avoid stopping by means of a cab signaling.

Definitely the most common solution is to give priority to trams in signalling, i. e. to match traffic lights to the smooth passage of the tram, rather than the driving behaviour of the drivers to the displayed signals. The savings achieved in this way can reach up to several percent regardless of the driving style of the driver and without introducing additional, expensive systems.

In Warsaw conditions, the priorities for trams are usually designed as accommodation algorithms, coordinated and open to equipment. The company Warsaw Trams Ltd. in cooperation with the Municipal Roads Administration, runs its own investment and research and development programme. It uses tools for microscopic simulations at the stage of designing and programming drivers and remote monitoring of traffic lights in the post-implementation period. The full priority, ensuring lossless tram passage, operates in Warsaw at 34 intersections, the high priority (average tram loss of less than 10 s per warehouse) – at 25 intersections, and the low priority (other cases) – at 43 intersections.

The priority in traffic lights affects the level of energy loss by minimizing the likelihood of a tram stopping or braking at a location other than a stop or speed limit. It follows from the above that only tram entries where no stops have been built have an impact on the energy balance. The optimal situation from the energy point of view is to ensure a full priority there. Moreover, shortening the travel time reduces the energy expenditure on the vehicle's own needs, independent of the momentary speed, such as: air-conditioning, air conditioning, ventilation, passenger information displays.

Full priority is achieved by blocking the possibility of simultaneous arrival of the tram and triggering a collision phase (in relation to to tram). Using the local priority, the tram must be detected, and the operation of the control process must be modified in advance of the given formula

$$t_w = t_{PF(T-K)} + t_{\min(K)} + t_{PF(K-T)} + t_r + \frac{1}{2} t_h, \quad (1)$$

where $t_{PF(T-K)}$ – duration of the phase-to-phase transition leading to the collision phase; $t_{\min(K)}$ – minimum duration of the collision phase; $t_{PF(K-T)}$ – duration of the phase-to-phase transition until tram groups are switched on; t_r – driver response time; t_h – braking time.

Energy losses occur as tram traffic increases. Since collision phase blocking is limited by the maximum acceptable duration of prohibitive signals for non-priority streams, there may be several a number of trams without reserves in the signaling cycle. The second source of loss, which should be considered as a design error, is the lack of sufficiently distant detection, especially when the tram has to trigger a signal.

The issue of energy losses can also be considered for the passive preference of trams in the coordinated traffic lights, not necessarily accommodative. The priority for trams in coordination requires that the width of the coordination beams in the signaling cycle be maximized. These beams are time windows within which the tram can smoothly and without wasting time through successive intersections. The wider the beam, the lower the level of time loss for trams, but to minimize energy loss it is also necessary to eliminate the cases of prematurely giving a permit signal for trams before the start of the coordination beam.

There are some similarities here to the coordination of signaling for vehicles. There are few works in which the conditions for integrated tram-vehicle coordination were described, such as the works of M. Kaczmarek [8]. Automation of computational processes in this area is practically unavailable at present. The results obtained based on the Transyt method available on the market [9], tested on the example of one of the designed tram routes, turned out to be unsatisfactory, so at present it is not possible to give up the "manual" work performed by the designer in this area.

Research method

A series of 8 crossroads on a 2600-metre section of Marymoncka Street, where full priority was applied, was selected as a testing ground. The level of the road is mostly flat with the exception of the crossroad with Zabłocińska Street, which is located in a hollow.

The street has a profile of 2×2 lanes with extensions at the entrance and a fully separated track on the eastern side of the road. It conducts individual traffic of the intensity of 1000–1100 PCE (Passenger Car Equivalent) in each direction in each direction. Two tram lines with numbers 6 and 17 running parallel to each other make 10 departures per hour in each direction except for the peak and 15 in the peak. Priority is given to trams at local level over and above coordination plans, which have been optimized for individual vehicle traffic in the absence of effective tram-vehicle coordination. The obtained priority for trams is full and provides a travel speed of 25.9 km/h in rush hour. Disturbances to the coordination beams due to the vehicle priority are minor and cover about 20 % of the cycles.

Giving priority to trams takes place at the local level over coordination plans, which have been optimized for vehicular traffic only. In the analyzed section tramcars with asynchronous drive type 120 Na (Pesa Swing) and 20-metre 134 N (Pesa Jazz) operate as well as with resistor-drive types (23.2 %).

The experiment consisted in temporarily switching off all active tram privileges and switching to fix-time control according to emergency programs with 80-second cycle. Since the coordination of signaling did not consider the preferences of trams, such signaling working conditions reflected a situation in which a tram accidentally gains or loses out on an individual traffic-oriented signaling system.

The study was carried out on a weekday from 11:00 a. m. to 8:00 p. m., so that both the inter-peak period and the afternoon peak were measured. The obtained results were compared to identical periods of the day from two other days when the weather conditions were analogous. In none of the days were unusual situations or traffic stoppages on the surveyed section recorded.

Data acquisition was carried out basically with the use of energy consumption recorders installed in the traction substation supplying the section of Marymoncka Street. The data were aggregated in 15-minute intervals. Supplementary measurements were carried out by means of recorders installed in trams type 134 N.

Energy consumption for traction purposes depends not only on fixed elements such as: route profile, inter-stop distances and location of stops, maximum speed, but also on vehicle load and start-up method [10, 11]. However, because the measurements were carried out in real conditions (different drivers and constantly changing vehicle filling), it was assumed that the total differences in these parameters are small and have negligibly little influence on the results of the experiment.

Results

The obtained results unequivocally indicate a significant relationship between the allocation of full priority in traffic lights and electricity consumption, which is illustrated by the diagram of accumulated hourly electricity consumption given in kW·h (Fig. 1). The continuous line in the graph shows the energy consumption on the day of priority switch-off. During the entire period of priority shutdown, i. e. 10 h, an increase in power consumption of 340 kW·h compared to the average consumption in the corresponding period on the remaining days was recorded, which represents an increase in energy consumption of 13.5 % over the entire period under investigation. The increase in the number of passing trams has a strong impact on energy consumption, but the relationship between these parameters is not unknown. The Pearson correlation coefficient was 0.68.

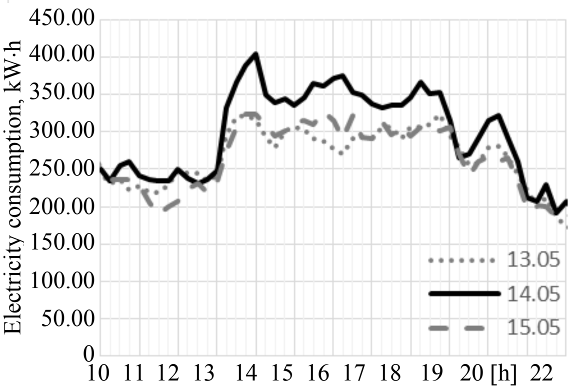

Fig. 1. Cumulative hourly electricity consumption for three consecutive days

The greatest deviation from the average values was recorded during the departure of additional brigades from the depot around 14:00, the peak of the afternoon peak and the exits to the depot after 20:00. It could be assumed that the relationship between the impact of the local priority on electricity consumption and the intensity of tram traffic on the route exists, but is not linear.

The increase in energy consumption can also be seen from the level of a single vehicle. The speed run shows additional stoppages before traffic lights and two stoppages and the energy consumed during this time. Data from the recorder in the vehicle indicate that the tram during one run in the tested sequence consumed about 2 kW·h of energy more than in the case of similar runs during the operation of the full priority. It should be remembered, however, that some of the energy consumed during braking is transferred to the network, and its amount is difficult to estimate. This energy can only be consumed on an ongoing basis if there is a second vehicle on the network that can receive it, otherwise it “escapes into the air”. According to the manufacturer’s data, recuperation covers up to 30 % of the energy consumed for braking.

However, regardless of the number of stoppages or brakes, in individual cases data from substations show real values and generalized to one-hour periods, so they also contains the energy taken from the recuperation instead of the network.

CONCLUSIONS

Although the pilot experiment did not cover the whole day, the analysis clearly showed that there is a close and important link between the full priority for traffic lights and the energy consumption of the tramway. The reading of the total energy consumption of trams in the form of traction substation showed an increase of 13.5 %, what means approximately 40 euro gross for the analyzed section (within 10 hours of measurement). By estimating energy consumption for the whole year – by introducing full priority in traffic lights on the tested track annually – the Company saves approximately 15 600 euro only from energy used to drive vehicles. In addition, it should be remembered that including the priority also means shorter tram journey times, i. e. shorter time of consuming the remaining 25 % of energy used for own needs (heating, air conditioning, displays). The experiment should be repeated by modifying it in such a way as to determine the relationship between the low and medium priority and energy consumption. In addition, consideration should be given to whether it is justified to omitted parameters such as driving style, type of rolling stock or vehicle filling. The relationship between the impact of a local priority on electricity consumption and tram traffic volume on the route exists but is not linear. In order to verify the thesis and find other factors, more detailed studies should be carried out and an attempt should be made to link the variables with each other and the way of control at the crossroads.

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A Two-Echelon Green Supply Chain for Urban Delivery

A. Rossolov[1], O. Lobashov[1], D. Kopytkov[1], A. Botsman[1], S. Lyfenko[1]

[1]O. M. Beketov National University of Urban Economy in Kharkiv (Kharkiv, Ukraine)

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Abstract. In recent years the urbanization to affect many countries of the world has made the significant changes to the material flow at all levels of the supply chain. The last mile logistics operating in the urban area has also changed notably. An increase in the volume of material flow within cities has led to a growth in the number of deliveries and the freight turnover, accordingly. The above-stated processes greatly reduce the sustainability of cities, which while keeping the urbanization trend, can lead to the serious negative results of the social and environmental nature not only for the cities, but also for the countries. One way to solve this problem is to create the green supply chains from the multi-echeloning principles. In the paper, the authors have presented a two-echelon green supply chain using the zero transport emissions within the second echelon. A multi-criteria function has been developed to assess the rational location of a transfer point in order to reduce the negative environmental impact from the transportation system. With the PTV Visum software product, a simulation has been conducted to evaluate the alternative scenarios for generating a green supply chain.

Keywords: supply chain, two-echelon system, sustainable effect, harmful substances

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Двухэшелонная зеленая цепь поставок для городских перевозок грузов

А. Россолов[1], А. Лобашов[1], Д. Копытков[1], А. Боцман[1], С. Лыфенко[1]

[1]Харьковский национальный университет городского хозяйства имени А. Н. Бекетова (Харьков, Украина)

Реферат. Процессы урбанизации, которые в последние годы затронули многие страны мира, внесли значительные изменения в продвижение материальных потоков на всех эшелонах цепи поставки. Особые изменения претерпела логистика последней мили, которая выполняется непосредственно на городской территории. Увеличение объема материального потока в пределах городов привело к росту количества поставок и соответственно транспортной работы. Эти процессы значительно снижают устойчивость городов, что при сохранении тенденции урбанизации может вызывать серьезные негативные последствия социального и экологического характера не только в городах, но и в странах. Одним из путей решения данной проблемы является построение зеленых цепей поставок на принципах мультиэшелонирования. В работе предложена двухэшелонная зеленая цепь поставок с использованием транспорта с нулевым выбросом CO_2 в рамках второго эшелона. Разработана многокритериальная функция оценки рационального расположения перегрузочного пункта для снижения негативного влияния на окружающую среду транспортной системы. Проведено имитационное моделирование в программном продукте PTV Visum для оценки альтернативных сценариев построения зеленой цепи поставки.

Ключевые слова: цепь поставок, двухэшелонная система, устойчивый эффект, вредные выбросы

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Адрес для переписки
Россолов Александр
Харьковский национальный университет
городского хозяйства имени А. Н. Бекетова
ул. Маршала Бажанова, 17
61002, г. Харьков, Украина
Тел.: +380 66 804-00-01
rossolovalex@gmail.com

Address for correspondence
Rossolov Alexander
O. M. Beketov National University
of Urban Economy in Kharkiv
17 Marshala Bazhanova str.,
61002, Kharkiv, Ukraine
Tel.: +380 66 804-00-01
rossolovalex@gmail.com

Introduction

The system of material support for cities with a tendency toward the population urbanization [1] requires a review of the main strategies for building the urban supply chains. In recent years, the number and frequency of deliveries to urban agglomerations have sharply risen resulting in a series of problems in the last mile logistics. The concentration of material flows without adapting the supply chain to the processes above can cause an increase in the goods final cost [2, 3], traffic flow deterioration [4] and, as a result, have a negative environmental impact on the urban territory [5, 6]. Removing the negative impact of freight transportation is possible with the efforts to change the delivery time, to make the off hours deliveries [7] or to create the two-echelon structures of urban material supply systems [8, 9].

So, the study considers the problem of building a two-echelon green supply chain to cut the negative transportation impact on the urban environment.

Literature review

Under the conditions of strict environmental protection and the increased business social responsibility, the need to implement the logistic functions determines the relevance of studying the green logistics. The paper [10] states the efficient green logistics operation through an interaction of its elements – warehouses, vehicles, intelligent transportation systems and financial mechanisms. In the research [11], there were the groups of techniques to increase a freight transportation decision making. These were the "air pollution-to-traffic congestion" correlation evaluation, off-hour freight deliveries and resource reallocation models. According to the author, the approaches are useful to minimize a negative environmental impact originated from the supply chain functioning. From the viewpoint of supply chain management, in order to convert the chain into green one, it is necessary to use the circular economy (CE) principle [12]. CE consists in improving the economic development while alleviating environmental and resource challenges. Within the CE levels (micro, meso and macro), the resourcing, purchasing, production, reprocessing are designed to consider environmental performance and human well-being.

The authors [13] consider the green logistics as the optimal combination of heavy duty, delivery truck and diesel rail CO_2 and PM emissions and transportation costs.

The authors of the study [14] suppose that the proper functioning of green logistics is possible only with the use of the present day software due to the complexity of the system organization (coordination of a large number of process participants, vehicles, considering the road and environmental conditions, delivery size etc.). This is to make this type of logistics flexible and applicable to successful supply task solution.

At the same time, the efficient supply chain operation is impossible without the participation of various transportation modes, among which the road transport is of great significance because of a series of advantages (high mobility, transportation speed, different carrying capacity etc.). However, the supply of this transportation mode is accompanied by a significant negative environmental impact to be decreased under the green logistic principles.

In this aspect, the multi-echelon supply chain organization is of great interest. In this field, literature refers to supply chain and inventory problems without studying the transportation system to optimize from the environmental viewpoint. In most recent works, the reduction of environmental pollution is towards to the problem of vehicles routing within the supply chain. The paper [15] deals with the routing issue to decrease the environmental and noise pollution in the first echelon through the Flow simulation product to generate a rational vehicle path. In the research [16], the routing problem consist in a vehicle assignment to serve the consumers in different echelons. M. Soysal et al. [17] consider a time-dependent routing problem and combine different objectives like distance traveled, travel time, vehicles and emissions in one weighted objective function. H. Li et al. [18] deal with a time constrained routing problem occurring in linehaul-delivery systems and consider an objective function consisting of different parts.

In recent years numerous papers have focused on environmental criteria as an additional objective in routing problems. These papers consider either emissions or fuel consumption [19–22].

Besides, external social criteria (noise, congestion, disturbance) are considered as a further objective by P. Nolz et al. (2014), B. Sawik et al. (2017) and J. Grabenschweiger et al. (2018) [23–25].

Thus, the above studies only partially reveal the problem of the functioning of supply chains. In the approach below, an attempt has been made to comprehensively estimate the technological (total vehicles' mileage in the supply chain) and social (emissions of harmful substances into the atmosphere) consequences from the green logistic principles in time of the urban supply chain operation.

Mathematical problem statement

The rational location of the transshipment point should guarantee the integrated efficiency of the transportation process at two levels of the supply chain. In this regard, it is suggested to determine the rational placement of the local depot from a multicriteria assessment:

$$RP = \\ = \operatorname{opt}\left\{\left(\min \forall L_i^G\right) \wedge \left(\min \forall W_i^G\right) \wedge \left(\min \forall T_i^G\right)\right\}, \quad (1)$$

where RP – local depot rational placement; L_i^G – two echelon vehicle mileage, km; W_i^G – two echelon freight turnover, t-km; T_i^G – two echelon goods delivery time, h; i is the local depot placement option;

$$D^G = D^{1e} + D^{2e} = \sum_{j=1}^{A} d_j^{1e} + \sum_{h=1}^{K} d_h^{2e}, \quad (2)$$

D^{1e}, D^{2e} – vehicle total mileage within the first and second echelons, respectively, km; d^{1e}, d^{2e} – transportation cycle length within the first and the second echelons, km; A, K – number of the transportation cycles required to serve the freight flow in the first and the second echelons, units.

Similarly to (2), for each alternative local depot placement, an assessment of the total freight turnover and the delivery time should be made:

$$W^G = W^{1e} + W^{2e} = \sum_{j=1}^{A} w_j^{1e} + \sum_{h=1}^{K} w_h^{2e}, \quad (3)$$

where W^{1e}, W^{2e} – vehicle total freight turnover in the first and second echelon supply chain, t-km; w^{1e} – first echelon vehicle freight turnover, t-km; w^{2e} – second echelon cargo bike total freight turnover, t-km;

$$T^G = T^{1e} + T^{2e} = \sum_{j=1}^{A} t_j^{1e} + \sum_{h=1}^{K} t_h^{2e}, \quad (4)$$

t^{1e}, t^{2e} – transportation cycle duration in the supply chain first and second echelons, h;

Research object mathematical model

The local depot operates as a "from trucks-to-cargo bikes" transshipment point. Within the first echelon, these are the vehicle deliveries. In the second echelon, the delivery system is originated from the small lot supply technology. Due to this, the second echelon transportation cycles are created on the principle of multistop delivery routes. In the study, the generation of transportation cycles is performed according to the Clark and Wright algorithm in the second echelon.

The two-echelon green supply chain system should be presented as follows

$$GSC = \langle P, T \rangle, \quad (5)$$

where GSC – green supply chain; P – supply demand; T – supply transportation system.

Transportation demand describes the goods average daily need of each consumer. From this, in the GSC equation it is of the following form

$$P = \langle \{l_c\}, \{Q_c\} \rangle, \quad (6)$$

where l – consumer's location at the service area (graph vertex); Q – customer's delivery amount, t; c – number of customers at the service area, units.

The transportation system, in turn, consists of the following subsystems

$$T = \langle G, L, FV, CB \rangle, \quad (7)$$

where G – transportation network; L – local depots on the urban transportation network; FV – freight vehicle subsystem; CB – cargo bike subsystem.

The transport network graph is presented according to the widely used approach to creating a road network two-dimensional model [8, 26]:

$$G = \left\langle \left\{ e_g \right\}, \left\{ v_x \right\} \right\rangle, \qquad (8)$$

where e – graph apex described from the two-dimensional coordinate system; v – graph arcs described by length, number of lanes, free flow velocity and road capacity; g – number of graph vertexes in the transportation network model, units; x – number of graph arcs in the transportation network model, units;

$$L = \left\langle e_{RP}, S_L, C_L \right\rangle; \qquad (9)$$

$$L \equiv RP, \qquad (10)$$

e_{RP} – vertex of the local depot rational placement; S_L – local depot area, m^2; C_L – local depot capacity, t.

The truck subsystem is as a connecting transport element between the shipper and the local depot subsystem.

In the first echelon, the use of simple transportation cycles does not improve the transportation process efficiency through the routing procedure. In this regard, one of the ways to increase the efficiency of transporting goods is to choose a rational rolling stock.

From the above-stated, the FV subsystem model is of the following form

$$FV = \left\langle \left\{ q_s^a \right\}, \left\{ u_s \right\}, \left\{ p_k \right\} \right\rangle, \qquad (11)$$

where q^a – vehicle carrying capacity, t; s – number of alternatives for the vehicle capacity, units; u – number of vehicles for each s^{th} alternative, units; p – vehicle body type with a characteristic difference in the unloading technique and the equipment used; k – number of vehicle body types, units.

The cargo bike subsystem provides the services to end consumers in the second echelon. Last mile logistics chain ends with the cargo bike delivery under the trip chain supply technology.

In the local depot, the shipment deconsolidation is made under the condition that its total volume remains unchanged. In this case, the cargo bike subsystem should create the necessary shipment discreteness to fulfill the condition (1). This is achieved by combining the number of cargo bicycles of various carrying capacities when generating the transportation cycles. So, the cargo bike subsystem is presented as follows

$$CB = \left\langle \left\{ q_g^b \right\}, \left\{ z_g \right\} \right\rangle, \qquad (12)$$

where q^b – cargo bike carrying capacity, t; g – series of cargo bike ranked by carrying capacity; z – number of cargo bikes of g^{th} type, units.

The models developed are the basis to create the alternative delivery systems, the efficiency of which is evaluated according to (1). The main components of functional (1) are presented in models (3)–(4) in a general form. To use them in experimental studies, it is necessary to provide the explanations on finding the model components (3) and (4). The results are presented below

$$w_{j(h)}^{ie} = \sum_{m=1}^{M} d_{j(h)}^{(m-1)-m} \cdot Q_{j(h)}^{m}, \qquad (13)$$

where m – customer serial number in $j(h)^{\text{th}}$ transportation cycle; M – total number of customers served in the $j(h)^{\text{th}}$ transportation cycle; $d_{j(h)}^{(m-1)-m}$ – truck (cargo bike) distance travelled between the adjacent customers in one transportation cycle, km; i – echelon number.

Under a $m = 1$ condition, the delivery is done between the shipment point and the first customer at a $d_{j(h)}^{0-1}$ distance, which corresponds to half the length of the j^{th} transportation cycle in the first echelon.

The duration of transport cycles is determined in relation to the vehicle mileage and road speed. Obviously, in the second echelon, the delivery speed will be lower than in the first one. In addition, due to differences in the creating the transportation cycles at different levels of the model, the duration of transportation cycles will differ.

In model (14), the components being common for two echelons are represented as *j(h)*, while the components assigned only to the second echelon are described with the index h

$$t_{j(h)}^{ie} = \sum_{m=1}^{M} t_{j(h)}^{(m-1)-m} + t_{j(h)}^{M-0} + t_{j(h)}^{load} + \\ + t_{j(h)}^{unload} + \sum_{m=1}^{M} t_{h\_dwell}^{m}, \tag{14}$$

where $t_{j(h)}^{(m-1)-m}$ – loaded truck (cargo bike) travel time between the $(m-1)-m$ customers, h; $t_{j(h)}^{M-0}$ – empty truck (cargo bike) travel time when moving back to the departure point, h; $t_{j(h)}^{load}$ – loading time per one transportation cycle, h; $t_{j(h)}^{unload}$ – unloading time per one transportation cycle, h; t_{h_dwell} – additional cargo bike technological downtime for customer service in the second echelon, h.

From the models and criteria presented, at the next stage of the study, an experimental assessment of the *GSC* system alternatives will be done.

Research object experimental study

Experimental studies on the creation of a *GSC* system rational option have been fulfilled on the example of town of Brovary, Kiev region (Ukraine).

The urban area is 34 km^2, the population is 107000 people. To create the *GSC* system, the delivery of dairy products through the urban retail network has been chosen. The echelon system is created as follows: in the first echelon, the dairy products are transported by refrigerated vehicles with a carrying capacity of 1.5 t. The isothermal boxes of cargo bikes with a capacity of 0.2 and 0.3 t are used in the second echelon.

Using the local depot transshipment system should generate the sustainable effect and reduce the negative consequences of the transport industry operation.

When constructing the two echelon *GSC* structures, the main task is to find a rational local depot placement on the urban core borders.

Alternative local depot options are indicated with the green triangles in Fig. 1.

Potential consumers (35 facilities) are located in the cultural and historical town core and are presented as the red dots in Fig. 1. In the first echelon, the goods shipping point is indicated with the yellow circle in Fig. 1.

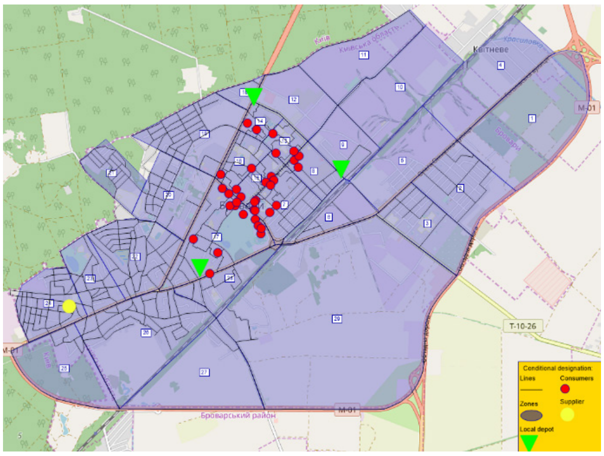

Fig. 1. Transportation network design

According to the criteria developed (1)–(4), to evaluate the local depot rational distribution, it is necessary to simulate the alternative options for the supply of goods within the second echelon. Each alternative second echelon system will be characterized by a set of delivery routes and a combination of the cargo bike types involved. Route modeling is performed from the Clark and Wright algorithm, which is resulted in a distance gain matrix. In this regard, it was decided to build a transport network local graph for displaying the road network of the urban core. The results of the construction are presented in Fig. 2.

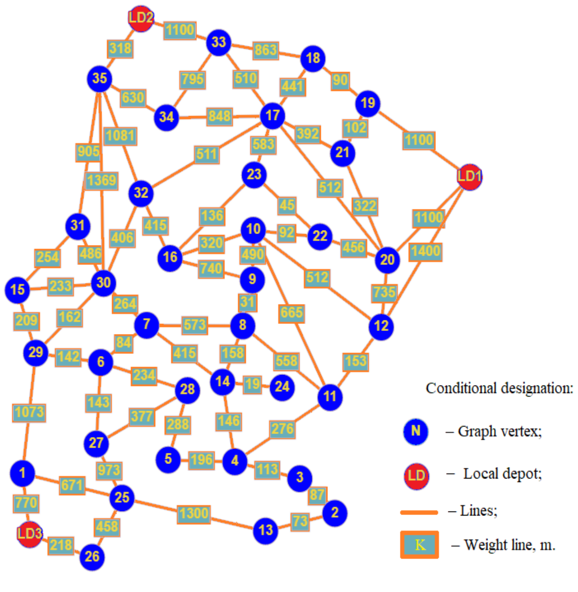

Fig. 2. Urban core network graph

The creation of the transportation volume database has been done using the apparatus of simulation modeling based on a preliminary assessment of the end consumers' delivery volume distribution. It has been established that this indicator is distributed according to the exponential law with a mathematical expectation of 0.02 t.

Upon completion of the simulation procedure for the three alternative supply systems in the second echelon, the first echelon transportation cycles have been added to each of the *GSC* systems.

The systems have been obtained from the proposed local depot placement options (green triangles in Fig. 1) and the main shipper stationary location (yellow circle in Fig. 1). The first echelon transportation cycles have been formed from the optimal shipper assignment procedure using minimal transportation links to consider the traffic conditions on the urban road network.

The results to obtain the alternative *GSC* systems are presented in Tab. 1. The alternative local depot options are given as LD1, LD2 and LD3. The numbers of the delivery points correspond to the numbers of the graph vertexes on the road network of the urban core (Fig. 2).

Table 1

Alternatives for green supply chain systems

GSC system options	Routes	Transportation mode
1	Supplier–LD1–Supplier	Truck
	LD1–6–27–25–26–1–15–31–35–34–LD1	Cargo bike 2
	LD1–12–11–24–14–8–9–10–16–23–22–20–LD1	Cargo bike 2
	LD1–13–2–3–4–5–28–7–30–32–LD1	Cargo bike 2
	LD1–19–18–33–17–21–LD1	Cargo bike 1
2	Supplier–LD2–Supplier	Truck
	LD2–6–28–5–7–27–25–26–1–29–LD2	Cargo bike 2
	LD2–22–10–12–11–4–3–2–13–9–8–14–24–LD2	Cargo bike 2
	LD2–31–15–30–32–16–23–20–21– 19–18–17–33–LD2	Cargo bike 2
	LD2–34–35–LD2	Cargo bike 1
3	Supplier–LD3–Supplier	Truck
	LD3–1– LD3	Cargo bike 1
	LD3–2–3–24–9–8–14–4–11–12–5–LD3	Cargo bike 2
	LD3–21–17–16–10–23–22–20–19–18–33–34–35–31– LD3	Cargo bike 2
	LD3–25–13–29–30–32–15–7–6–28–27–LD3	Cargo bike 2
	LD3–26– LD3	Cargo bike 1

At the next stage of finding a rational *GSC* option, the road network load has been simulated in case of goods delivery by cargo bikes. The simulation has been done in the PTV Visum software. For this, each end-user was allocated to a separate transport area. In the case of proximity, the customers were merged into one area.

The task of compiling the freight destination matrices (demand model) was solved by adding the volumes of goods moving from one transport area to another area.

The size of the resulting matrix is 28×28, where 27 transport areas with customers and one area that correspond to an alternative local depot placement were allocated.

The freight flow simulation results are presented in Fig. 3–5.

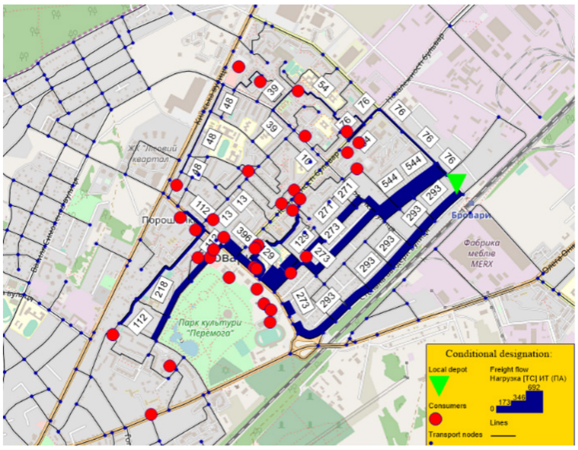

Fig. 3. The second echelon *GSC* freight flow chart, 1st option

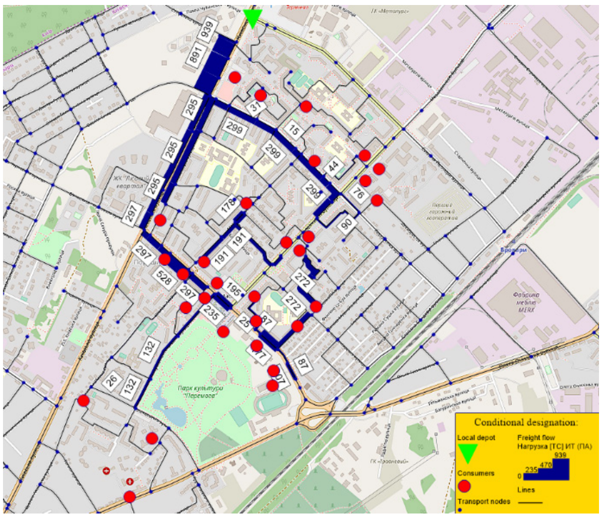

Fig. 4. The second echelon *GSC* freight flow chart, 2nd option

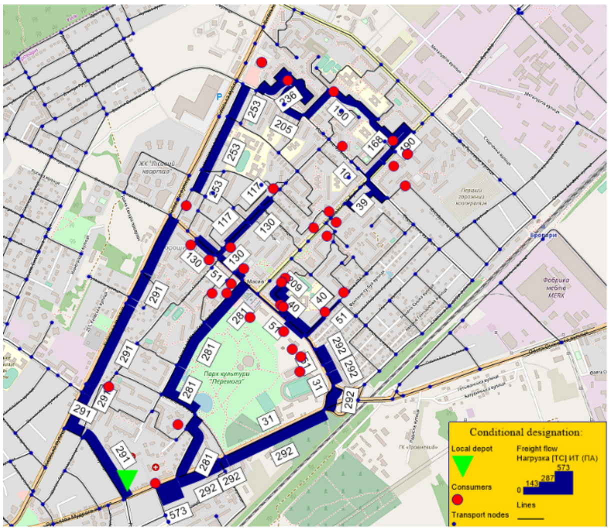

Fig. 5. The second echelon *GSC* freight flow chart, 3rd option

In the first delivery model, when using cargo bikes the maximum network load was 692 kg, in the second model – 939 kg, in the third model – 573 kg. It should be noted that an increase in the concentration of freight traffic on the road network does not lead to an increase in the negative effect of the transport use. This is due to the cargo bikes operation in the second echelon.

A graphical interpretation of the network load according to the three alternative *GSCs* made it possible to conclude that the *GSC* No 2 is preliminary effective, since for this system option the density and compactness of the cargo flow distribution over the network is the highest.

It has been suggested that this state of the object under research should guarantee the minimum freight turnover of cargo bikes. To test this hypothesis, the system performance indicators have been calculated using the models (13), (14), followed by consolidation into general system indicators according to (2)–(4). From the obtained values, an assessment of the rational local depot placement has been made by function (1).

The assessment results the under models (2)–(4) are presented in Fig. 6–8. On the data obtained, a matrix of rational options of local depot placement has been generated and its most effective location has been determined (Fig. 9).

Thus, according to the results presented, it is possible to make a conclusion that the most effective local depot placement is the GSC option No 2.

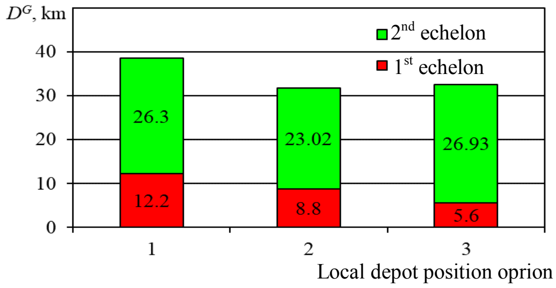

Fig. 6. Alternative *GSC* total mileage

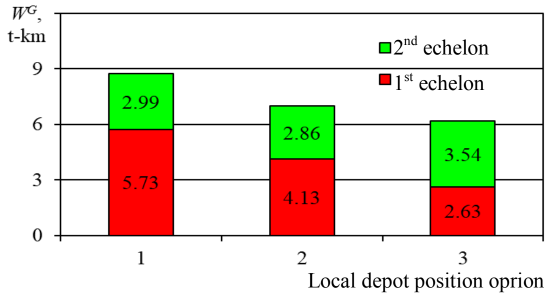

Fig. 7. Alternative *GSC* total freight turnover

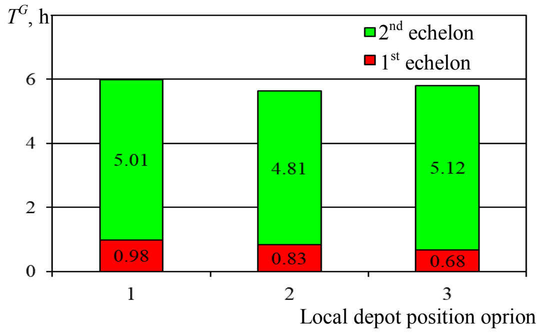

Fig. 8. Alternative *GSC* total delivery time

Criterion	*GSC* options		
	1	2	3
	Rational local depot position		
D^G		Rational	
W^G			Rational
T^G		Rational	
RP		Opt	

Fig. 9. Rational local depot placement matrix

Evaluation of the research results

The purpose of the *GSC* is to ensure the viability of urban centers in the context of sustainable urban development. Achieving this goal is possible by the mileage reducing and, as a result, the amount of harmful emissions through rational placement of local depot in the first echelon as well as their complete elimination by using the green mode of transportation in the second echelon. In order to evaluate the presented GSC from the environmental efficiency viewpoint, a comparison should be made with the previous supply model, when the distribution of goods is performed only by trucks.

The technique [27] was used to calculate the reduced value of emissions of harmful substances released during the internal combustion engine operation. Reducing the mass of emissions is used to reflect the danger of atmospheric pollution in a comparable way with the weight coefficients

$$M = \sum_{i=1}^{n} A_i m_i, \qquad (15)$$

where M – reduced mass of the annual emission by motor vehicles, conv. t/year; n – total amount of impurities that are released into the atmosphere per year; A_i – indicator of the relative impurity aggressiveness of the i^{th} type (Tab. 2); m_i – annual emission mass of the i^{th} impurity into the atmosphere, t/year.

Table 2

Values of A_i for substances released into the atmosphere by trucks with a carrying capacity of 2 t

Substance	Index of relative impurity aggressiveness
Carbon monoxide – CO	1
Nitrogen oxides (by weight) – NO_x	42.1
Hydrocarbon gas vapours (by carbon) – CH	1.5

These substances are known to be dangerous for humans – carbon monoxide prevents the blood oxygen transfer, nitrogen oxides lead to irritation and damage to the mucous membranes, and hydrocarbon gasoline vapors are of a significant narcotic effect. In addition, they negatively contribute to an increase in atmospheric temperature and water and soil pollution.

The mass of the annual emission of the i^{th} impurity into the atmosphere is calculated by the dependence

$$m_i = m_{i*} D K_1 K_2 K_3 \cdot 10^{-6}, \qquad (16)$$

where m_{i*} – specific emission of i^{th} impurity per 1 km, g/km (Tab. 3); D – vehicle annual mileage, km; K_1, K_2, K_3 – influence coefficients of the rolling stock average age, technical state, environmental and climatic conditions, respectively (Tab. 3).

For the existing consumers and suppliers' network the goods distribution is along the route: Supplier–1–27–29–15–31–35–34–33–17–18–19–21–20–10–22–23–16–32–30–7–6–28–5–12–11–4–9–8–14–24–3–2–13–25–26–Supplier, in this case D =19.127 km/day. The dairy products are assumed to be delivered every day, then D = 6981.36 km/year. Thus, the calculated value of the reduced mass of emissions of harmful substances into the atmosphere will be equal 2.42 conv. t/year (Fig. 10).

Table 3

Values of m_{i*}, K_1, K_2, K_3 for internal combustion engine trucks

Substance	m_{i*}	K_1	K_2	K_3
CO	26.80	1.33	1.80	1.20
NO_x	5.10	1.00	1.00	1.20
CH	2.70	1.20	2.00	1.20

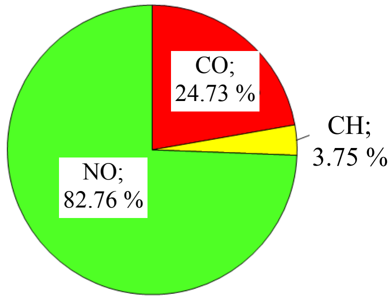

Fig. 10. Reduced mass of truck annual emission

With the selected rational local depot placement for the *GSC* No 2 option, the value of the reduced mass of pollutants will make 1.11 conv. t/year.

CONCLUSIONS

1. According to the research, it possible to make a conclusion that a two-echelon system of urban material supply should be created from the viewpoint of the sustainable urban development.

2. As a criterion for determining the local depot rational placement, it is advisable to use a comprehensive indicator to provide a simultaneous assessment of the freight turnover, delivery time and the vehicles' total mileage within two echelons. The three alternative systems of the urban supply chain have revealed a trend in the freight turnover when providing services with cargo bikes to end customers in the second echelon. From the distribution of freight flows over the network (within the second echelon), it has been established that the minimum freight turnover of cargo bicycles corresponds to the greatest load on the road network. At the same time, the use of freight bikes eliminates the congestion and guarantees the delivery of goods to end consumers with a minimal time window.

3. The study has also substantiated that the two-echelon green supply chain provides a significant reduction in the road transport negative environmental impact. It has been determined that even for an area of 3.88 km^2, the replacement of the in-

ternal combustion engine trucks with the cargo bikes can lead to an annual decrease in harmful emissions of 2.42 conventional tons (reduced CO, CH and NO_x units).

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The Analysis of Available Data on Energy Efficiency of Electric Vehicles to be Used for Eco-Driving Project Development

M. Maljković[1], D. Stamenković[1], I. Blagojević[1], V. Popović[1]

[1]University of Belgrade (Belgrade, Republic of Serbia)

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Belarusian National Technical University, 2019

Abstract. The goal of this paper is to analyse the collected data on energy efficiency of electric vehicles from researches done by other authors and also to summarise all the factors affecting it. The majority of data available are obtained through simulations – therefore the emphasis in this paper will be placed on experimentally acquired data. The results of the analysis will be used for the planned e-bus eco-driving project for the purpose of Belgrade's public transportation system. Currently there are only 5 (ultracapacitor type) e-buses operating in Belgrade city public transport, which makes only 0.2 % of all vehicles in rolling stock (making 16 % together with other electric-powered vehicles – trams and trolleybuses), but there are plans to acquire new 80 electric buses. With the rise of the number of electric vehicles, appropriate training of drivers is gaining more and more importance, and the results of the presented analysis make the basis for such training. This will hopefully increase the range of the buses used and help save the energy spent by public transportation, thus giving a little contribution to global fight for cleaner planet.

Keywords: electric vehicles, energy efficiency, energy consumption, eco-driving, public transportation

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Анализ имеющихся данных по энергоэффективности электромобилей, которые будут использоваться для разработки проекта экологического вождения

М. Малькович[1], Д. Стаменкович[1], И. Благоевич[1], В. Попович[1]

[1]Белградский университет (Белград, Республика Сербия)

Реферат. Целью работы является анализ собранных ранее разными исследователями данных об энергоэффективности электромобилей, а также обобщение всех факторов, влияющих на нее. Большая часть из них получена с помощью моделирования, поэтому особое внимание в этой статье уделяется экспериментально установленным характеристикам. Результаты анализа будут использованы в рамках запланированного проекта по применению экологичного электробуса в системе общественного транспорта Белграда, где в настоящее время функционируют только пять электробусов (ультраконденсаторного типа), что составляет всего 0,2 % от числа всех транспортных средств подвижного состава (16 % вместе с другими электромобилями – трамваями и троллейбусами), но планируется приобрести 80 новых электробусов. С ростом количества электромобилей все большее значение приобретает соответствующая подготовка водителей, и результаты представленного анализа служат основой такой подготовки. Данный подход позволит расширить ассортимент используемых автобусов и сэкономить энергию, затрачиваемую общественным транспортом, что внесет определенный вклад в глобальную борьбу за чистую планету.

Ключевые слова: электромобиль, энергоэффективность, потребление энергии, эковождение, общественный транспорт

Для цитирования: Анализ имеющихся данных по энергоэффективности электромобилей, которые будут использоваться для разработки проекта экологического вождения / М. Малькович [и др.] // *Наука и техника*. 2019. Т. 18, № 6. С. 504–508. https://doi.org/10.21122/2227-1031-2019-18-6-504-508

Адрес для переписки
Благоевич Иван
Белградский университет
ул. Кральице Марие, 16,
11120, Белград 35, Республика Сербия
Тел.: +381 11 337-02-66
iblagojevic@mas.bg.ac.rs

Address for correspondence
Blagojević Ivan
University of Belgrade
16 Kraljice Marije str.,
11120, Belgrade 35, Republic of Serbia
Tel.: +381 11 337-02-66
iblagojevic@mas.bg.ac.rs

Introduction

By looking at Tab. 1, it can be seen that currently there are only 5 electric (ultracapacitor type) buses operating in Belgrade public transportation system, with 80 new e-buses planned. It is expected that this trend will continue [1], so it is very important to take all the advantages of electric buses usage. In order to make it possible, a new eco-driving project is planned. As a preparation for this project, a research on energy efficiency of electric buses needs to be conducted. There are many factors affecting it [2], and this paper will try to summarise them.

Table 1

Belgrade public transportation system rolling stock

Buses	2000
Trolleybuses	119
Electric buses	5 (80 new planned)
Trams	247
Total	2371 (2451)

The analysis

Two hundred electric vehicles (3 models made in the same factory and sharing the same platform) were driven by 741 drivers travelling more than two million kilometres during two years to explore the effects of weather conditions, travel distance and vehicle speed on the energy consumption [3]. The results show that winter period increases the consumption by 34 % compared to summer period, reducing the autonomy by 25 %. The outside temperature of 14 °C was found to be the most suitable.

The effects of ambient temperature and vehicle auxiliary loads (air conditioning, heating and ventilation) were investigated in another study [4], collecting data from 68 electric vehicles in Japan for one year period, showing that the temperature range of 21.8 to 25.2 °C is most favourable to energy efficiency of the vehicle. Another important conclusion is that about 10 % of energy can be saved by minimising unreasonable auxiliary loads.

Technical Research Centre of Finland (VTT) conducted a research in their laboratory using different driving cycles (Tab. 2) [5].

The research showed that 23/–20 °C temperature drop, with cabin heater turned off, will shorten the range by 20 % (30 % in worst case). The results for each cycle are shown in Tab. 3. The use of 4.5 kW cabin heater can shorten the range for more than 50 % in urban driving cycles and by approximately 20 % on open road (Tab. 4).

Table 2

The main parameters of driving cycles used

Cycle	Distance, km	Fverage speed, km/h	Maximum speed, km/h	Stops during cycle	Run time, s
EURO	11.007	33.6	120	12	1180
ECE15	4.052	18.7	50	4	780
EUDC	6.955	62.6	120	0	400
Helsinki city	6.600	19.1	55	17	1360
Artemis urban	4.488	17.6	58	19	993
Road, FIN	24.800	81.3	120	1	1370
Artemis road, EV*	16.641	60.3	111	1	981
Artemis motorway, EV*	23.793	105.6	130	0	736

Table 3

Estimated range for each driving cycle

Cycle	Estimated range		Difference –20 vs +23, %
	+23 °C, km	–20 °C, km	
EURO	124	88	–29
Helsinki city	125	106	–15
Artemis urban	99	74	–26
Road, FIN	91	70	–23
Artemis road, EV*	113	90	–20
Artemis motorway, EV*	72	53	–26
Average, all cycles	100	79	–21

Table 4

The impact of cabin heater use for each driving cycle

At –20 °C, 4.5 kW heater cycle	Heater energy, kW·h	Total energy, kW·h	Estimated range, km	Relative impast, %
EURO	0.134	0.334	53	–40
Helsinki city	0.236	0.402	44	–59
Artemis urban	0.256	0.494	36	–52
Road, FIN	0.055	0.307	57	–18
Artemis road, EV*	0.075	0.270	65	–28
Artemis motorway, EV*	0.043	0.371	47	–11

One research showed that the most economical average vehicle speed is between 45 and 56 km/h (Fig. 1), and that electric vehicles are more energy efficient for longer trips [3].

In another research, converted electric vehicle was driven for five months in real-world conditions [6]. The results showed that electric vehicles are more efficient in urban driving conditions than on highway, owing it to lower speeds and more frequent recuperation. However, this advantage cannot be always used, because the regenerative braking is not in function when battery is in high state of charge or when battery temperature is high [7]. By comparing several electric vehicles in 16 different driving cycles [8], it was shown that in urban conditions, a vehicle with a higher weight can benefit more from regenerative braking.

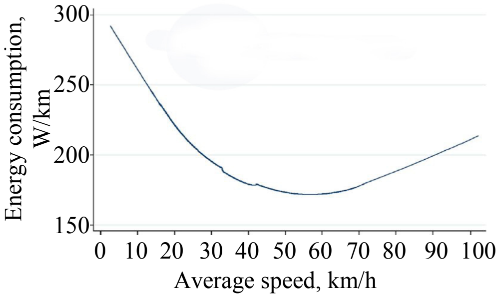

Fig. 1. The effect of average vehicle speed on the energy consumption

The results of another research [9] show that speed lower than 40 km/h and ambient temperature about 20 °C are optimal in terms of energy efficiency of electric vehicles. The researches founded that in some specific driving conditions auxiliary systems can reduce vehicle autonomy by 50 %. They also found that about 1 % of energy is consumed by light and signalling devices.

Tab. 5 shows the impact of auxiliary systems on energy efficiency of electric vehicles [10] obtained by the Idaho National Laboratory. Again, cabin heater is identified as most influential, leaving air conditioning device closely behind.

Table 5

Impact of auxiliary systems on electric vehicle energy consumption

Impact of equipment on EV performance		
Accessory	Range impact	Comments
Air conditioning	Up to 30 %	Highly dependent on ambient temperature cabin temperature, and air volume
Heating	Up to 35 %	Highly dependent on ambient temperature and cabin temperature
Power steering	Up to 5 %	
Power brakes		
Defroster		Depending on use
Other lights, stereo, phone, power-assisted seats, windows, locks		

The research conducted in laboratory conditions on 3 different electric vehicles tested in few driving cycles in accordance with SAE J1634 showed that autonomy at –7 °C is reduced by approximately 20 % in comparison with 20 °C, with cabin heater reducing it for additional 25 %. At –20 °C the autonomy is reduced by 60 % with cabin heater turned on [11].

A project [12] sponsored by the French Environment and Energy Management Agency and conducted with the help of few vehicle manufacturers also gave some conclusions on electric vehicle energy consumption influencing factors, based on simulation results, validated through certain driving cycles performed on chassis dynamometer. It is stated that auxiliary systems consume about 15–40 % at average speed of 20 km/h and 5–15 % at average speed of 60 km/h. Regenerative braking also has a great (positive) influence on energy consumption with efficiency of about 50 % at 20 km/h and about 30 % at 60 km/h. The study also showed that economical driver (0.38 m/s^2 mean acceleration) can save approximately 40 % of energy at low speeds and 10 % at high speeds, compared to aggressive driver (1.03 m/s^2 mean acceleration).

Researchers at the Aalto University performed simulations using several driving cycles (Tab. 6) in different operating conditions and for two different electric bus configurations, the first (EV1) with 77 kW·h battery and second (EV2) with 373 kW·h battery [13].

Table 6

Simulated driving cycles

	BR	E11	H550	H3	L51B	MAN
Time, s	1740	1548	3384	902	4283	1089
Distance, km	10.9	10.2	28.7	10.3	16.1	3.3
Maximum speed, km/h	58.2	58.4	74.9	71.7	59.0	40.5
Average total speed, km/h	22.5	23.8	30.5	41.2	13.6	10.9
Average speed, km/h	30.1	27.9	36.0	48.4	20.2	17.1
Stops per, km	2.7	1.8	1.3	0.9	4.3	6.1
Aggressiveness, m/s^2	0.235	0.152	0.206	0.195	0.281	0.306
Climbing gradient, m/km	0.00	5.75	6.80	0.00	7.27	0.00
Descending gradient, m/km	0.00	–5.83	–6.64	0.00	–7.26	0.00
Number of buses in a fleet	7	7	13	5	16	5

Simulations were performed for vehicles loaded with half of passenger capacity and with constant power demand (6 kW) for auxiliary systems. Energy loss distribution for EV1 is shown in Fig. 2. It can be seen that main impacts on the energy consumption come from auxiliary systems, transmission and tyres. It can be seen that energy loss coming from rolling resistance is almost constant for all driving conditions. Aerodynamic drag also takes big part in energy loss at high speeds. Energy losses caused by auxiliary systems and in transmission are higher in driving cycles characterised by higher number of stops and lower average speed. The impact of vehicle weight due to passenger load is shown in Fig. 3. Again, this impact is more pronounced in driving cycles with lower average speed and higher number of stops. Fig. 4 shows the results of the same study and it shows that a higher aggressiveness increases the impact of passenger load on energy consumption in electric bus.

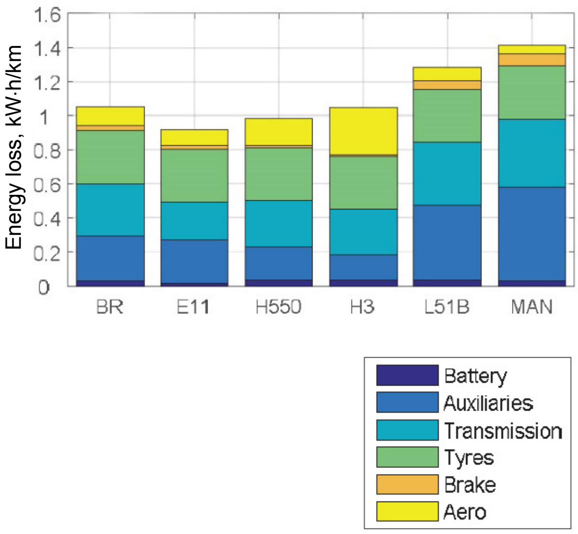

Fig. 2. EV1 energy loss distribution

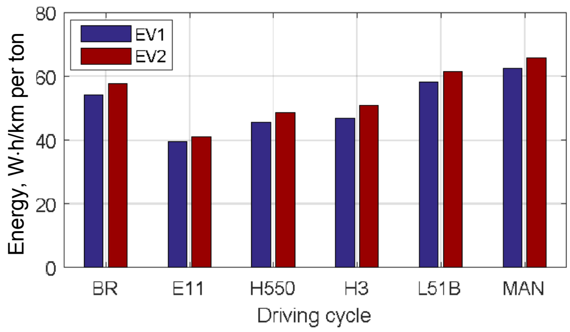

Fig. 3. Passenger load impact on energy consumption

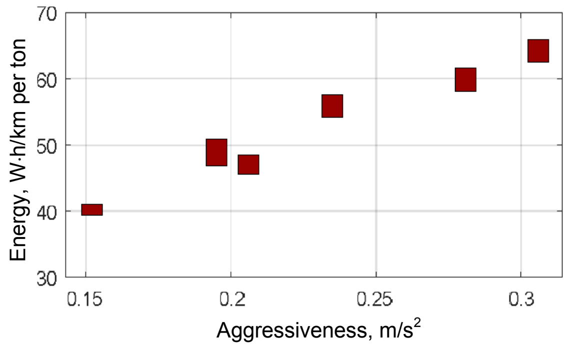

Fig. 4. Passenger load
and driving aggressiveness combined

CONCLUSIONS

1. There are steps that can be taken in design process [14] to make vehicles more efficient. However, the authors found three main factors, not relating to the vehicle itself, affecting the energy efficiency of electric vehicles – ambient temperature (as a trigger for auxiliary loads), traffic conditions (urban vs. extra-urban) and driving style.

2. There is a little that can be done to lower the effects of ambient temperature. The fact that electric vehicles are more economical in city driving conditions, primarily due to the regenerative braking, is advantageous for public transportation. The biggest contribution to more efficient usage of electric vehicles can be made by changing the driving style, which is the goal of the future eco-driving project that will hopefully taught the drivers to avoid high speeds, accelerate moderately, drive in anticipatory manner, minimise the auxiliary loads (within the limits), use regenerative braking more often and coast whenever possible [15].

3. Future research will incorporate the real-world tests to confirm the findings and make the best possible input for the mentioned eco-driving project.

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UDC 621

Increasing the Quality of Transient Processes in the Vehicle Transmission

A. Taratorkin[1], V. Derzhankii[1,2], I. Taratorkin[1]

[1]Federal State Budgetary Scientific Institution “Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences” (Ekaterinburg, Russian Federation),
[2]Kurgan State University (Kurgan, Russian Federation)

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Abstract. The paper shows results of an experimental and theoretical study of dynamic processes in the vehicle transmission after kinematic alignment of elements during gearshifts. The purpose of the research is increasing the quality of transient processes in the vehicle transmission. Applying an analysis of experimental results obtained through looking into dynamics of a 3-ton vehicle transmission and studying literature sources it was established that dynamic loading of the transmission after the kinematic stage of shifting (i. e. synchronizing speeds of driving and driven elements in the gearbox) is influenced by oscillations which are in the single-node mode. Solving the task of increasing transient processes is achieved by applying a method of control power redistribution. By employing simulation models a number of methods were used to regulate power redistribution. Results of computations made it possible to determine that the efficiency of power redistribution are closely related to initial conditions of the process under the study. In the progress of the research a method for identifying the initial conditions was developed. This method is based determining signatures of the torque and its derivatives. In accordance with the research results it turned out that it is appropriate to apply the ZVD (zero vibration derivation) algorithm of power redistribution for low gears (below 4th) from point of view achieving better overshoot and robustness characteristics and a satisfactory response rate level. For higher gears it is recommended that the Ramp algorithm (linear increase in the control input) be used for the cases when the response rate is not longer than period of the single-node mode of oscillations occurring in the dynamic system during a gear shift. Application of the proposed algorithms allows to bring down dynamic loading of the transmission and also to improve the comfort in vehicles.

Keywords: vehicle, gearshift, control, process, power redistribution

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Повышение качества переходных процессов в трансмиссии автомобиля

А. Тараторкин[1], В. Держанский[1,2], И. Тараторкин[1]

[1]Федеральное государственное бюджетное учреждение науки Институт машиноведения Уральского отделения Российской академии наук (Екатеринбург, Российская Федерация),
[2]Курганский государственный университет (Курган, Российская Федерация)

Реферат. В статье излагаются результаты экспериментального и теоретического исследования динамических процессов при переходных режимах в трансмиссии транспортного средства на стадии после кинематического выравнивания ведущих и ведомых элементов включаемой передачи. Целью исследования является повышение качества переходных процессов в трансмиссии автомобиля. На основе анализа экспериментальных данных, полученных при испытаниях автомобиля массой три тонны, установлено, что характер динамического нагружения трансмиссии после кинематической стадии переключения (т. е. после окончания синхронизации скоростей ведущих и ведомых элементов в коробке передач) соответствует низшей, одноузловой форме колебаний. Новизна результатов исследования заключается

Адрес для переписки
Тараторкин Александр
Федеральное государственное бюджетное учреждение науки
Институт машиноведения
Уральского отделения Российской академии наук
ул. Комсомольская, 34,
620049, г. Екатеринбург, Российская Федерация
Тел.: +7 906 778-76-98
alexandr.taratorkin@mail.ru

Address for correspondence
Taratorkin Alexander
Federal State Budgetary Scientific Institution
“Institute of Engineering Science,
Ural Branch of the Russian Academy of Sciences”
34 Komsomolskaya str.,
620049, Ekaterinburg, Russian Federation
Tel.: +7 906 778-76-98
alexandr.taratorkin@mail.ru

в применении метода перераспределения силового управляющего воздействия при обосновании способа идентификации начальных условий по сигнатурам крутящего момента и его производных. По результатам расчетно-экспериментального исследования установлено, что для низших передач (ниже 4-й) целесообразно применять ZVD-алгоритм (zero vibration derivation) перераспределения управляющего воздействия. Он позволяет достичь лучших характеристик перерегулирования и робастности при удовлетворительном уровне быстродействия. Для более высоких передач рекомендуется использовать алгоритм линейного изменения (линейное увеличение управляющего воздействия) для случаев, когда время достижения «уставки» равно или больше периода одноузловой формы колебаний на включаемой передаче. Применение предложенных алгоритмов позволяет снизить динамическую нагрузку в трансмиссии, а также повысить уровень комфортабельности транспортного средства.

Ключевые слова: управление, процесс, переключение передач, транспортное средство, перераспределение управляющего воздействия

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Introduction

Application of modern high-torque engines results in generating intensive vibrations in the transmissions of vehicles when they starts to move and when gears are shifted. It reduces the riding comfort. Low-frequency oscillations in the transmission are quite natural; they are generated when the driving torque in a dynamic system rises sharply at its lowest natural frequency, which is in fact the first single-node oscillation mode. This phenomenon made a full-scale manifestation as a 3-ton transportation vehicle fitted with a hybrid power plant, which contained a 650 hp eight-cylinder engine, was subjected to an experimental study. When the dynamic load of the vehicle was estimated, it was established that low-frequency torsional oscillations in the transmission initiate intense longitudinal vibrations of the vehicle's body with the acceleration ranging from 2 to 4 m/s^2.

Analysis of low-frequency oscillations occurring in transient processes while a vehicle is beginning to move from rest and gear are shifted

Kinematic and power parameters were measured which describe the dynamics of the power plant and of the vehicle. Fig. 1 shows an oscillogram characterizing the dynamics of an engine-transmission system in the process when the vehicle accelerates. The figure also shows variations of the gearbox input shaft rotation speed, the vehicle velocity, and the longitudinal acceleration of the vehicle's body.

Fig. 1 shows that changing gears from the first gear to the fifth one results in initiating low-frequency oscillation in the transmission. Alongside with it, the torque amplitude reaches the values of 1.3–1.5 of the maximum engine torque. At the same time, the longitudinal accelerations of the vehicle's body are 2–4 m/s^2. It should be noted that the parameters of the transient process are considerably influenced by variations of the natural frequency of the dynamic system which is related to the engaged gear in the transmission. When the number of the engaged gear goes up, the natural frequency increases from 1.6 to 6.9 Hz (Tab. 1, line 4). Insignificant mismatching between calculated and experimentally derived values of the natural frequency (for example, from 2.1 to 2.5 Hz at the second gear) might be caused by a nonlinearity of the dynamic system, the changing weight of the vehicle depending on its load (number of passengers, amount of fuel, oscillations of the sprung mass), temperature, pressure in the tyres, etc. At the same time, changes of the natural frequency values depending on which gear is in are related to the values of the equivalent moment of inertia of the engine to the vehicle weight. Thus, the effect of varying natural frequencies should be taken into consideration when the algorithm for oscillation damping is to be developed, and it should be estimated by making use of the robustness parameter of the dynamic system.

It is worth mentioning that according to the results of numerical modeling and experimental data equalizing the angular velocities of sliding friction elements is also accompanied by torque variations at higher frequencies but with lower amplitudes (Fig. 1 – from 37.5 to 38.8 s, from 40.6 to 41.5 s, from 43.2 to 43.8 s). It is related to the ambiguity of the structural condition of the dynamic system during the slippage of friction elements when the equivalent moment of inertia is significantly lower. These oscillations do not influence as much the dynamic load and the comfort (longitudinal accelerations) in the vehicle due to their higher frequencies and insignificant amplitudes of the torque. This type of oscillation damping needs further research.

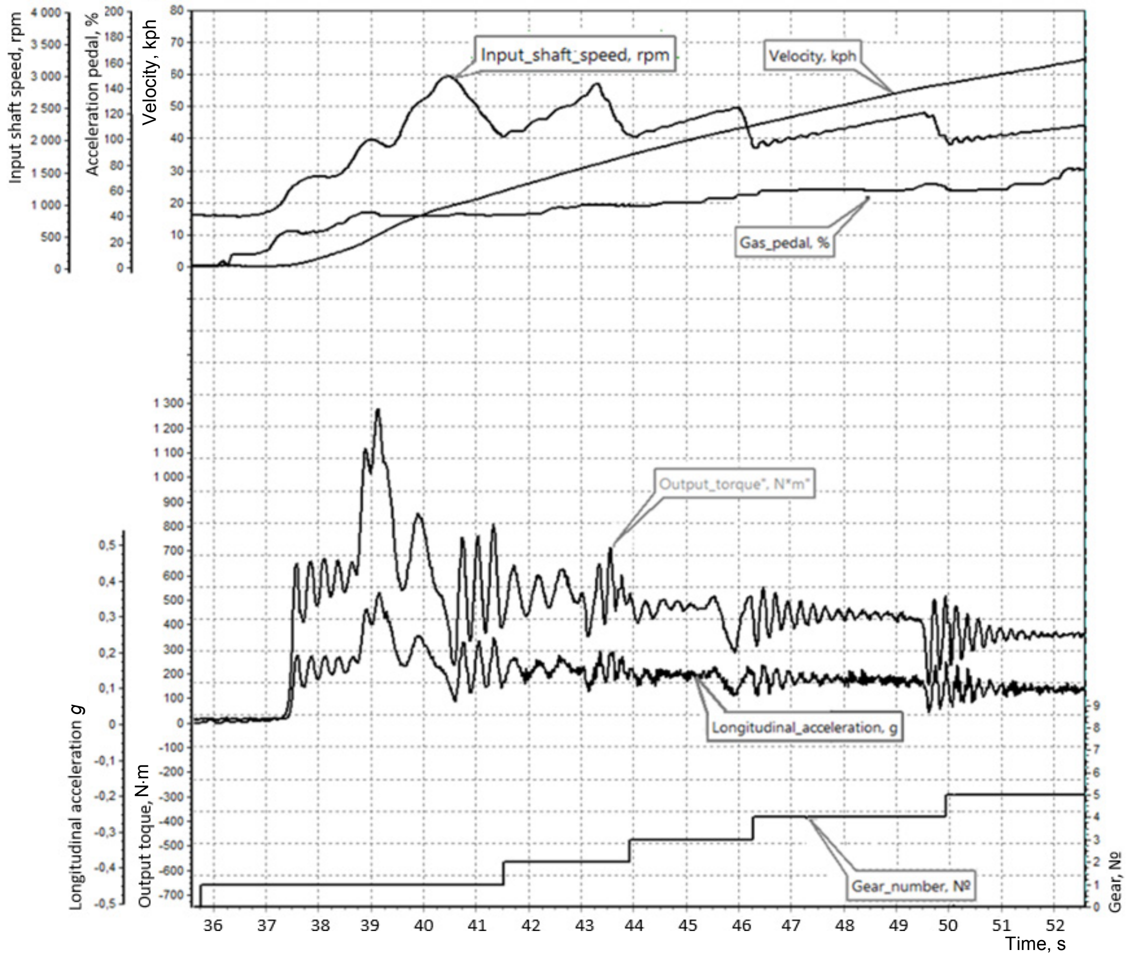


Fig. 1. Fragmented oscillogram illustrating the ways the movement parameters changed when the vehicle moved from rest and accelerated

Table 1

Natural frequencies of the system

Gear	1	2	3	4	5	6	7	8	9
Gear ratio	5.72	3.02	2.05	1.51	1.20	1.00	0.86	0.75	0.66
Experimental frequency, Hz	1.5–1.8	2.1–2.5	3.2–3.4	3.9–4.4	4.4–4.8	4.6–5.0	5.0–5.6	5.5–6.1	6.7–7.0
Estimated frequency, Hz	1.6	2.3	3.3	4.2	4.8	5.1	5.9	6.3	6.9

Referring to researching into the transient processes occurring at the beginning of the motion and when gears are shifted, the regulation action can be regarded as a unit function because at the time when a vehicle is accelerating after the angular velocities of control elements are equalized the required specific moving force is calculated applying the following formula

$$f_d = \frac{\dot{v}}{g\delta_j} + f_r,$$

where f_d, f_r – specific driving force and tractive resistance respectively; $\dot{v}$ – required vehicle acceleration, $f_r = 0.02$; g – gravitational acceleration (g = 9.81 m/s^2); δ_j – rotary inertia coefficient with j-gear engaged.

Hence, when a vehicle accelerates in the first gear at an acceleration of 2.5 m/s^2, the relation is $\frac{f_d}{f} = 9.45$, in other terms, the required regulating action exceeds the rolling resistance torque by nearly ten times. The response of the system to this regulating action may be regarded as a response to a unit regulation function.

The most intensive generation of these oscillations can be observed when the fuel feed goes up quickly in the kick-down mode. This assertion is well defined in the graphs in Fig. 2.

When the vehicle is moving with the first gear in, the quick increase in fuel supply at the 78th and 82th seconds results in changing the torque at the transmission output shaft with an amplitude of up to 1760 N·m. This process goes together with longitudinal oscillations of the vehicle body at an amplitude of 4.5 m/s^2 its frequency being f = 1.6 Hz: it corresponds to the first single-node mode. Thus, analyzing the experimental results it was discovered that dynamic and inertial loads in the required frequency range are created in correspondence with the single-node oscillation mode with the node in the axial shaft area.

This phenomenon is the Bonanza effect and is described in the book by Robert Fischer et all (see below). The energy of these oscillations is proportional to the squared torque divided by the double value of the angular rigidity of the system. As gear shifts occur (lower gears in particular) in the transmission of a transportation vehicle, the current torque is at its maximum while the equivalent angular rigidity is limited. It leads to an intensive accumulation of oscillation energy with low natural frequencies in the shifts at lower gears. The energy and amplitude of these oscillations can be reduced by varying the parameters of the system that would increase the natural frequency. Anyhow, it can hardly be achieved in real structures. The closest approach to it, regarding its technical essence and achievable results, is the method of damping oscillations detailed in [1] (Fig. 2.28, p. 78). This method implements damping of low-frequency oscillations in transportation vehicle transmissions at the stage following kinematic equalizing of velocities of driving and driven components by creating an antiphase regulating action at the natural frequency of a dynamic system. It also implies estimating the quality of transient processes, i. e. overshoot and duration based on modeling the dynamics of the system in which a unit regulating action is applied (quick application of the engine torque). In other words, the paper mentioned above proposes to alter the function of the regulating signal (in this particular case the regulating signal of the torque): to make it ramp-like (RAMP – a gradual increase of the engine torque in terms of time) or step-like, correlating the duration of the stages of the regulating function with the period (frequency) of the natural oscillation of a dynamic system.

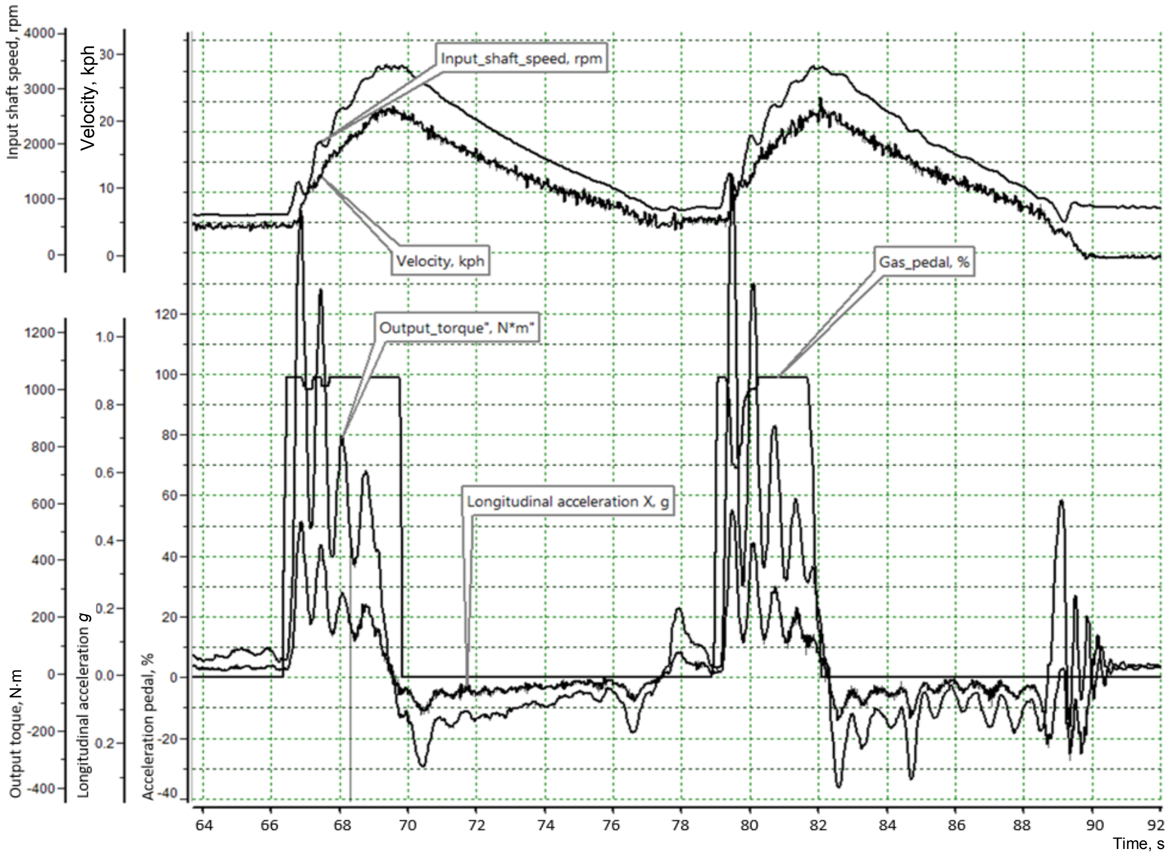


Fig. 2. Oscillogram fragment showing changing parameters during the motion at a minimal velocity in the first gear when the motion was periodically accelerated by quick shifts of the gas pedal from 0 to 100 %

This engineering solution, based on the idea of oscillation damping by means of generating regulating pulses that are antiphase to the oscillations, i. e. by means of redistributing the regulating input in terms of time and relating it to dynamic properties of the system, is implemented by the method which is known as Input Shapers [2–6]. This method is widely used in various commercial applications, and it has resulted in improving performances of various units: satellite systems [7], disk drives [8], cranes [9–11], coordinate measuring machines [12, 13], remotely piloted planes [14], milling machines, etc.

At the same time, if to speak about transport vehicles, these regulating algorithms have not been widely applied. To evaluate the possibility of utilizing this well-formalized method in vehicles for the purpose of improving the transient processing of shifting at the stage following the kinematic equalizing of angular velocities the researchers [15] performed a comparative estimation of how efficient different algorithms of torque redistribution are. To do it a two-mass mathematical model is used. In addition to it, these papers present a list of indicators that show the efficiency of various algorithms for torque redistribution and their applicability related to the criterion of optimizing gear shifts: acceleration intensity of vehicles, comfort when in motion, minimizing dynamic loads, etc. These indicators are in fact overshooting, rapidity of action and robustness.

Estimating the effectiveness of the proposed method by applying the extended multi-mass model of the dynamic system

To estimate the efficiency of input regulators in application to the research subject a more complicated simulation model was developed; it is presented below. In this model components are grouped in two major unities.

The first one is shown in Fig. 3; it describes how the following transmission elements interact: the engine, the double-clutch, the gears and shafts in the gearbox (even and odd branches, the cardan shaft and the axle shafts. It also contains a separate component simulating the vehicle body.

In the mathematical model the internal combustion engine is modeled as a 3*D* dependence of the torque on the rpm of the engine crankshaft and the fuel feed percentagewise (Fig. 4). This dependence allows modeling the engine in the traction mode employing external and partial characteristics and in the braking mode.

The second unit of the elements describes the operation of the gearbox controller and that of the engine controller. The control logic of the gearbox is implemented by two actuating mechanisms; they actuate the gearbox control unit and the doubled clutch friction regulating unit. The gearbox control unit makes use of the current values of the mechanical model of the gearbox (the gear shifted in, the selector position, the current velocity of the vehicle) to generate a request for a gearshift as per the gearshift pattern.

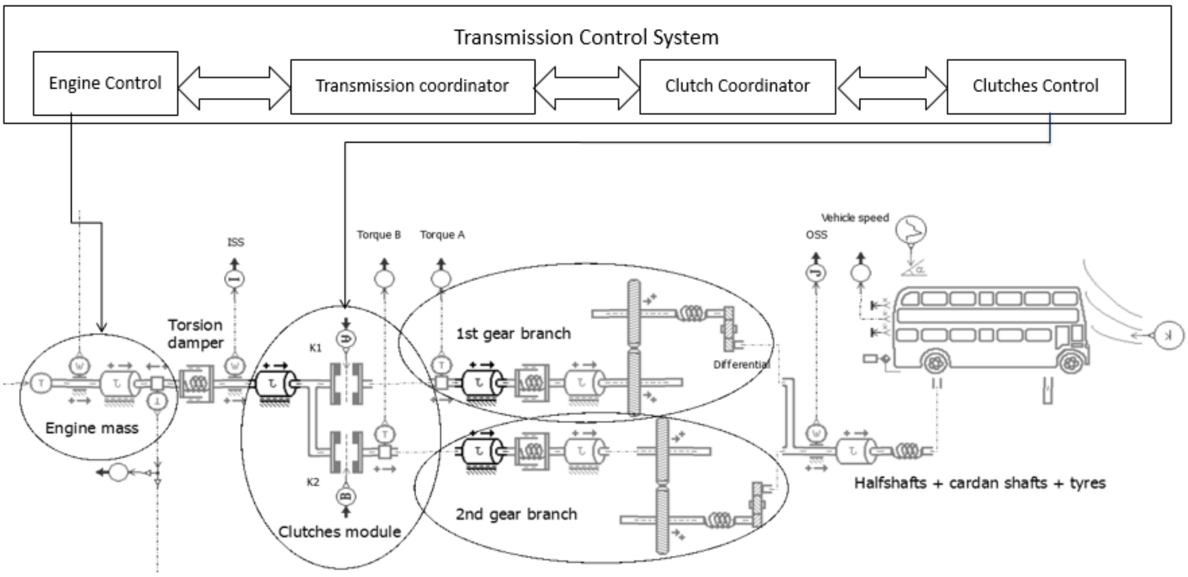


Fig. 3. Model elements describing mechanical components of the transmission

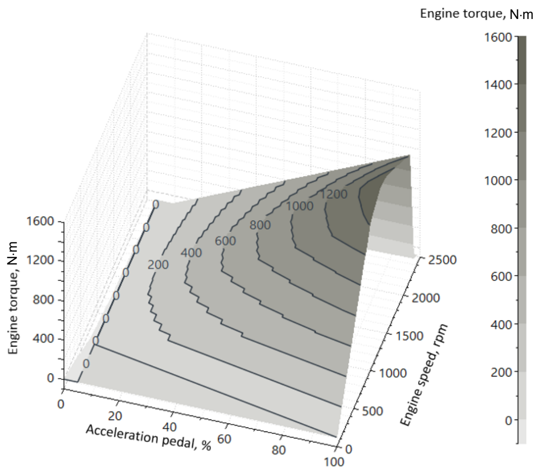


Fig. 4. Dependence of engine torque on crankshaft speed and fuel supply

The doubled clutch regulator defines the required condition of the friction elements for different stages of gear shifts. Five conditions of the friction elements are implemented: engaged (open), a linear increase of the friction torque at the stage of passing the rotational toque from the friction clutch of the gear being disengaged to the friction clutch of the gear being engaged (torque ramp up), a linear increase of the friction torque at the stage when there is a kinematic change in the gear ratio in the gearbox (torque ramp up), fully engaged (close), a linear decrease of the friction torque at the stage of passing the rotational toque from the friction clutch of the gear being disengaged to the friction clutch of the gear being engaged (ramp down).

Fig. 5 illustrates the way the rotational torque changes in the friction elements when gears are being shifted. The employed logic allows performing a gearshift by dividing the shift process into a force phase and a kinematic one. The logic of the engine control covers the switching of the modes of its operation comprising three conditions of the fuel feed control: the driver's mode, electronic maintenance of the torque, transferring the fuel feed control from the electronic unit to the driver. When the engine is controlled by the driver, the fuel is fed depending on the position of the accelerator pedal. The mode of maintaining the torque is actuated at the time when gears are being shifted; it time when specific conditions for a gear shift are needed. With the existing systems in operation the driver hardly feels when a short-time switchover of the control mode from the driver to the electronic unit takes place. At the same time, it helps to economically use the computational resources of the electronic gearbox control unit. The signal for switching modes is generated by the gearbox control unit when the torque is switched and when the kinematic equalizing occurs.

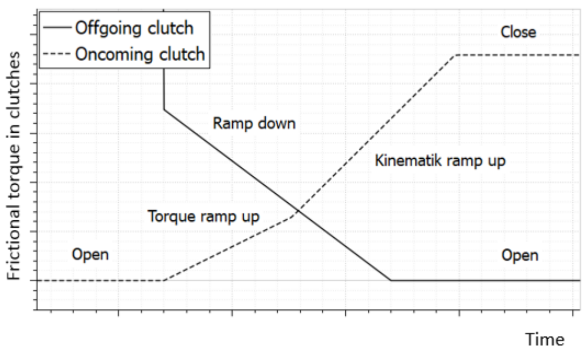


Fig. 5. Illustration of torque change in friction elements

To transfer the controls of the engine from the electronic unit back to the driver, there exists a transit mode which operates according to a certain law. This control law can be applied when a gearshift is completed or when the driver quickly changes the position of the acceleration pedal and when there is a substantial longitudinal acceleration of the vehicle body accompanied by oscillations of the vehicle body. To put this law into practice a ZV-shaper, a ZVD-shaper and a linear ramp of various duration equal to period fractions ($T/2$, T, $1{,}5\times T$) can be applied as is shown in Fig. 6.

A full-scale model of this system is implemented in the LMS Imagine. LAB Amesim. Software. Fig. 7 illustrates the results of modeling applying the Tip-in and Tip-out modes and utilizing the ZV-shaper and the ZVD-shaper. As is shown in the chart, the gearbox control unit makes use of the shapers if the driver has to quickly change the position of the acceleration pedal. Together with it, an electronic pedal mode is actuated; this mode follows the algorithm of redistributing power of the control torque depending on which shaper is in operation. Analyzing the results proves that the redistribution of the gearshift torque power is efficient (see the graphs in the upper part of the Fig. 7).

The graphs in the lower part of Fig. 7 show how efficient the results are. From analyzing the results of the modeling it can be derived that the ZVD-shaper manifests the highest efficiency in setting limits for the redistribution at acceptable values of response time and robustness. In general, the analysis proves that the redistribution of torque power during gearshifts is efficient.

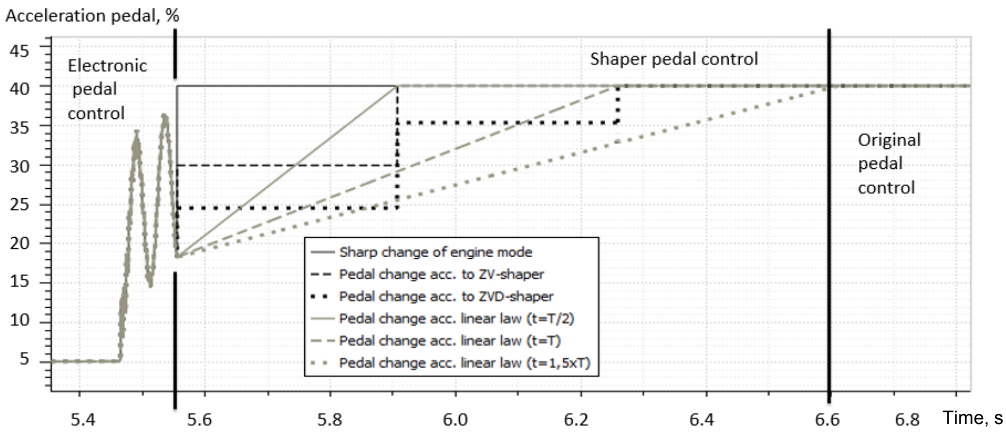


Fig. 6. Various control laws to change the electronic engine control mode for the driver engine control mode

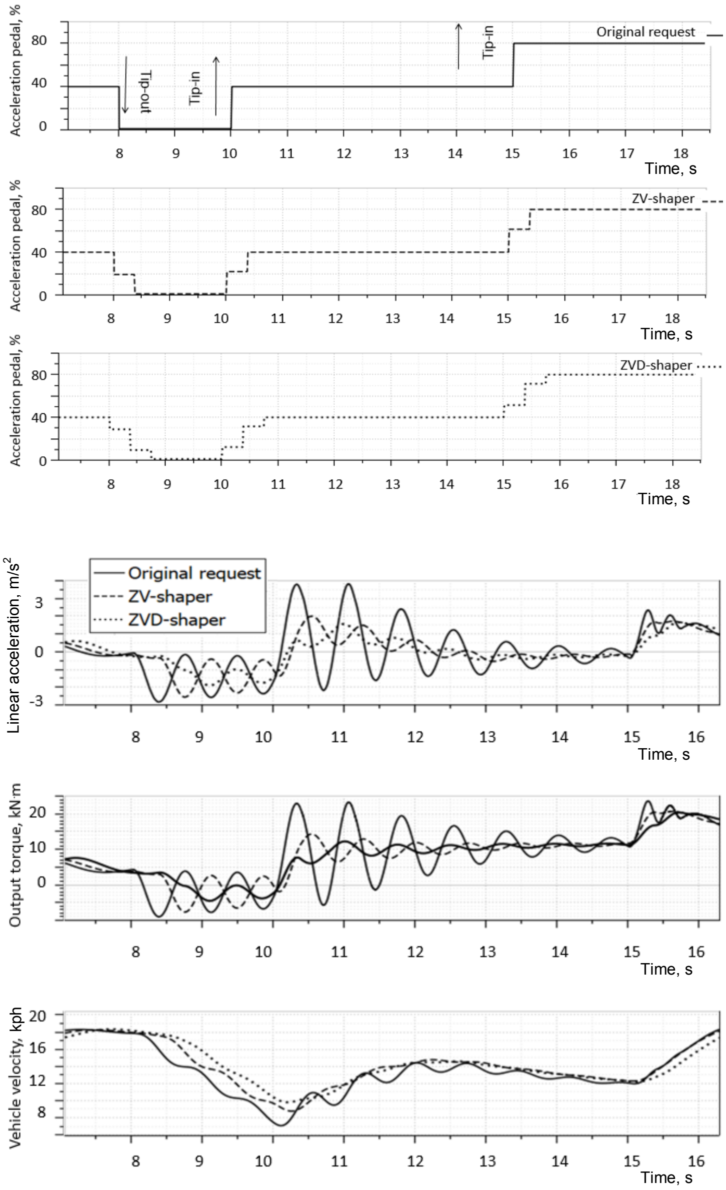
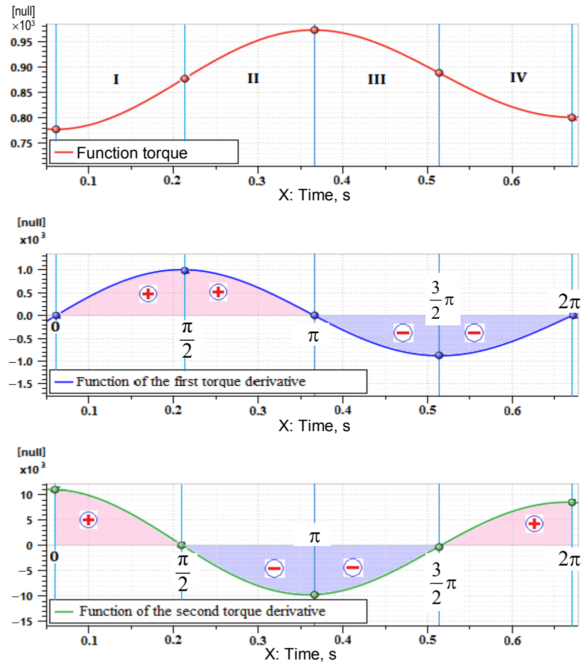


Fig. 7. Stability of dynamic gear shifting in a vehicle transmission by applying an input shaper

Somehow, the modeling of an extended multi-mass model of the dynamic system also showed that applying the input shapers as is to be done in compliance with the method detailed by R. Fischer is efficient only in the initial zero conditions. In real systems, which maintain control over gear-shifts in transportation vehicles, the initial conditions occurring after equalizing the speeds of the driving and driven elements are not zero conditions; they evolve at random being related to a combination of factors determined by the engine toques, tractive resistance together with oscillations of the dynamic system.

To further improve the efficiency of synthesized shapers an algorithm was developed within the framework of this research to identify the initial conditions to make use of the value of the engine torque and its derivatives as a reference. The essence of the method that is being proposed is as follows: employing the signatures of the first and second derivatives of the torque it is to be found in which of the quarter of the period of the natural oscillation (quartile) the oscillatory motion of the dynamic system takes place (see table in Fig. 8). For example, if the process occurs in the first quartile, the signature of the first derivative is positive and that of the second derivative is negative. If the process occurs in the second quartile, the sign of the first and of the second derivatives are negative. And if the process takes place, the signs are positive. Data for the correlation are given in Tab. 1 (lines 1–4). Meanwhile, the time, when the shaper is actuated, is also established by the meanings of the signatures (changes of their signs) of the corresponding derivatives of the torque (in Tab. 1, lines 5–7). For instance, when the process is in the first quartile, the time to actuate the shaper $\left(\frac{\pi}{2}\right)$ is determined by the zero value of the first derivative (the derivative's sign changes from positive to negative); in the second quartile the actuation time for the shaper (π) is defined by the zero value of the second derivative (its sign changes from minus to plus); in the third quarter of the period the actuation time for the shaper $\left(\frac{3\pi}{2}\right)$ is determined by the zero value of the first derivative (its sign changes from minus to plus); and in the fourth quartile period the actuation time for the shaper (2π) is determined by the zero value of the second derivative (its sign changes from plus to minus).

After determining the shaper actuation time the control system that being proposed in this paper operates following the developed algorithm. In addition to it, the control program provides for finding the natural frequency of the system as a function of the number of the gear which is engaged and an arrangement for actuating driving axles.



Determining the torgue signatures, derivatives and shaper actuation time

Estimated parameters		$0\leftrightarrow\frac{\pi}{2}$	$\frac{\pi}{2}\leftrightarrow\pi$	$\pi\leftrightarrow\frac{3\pi}{2}$	$\frac{3\pi}{2}\leftrightarrow 2\pi$
Signature sign	M	$\pm$	$\pm$	$\pm$	$\pm$
	$\dot{M}$	+	–	–	+
	$\ddot{M}$	–	–	+	+
Shaper actuation time		$\frac{\pi}{2}$	π	$\frac{3\pi}{2}$	2π
Direction of the sign change	$\dot{M}$	$+\to-$		$-\to+$	
	$\ddot{M}$		$-\to+$		$+\to-$

Fig. 8. Identification chart for the initial phase of the torque oscillations; the torque applies load to the transmission after the stage for kinematic equalizing of the driving and driven transmission components is completed

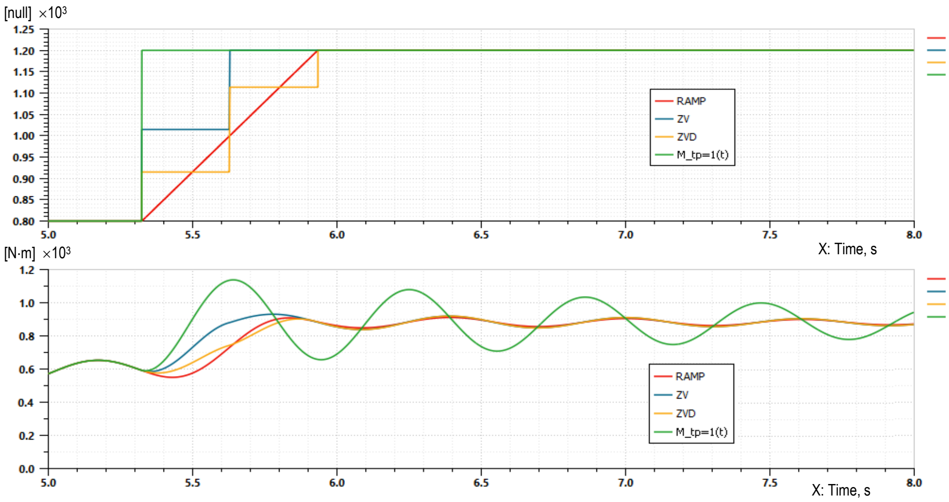
Also, the relative angular speed of the driving and driven elements and this allows identifying the completion of the kinematic equalizing stager. After the kinematic equalizing $\Delta\omega = 0$ is done, the measuring control system (MCS) of the vehicle generated an inquiry for the required engine torque M_{tp}, a computational torque is determined as a response to the unit regulation action. Then, a procedure is done to compare the overshoot σ and the acceptable value. If the overshoot exceeds the acceptable value, a calculation procedure is performed to determine the parameters defining the power redistribution of the control signals A_i and t_i (amplitudes and their duration) for the shaper type (shaper-filter) that would produce the required value of the priority parameter which is to provide for the quality of the transient process (overshoot, rapidity of action and robustness). To find the function of the torque (measured torque) corresponding to the first single-node oscillation mode filtering is done by applying a rejection filter at the natural frequency ω_c of the system with the pass band $\pm(\Delta\%)\omega_c$. In this expression $\Delta\%$ allows for a possibility of varying the natural frequency of the system and determines the priority of the selected shaper regarding the degree of its robustness. For example, the results of the modeling show that for the first gear of a 3 t vehicle, for the ZV-shaper with the overshoot set to 10 % the pass band is $\Delta\% \approx \mp 5$, for the ZVD-shaper with the overshoot set to 10 % the pass band is $\Delta\% \approx (\pm 20)$ %, and for the for the ZV-shaper with the overshoot set to 10 % the pass band is $\Delta\% \approx \mp 5$; for the ZVD-shaper with the overshoot set to 10 % the pass band is ZV-shaper with the overshoot set to 10 % the pass band is $\Delta\% \approx \mp 5$; for the ZVDD-shaper with the overshoot set to 10 % the pass band is $\Delta\% \approx (\pm 30)$ %.

Further on, making use of the signatures of the obtained (filtered) torque, its first and second derivatives the number of the current quartile of the oscillation process and its time boundaries are found. The right boundary of the interval helps to determine the time for the control action of the synthesized shaper to be applied. After it, the parameters of the synthesized shaper are transmitted into the system controlling the fuel feed rate. At this stage the operation of the algorithm is completed.

Fig. 9 presents the results of modeling the dynamics of the system under the control of the three shapers.

The results of the modeling illustrate the efficiency of the synthesized shapers for damping low-frequency oscillations. The graphs in Fig. 9 prove that the ZVD algorithm brings about the highest efficiency in restricting the overshoot under acceptable values of rapidity and robustness. On the whole, the analysis of the results proves that the redistribution of the control torque at gearshifts is efficient.

At the same time, from the results of the modeling the dynamics of the power plant installed in the object under research it can be inferred that in the case of the first three gears it is appropriate to employ the ZVD-shaper. If a higher rapidity action is needed, usage of the ZV-shaper is possible. Regarding the engagement the fourth and higher gears, it is appropriate to utilize the RAMP algorithm. If it is so, the time of the control action ramp should match the natural frequency period of the selected gear. Application of the control action within the time which is shorter than the period duration leads to poorer indicators of overshoot and robustness.



Estimated efficiency of the algorithms under consideration

Shaper type	Rapidity of action	Overshoot	Robustness
ZV-shaper	1	3	3
ZVD-shaper	2–3	1	1
RAMP	2–3	2	2

Fig. 9. Results of modeling the dynamics of the system with different control versions to illustrate the efficiency of the synthesized shapers designed to damp low-frequency oscillations

Application of the control action within the time exceeding the period duration of natural oscillations results in declined acceleration dynamics, and it is unacceptable.

CONCLUSIONS

1. Hence, in the process of performing the present research a method was devised for damping low-frequency oscillations in transmissions of transportation vehicles at the stage following kinematic equalization of speeds of driving and driven components; to do so an antiphase control action was developed that would operate at the natural frequency of dynamic systems which is in the lowest single-node oscillation mode.

2. The novelty lies in synthesizing a shaper on the basis of computing parameters for redistributing in time the control action under the following algorithms: ZV (Zero Vibration), ZVD (Zero Vibration and Derivative), ZVDD (Zero Vibration and Double Derivative), RAMP, etc. The amplitude and the duration of the stages as well as the stage when an algorithm begins to function are derived from the initial conditions of the oscillation process in dynamic systems; these conditions are identified with the help of the signatures of the first and second derivatives of the torque. The type of a regulator (shaper filter) is selected depending on the choice of the priority parameter that characterizes the quality of the transient process – overshoot, rapidity of action or robustness.

3. It was established that to damp low-frequency oscillations related to the gear shifting in the transmission of a transport vehicle the ZVD-algorithm yields the highest efficiency in restricting overshooting at acceptable values of the rapidity of action and robustness. When a more rapid action is required, the ZV-shaper can be used. It is also adequate to apply the RAMP-algorithm if the value of the natural frequency of the lowest single-node oscillation mode is equal to 4 Hz or higher.

4. On the whole, the analysis of the achieved results proves that the redistribution of the power control action at the stage after kinematic equalizing in the process of gear shifting in transmissions of transport vehicles is highly efficient.

5. The efficiency of the proposed method resides in damping oscillations in transmissions of transport vehicles when gear shifting is in progress following the stage of kinematic equalizing. The proposed method brings about better service properties such as the acceleration rate, comfort, etc.

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Signal Pre-Selection for Monitoring and Prediction of Vehicle Powertrain Component Aging

A. Udo Sass[1], E. Esatbeyoglu[1], T. Iwwerks[1]

[1]Volkswagen AG (Wolfsburg, Federal Republic of Germany)

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Abstract. Predictive maintenance has become important for avoiding unplanned downtime of modern vehicles. With increasing functionality the exchanged data between Electronic Control Units (ECU) grows simultaneously rapidly. A large number of in-vehicle signals are provided for monitoring an aging process. Various components of a vehicle age due to their usage. This component aging is only visible in a certain number of in-vehicle signals. In this work, we present a signal selection method for in-vehicle signals in order to determine relevant signals to monitor and predict powertrain component aging of vehicles. Our application considers the aging of powertrain components with respect to clogging of structural components. We measure the component aging process in certain time intervals. Owing to this, unevenly spaced time series data is preprocessed to generate comparable in-vehicle data. First, we aggregate the data in certain intervals. Thus, the dynamic in-vehicle database is reduced which enables us to analyze the signals more efficiently. Secondly, we implement machine learning algorithms to generate a digital model of the measured aging process. With the help of Local Interpretable Model-Agnostic Explanations (LIME) the model gets interpretable. This allows us to extract the most relevant signals and to reduce the amount of processed data. Our results show that a certain number of in-vehicle signals are sufficient for predicting the aging process of the considered structural component. Consequently, our approach allows to reduce data transmission of in-vehicle signals with the goal of predictive maintenance.

Keywords: predictive maintenance, feature extraction, signal selection, time series, machine learning, model explanation

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Предварительный выбор сигнала для мониторинга и прогнозирования старения компонентов силовой передачи автомобиля

А. Удо Сасс[1], Э. Эсатбейоглу[1], Т. Ивверкс[1]

[1]АО «Фольксваген» (Вольфсбург, Федеративная Республика Германия)

Реферат. Прогнозное техническое обслуживание является важным для предотвращения незапланированных простоев современных транспортных средств. С расширением функциональности одновременно происходит быстрый рост обмена данными между электронными блоками управления. Большое количество бортовых сигналов позволяет осуществлять мониторинг процесса старения. Старение компонентов автомобиля зависит от того, как они используются. Элементы старения выявляются благодаря наличию ряда бортовых сигналов. В данной статье предложен метод выбора бортовых сигналов с целью определения соответствующих для проведения мониторинга и прогнозирования старения компонентов силовой передачи транспортных средств. Процесс старения рассматривается на основе степени засорения конструктивных элементов. Измерение процесса старения компонентов осуществляется в определенные промежутки времени. Благодаря такому подходу данные, полученные в неравномерно распределенные промежутки времени, предварительно обрабатываются для формирования сравниваемых бортовых показателей. На первом этапе агрегируем данные в определенные интервалы. Тем самым динамическая база бортовых данных уменьшается, что позволяет более эффективно анализировать сигналы. Также используем алгоритм машинного обучения с целью создания цифровой модели для измерения процесса старения. С помощью методологии локальных интерпретируемых модельно-агностических объяснений модель становится интерпретируемой. Это позволяет извлекать наиболее релевантные сигналы и тем самым сокращать объем обрабатываемых данных. Полученные результаты показывают,

Адрес для переписки
Удо Сасс Андреас
АО «Фольксваген»
Бриффах 17772,
38436, г. Вольфсбург, Федеративная Республика Германия
Тел.: +7 916 940-00-06
andreas.udo.sass@volkswagen.de

Address for correspondence
Udo Sass Andreas
Volkswagen AG
Brieffach 17772,
38436, Wolfsburg, Federal Republic of Germany
Tel.: +7 916 940-00-06
andreas.udo.sass@volkswagen.de

что для прогнозирования процесса старения рассматриваемого структурного компонента достаточно определенного количества бортовых сигналов. Таким образом, предлагаемый подход позволяет сократить передачу данных бортовых сигналов для проведения профилактического обслуживания.

Ключевые слова: прогнозное техническое обслуживание, выделение признаков, выбор сигнала, временные ряды, машинное обучение, объяснение модели

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Introduction

A massive amount of information is transmitted in a modern vehicle. This information is used for communication between various Electronic Control Units (ECU). These information are transmitted via the Control Area Network (CAN) bus in form of signals, which can be triggered by different ECUs (e. g. vehicle speed, outside temperature, turn signal status). Due to the utilization and prioritization of the CAN bus, the signals cannot be transmitted in real-time. Because of more safety functions, more driver assistant systems and a higher in-vehicle entertainment the complexity of such vehicles grows rapidly.

Our goal is to provide component aging indicators for the use in a health management or in sense of predictive maintenance. Therefore, we identify relevant groups of signals concerning an observed physical aging process. With the help of this approach, the transmitted in-vehicle signals can be reduced to a small group of relevant signals. Due to the massive amount of data and complex aging process (the selected physical aging process cannot be identified by using only one signal), a manually identification of aging-relevant signals is not suitable. The analyzed prototypes transmit hundreds of signals in a day. After preprocessing, the transmitted data of a prototype's signal contains up to 65 mio. value samples. Therefore statistical features are extracted out of the raw information to reduce this massive amount of data.

This paper is structured as follows. In the section 2 we briefly present some of the related work and background information. Afterwards, we describe the analyzed data and the preprocessing step for generating suitable datasets in section 3. In section 4 our approach for preselecting relevant in-vehicle signals is presented. In section 5 our results are given and evaluated. To the end, section 6 concludes this paper and we give an outlook of future work.

Background

In this section, we provide background information and related works. Different commercial vehicles are equipped with CAN loggers to save the in-vehicle signal streams, including sensor readings, actuator readings and internal parameters of control models. With the help of these loggers, hundreds of in-vehicles signals can be recorded.

In our work we estimate a degree of aging of an Exhaust Gas Recirculation (EGR) cooling system. This aging value can be used for further predictive maintenance approaches. Some authors used special sensors to detect faulty state of the observed component [1–3]. As described in section 1, the amount of information is massive and has to be aggregated to filter the important information. H. Guo et al. shows an approach, to reduce the transmitted information with the help of a cloud [4]. Common feature extraction is a widely used method to keep the amount of samples in a suitable way [5, 6].

The examined prototypes with diesel engines have in common, that the EGR cooling system is observed in various time periods in workshops. With the help of this information, a health status of this component aging is given. The recirculated exhaust gas of the engine back into the intake tract is set from the EGR valve. Due the combustion of sulfur-containing diesel fuel, different types of emissions are released. The EGR rate determines the proportion of exhaust gas mass flow based on the total mass flow filling the engine cylinders. By changing the EGR rate the emissions can be influenced positively [7, 8]. Though, a too high EGR rate causes a fouling in EGR coolers [9, 10].

In addition to the given explanation of the physical aging process, the quality of Machine Learning models for predicting fault diagnosis or health states are related to the quality of input data. In order to increase the quality of the models and to reduce the computational complexity a feature selection is necessary. K. H. Hui et al. present an approach for selecting a subset of features for predicting machinery faults by using vibration signals [11]. In the first iteration step the best feature is selected. Furthermore, in the next iteration step all other combinations of this feature are tested. The best combination of this iteration is selected. This is repeated until all features are selected. In the end, a subset of feature combinations with the best accuracy and the lowest number of features is selected. The approach shows a accuracy improvement from 74 % to 81 % selected by the features [11].

R. Prytz et al. implement an approach to identify dependencies between on-board signals in a truck [12]. First, the external influences are separated from the internals. In the next step, important relations are found by using Least Absolute Shrinkage and Selection approach (LASSO) and Recursive Least Squares approach (RLS). Zhang et al. select different features for predicting the Remaining Useful Life (RUL) of rolling element bearings [13]. Different statistical features are calculated from the origin monitored signals by processing time domain, frequency domain and time-frequency domain. The features are evaluated by different goodness metrics, such as correlation, monotonicity and robustness. The signals are selected by calculating the weighted linear combinations of the several goodness metrics.

A. Mrowca et al. identify groups of signals in in-vehicle network traces [14]. In this approach, redundant signals are discovered to reduce potentially identical information on the bus load. The authors of this work distinguish between categorical and numerical signals. In order to represent the signal behavior, various features are extracted with respect to the overlapping windows. Furthermore, the feature subset with the best prediction quality is found. With the help of the most important feature subset, the signals can be clustered in several groups [14].

J. A. Crossman et al. analyze signal fault analysis of vehicle engine data in order to find relevant signal features [15]. In a first step the input data is segmented in several dynamic windows. These windows are used to generate signal features. The algorithm ranks the features according to the linear separability of these features. For the current features set the error rate is calculated. In order to reduce the feature set, the backward selection algorithm eliminates the lowest ranked feature until the best error rate. The authors show, that classification accuracy rises from 61.92 % to 83.84 % by reducing the selected features [15].

Besides the signal reduction, machine learning methods are also implemented to predict an observed target value. M. J. Kane et al. shows in the work, that the Mean Squared Error can be improved with a Random Forest approach for prediction of avian influenza outbreaks [16]. The Support Vector Regression (SVR) is used for predicting the urban air quality of Beijing and cities next to Beijing.

In our paper, we implement a signal pre-selection to reduce the whole signal variance by using Local Interpretable Model-agnostic Explanations (LIME). M. T. Ribeiro et al. present an algorithm to interpret complex classifiers or regressors in a faithful way [17]. In order to achieve this, the algorithm has to be interpretable for humans and the results should be similar to the origin prediction locally. The explanation is defined as following

$$\xi(x) = \underset{g \epsilon G}{\operatorname{argmin}} \mathcal{L}(f,\ g,\ \pi_x) + \Omega(g),$$

where x – origin representation of an instance and x' the binary vector of its interpretable instance; G – class of potentially interpretable models; $\Omega(g)$ – measured complexity [17].

For the representation randomized samples around π are used and with the distance weighted. The fidelity function Λ approximates the global function locally. Furthermore, LIME tries to minimize the complexity and to maximize the quality.

Besides the relevance of a signal, different samples of a signal can cover various amount of the whole database. In order to identify the samples with the highest coverage, LIME has implemented a submodule pick algorithm [17].

Data description

For the further analytics the vehicle internal network traces from the CAN-bus are applied. This network traces consists of a various signal variety of sensors/actors readings and internal parameters of control models. The given prototypes are analyzed regarding their EGR cooler aging. This aging-value is observed for every prototype in certain intervals in workshops. We use these values as training set target value (ground truth).

The in-vehicle signals from the internal network traces include high frequent and unevenly spaced time-series. It is necessary to transform this data in a analyzable form. First, the time-series are cleaned from invalid values. Afterwards, the time-series are synchronized to a 100 ms raster. Instead of interpolating the values, only the associated timestamps of each value-time-pairs are changed to a unified and equidistant time raster. With the help of this method it is ensured, that no measured value is changed and the signals keep its origin behavior. For each recording a trigger signal defines the start and end time. All signals for that recording are cut regarding the length of the trigger signal. Therefore, all signals have the same length within the recordings. Afterwards, for every signals the recordings are merged to a coherently dataset.

The data is segmented regarding several time periods. The associated target value is averaged for that given time period. As mentioned in our previous work [18], a too high dynamic in the dataset will predict an aging-value with a less quality. In order to decrease this dynamic and to reduce the amount of samples, we calculate statistical features directly from the original equidistant signal for a given time period of 9 h. We use similar statistical features as mentioned in [15] as basic features to aggregate the signals: arithmetical mean, 25th and 75th percentile and the standard deviation of the values in each time period. The Fig. 1 shows the signal segmentation and aggregation. This approach is done for the whole vehicle lifetime and for all signals.

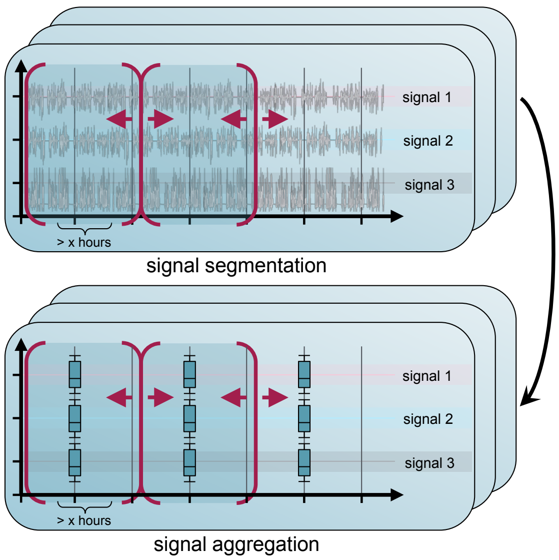

Fig. 1. Example for the signal segmentation and signal aggregation for the synchronized time-series of the vehicle lifetime

Signal preselection

In this section we present our approach to preselect a small amount relevant signals from the whole dataset. First, a machine learning model is used to predict the observed aging-value of the component with the help of the calculated signal aggregations. The focus of our work is the preselection of the signals, for that purpose we use the Random Forest Regression as default model.

As described in the previous section, the final datasets have the same length for all signals. Thus, the dataset is split into a training (2/3) and test dataset (1/3).

Different representative samples of the trained model are picked to explain the model locally. For that purpose we apply the LIME algorithm [17]. As a result we get the weights for explaining the signal relevance locally. To show the local relevance heatmaps are created for every sample. The heatmaps include local scores for the used features (arithmetical mean, 25th and 75th percentile and the standard deviation) of the signals.

Finally, the global score φ is created from the local heatmaps of every signal regarding all statistical features. In order to calculate the score φ_s, h is defined as the amount of heatmaps, the amount of feature for every signal is n and the processed signal s of all signals S. s_{ij} is defined as local weight of a feature j from the signal s within the heatmap i. The score calculation is defined as follows

$$\varphi_s = \sum_{i=1}^{h} \frac{\sum_{j=1}^{n} \frac{s_{ij}}{n} \cdot 100}{h} \quad \forall s \in S.$$

After determination we sort the results regarding the global score (relevance).

Results

In this section, we present our results for preselecting in-vehicle signals of a powertrain aging component purpose. The determined in-vehicle signals are evaluated with the help of the root mean square error (RMSE) regarding the predicted aging-value.

The Fig. 2 shows the score map of the top ten in-vehicle signals regarding the relevance (global score) for predicting the aging-value for a selected prototype.

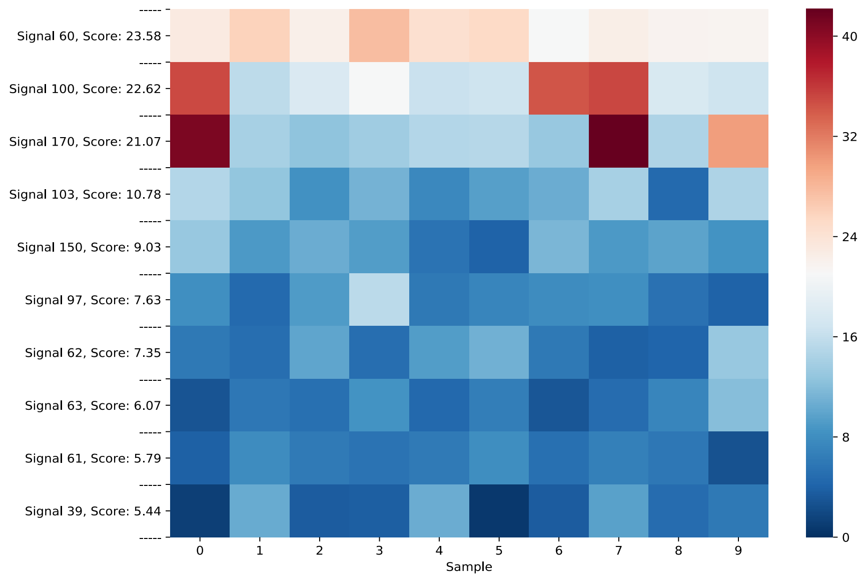

Fig. 2. Score map of the top ten in-vehicle signals regarding the relevance (global score) for predicting the aging purpose for a selected prototype, the x-axis shows different samples with the highest coverage regarding LIME

Different samples cover a various amount of the analyzed database. The submodule pick algorithm identifies the samples with the highest coverage regarding the aging purpose. The colored boxes in a row represent the local score of each signal in the given sample. Each local score is determined by using the four statistical features. The following Tab. 1 shows the description of the determined signals in Fig. 2.

Table 1

Description of the relevant signals for predicting the aging purpose for a selected prototype

Signal number	Description
39	Information about activity on CAN bus
60–63	Different log information
97	Mass of ash in particle filter
100	Mass of soot in particle filter
103	EGR mass flow
150	Oil level information
170	Temperature in EGR valve

In order to evaluate the calculated signals, we apply the RMSE to calculate the goodness of the model. A tuple of ten signals is used to predict the aging-value, for that prediction the RMSE is calculated. The Fig. 3 shows the RMSE, which result from the tuples of signals. The error of the trained models increases with the selection of the worse rated signals. Some outliers do not fit into the global trend. These outliers can be caused differently. On the one hand, the score calculation based on the four statistical features of the signal. If a signal has only a single highly relevant feature and another signal has four semi-relevant features, the resulting score can be the same. For this reason, a lower rated signal could return better results than a higher rated. On the other hand, LIME uses different models as explanations. In order to keep the origin signal behavior, the analyzed statistical feature from the signals are not normalized.

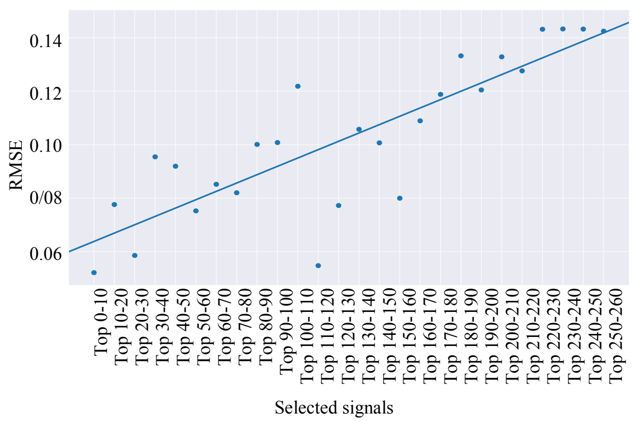

Fig. 3. Overview of the RMSE regarding the in-vehicle signals to predict the aging-value, ten signals (sorted by global score) are combined to calculate the error

When using a linear model, a feature with a very high absolute value could be represented from a low factor in the linear model, although the influence of that feature is very relevant. Because of using features in a similar range, this behavior appears only in exceptional cases. Despite the outliers, the figure shows well weighted scores in order to explain their relevance regarding the physical aging process.

CONCLUSIONS

1. In this work we analyzed dynamic in-vehicle signals and predicted the aging value. The recorded network traces are cleansed and synchronized. After that, the time series of the signals are segmented and aggregated to equidistant datasets. With the help of LIME a small group of relevant signals are preselected for further analytics. The whole amount of analyzed data is compressed multiply by comparison the origin network traces to the preselected aggregated datasets. Our goal is to deliver component aging indicators for the use in predictive maintenance. With the help of our approach, a selected physical aging process can be assigned to a unique group of relevant signals.

2. In the future, unknown aging processes can be identified by using the assignment of preselected signal groups and the aging processes. A cloud can save various signal groups and aging type configurations and transmit it to all the vehicles within analyze cluster. In this case, an expensive aging observation must be only for one vehicle done and the resulting signal groups can be used for all the other vehicles. Furthermore, an aging model of all known aging processes can be used to implement in a health management by using the relevant signal groups and can inform the customers in sense of predictive maintenance.

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UDC 656

Validation of an Assistance System for Merging Maneuvers in Highways in Real Driving Conditions

S. Sanchez-Mateo[1], E. Perez-Moreno[2], F. Jimenez[1], F. Serradilla[1], A. Cruz Ruiz[1], S. de la Fuente Tamayo[1]

[1]Technical University of Madrid (Madrid, Kingdom of Spain),
[2]Complutense University of Madrid (Madrid, Kingdom of Spain)

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Belarusian National Technical University, 2019

Abstract. In the latest study conducted by the National Highway Traffic Safety Administration in 2018, it was published that human error is still considered the major factor in traffic accidents, 94 %, compared with other causes such as vehicles, environment and unknown critical reasons. Some driving scenarios are especially complex, such as highways merging lanes, where the driver obtains information from the environment while making decisions on how to proceed to perform the maneuver smoothly and safely. Ignorance of the intentions of the drivers around him leads to risky situations between them caused by misunderstandings or erroneous assumptions or perceptions. For this reason, Advanced Driver Assistance Systems could provide information to obtain safer maneuvers in these critical environments. In previous works, the behavior of the driver by means of a visual tracking system while merging in a highway was studied, observing a cognitive load in those instants due to the high attentional load that the maneuver requires. For this reason, a driver assistance system for merging situations is proposed. This system uses V2V communications technology and suggests to the driver how to modify his speed in order to perform the merging manoeuver in a safe way considering the available gap and the relative speeds between vehicles. The paper presents the results of the validation of this system for assisting in the merging maneuver. For this purpose, the interface previously designed and validated in terms of usability, has been integrated into an application for a mobile device, located inside the vehicle and tests has been carried out in real driving conditions.

Keywords: merging, human factor, assistance systems, driver behavior, cognitive load

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Проверка эффективности вспомогательной системы для маневрирования в местах слияния автомобильных потоков в режиме реального вождения автомобиля

С. Санчес-Матео[1], Э. Перес-Морено[2], Ф. Хименес[1], Ф. Серрадилла[1], А. Крус Руис[1], С. де ла Фуэнте Тамайо[1]

[1]Мадридский политехнический университет (Мадрид, Королевство Испания),
[2]Мадридский университет Комплутенсе (Мадрид, Королевство Испания)

Реферат. В исследованиях, проведенных в 2018 г. Национальным управлением по безопасности движения автотранспорта, отмечено, что основной причиной дорожно-транспортных происшествий является человеческий фактор (94 % от всех других происшествий, которые вызваны такими причинами, как транспортное средство, окружающая среда и прочие критические ситуации). Некоторые сценарии вождения автомобиля носят особенно сложный и комплексный характер, например это переходно-скоростные полосы, когда водитель получает информацию для принятия решения о проведении плавного и безопасного маневра из окружающей среды. Незнание намерений водителей приводит к созданию рисковых ситуаций, которые вызваны отсутствием взаимопонимания или же ошибочными пред-

Адрес для переписки
Санчес-Матео София
Мадридский политехнический университет
Карретера де Валенсия (A-3), 7-й км,
28031, г. Мадрид, Королевство Испания
Тел.: 003469 958-90-57
Sofia.sanchez@upm.es

Address for correspondence
Sanchez-Mateo Sofia
Technical University of Madrid
km 7 Carretera de Valencia (A-3),
28031, Madrid, Kingdom of Spain
Tel.: 003469 958-90-57
Sofia.sanchez@upm.es

положениями и восприятием. Именно по этой причине рекомендуется использовать передовую вспомогательную систему вождения, которая предоставляет информацию для проведения безопасных маневров в критических ситуациях. В предыдущих работах поведение водителя в момент въезда в поток движущихся автомобилей на автостраде изучалось с помощью визуальной системы слежения, при этом наблюдалась когнитивная нагрузка вследствие огромной степени внимания, которого требует проведение того или иного маневра. Поэтому и предлагается применять вспомогательную систему вождения, которая наиболее эффективна в местах слияния автомобильных потоков, использует коммуникационные системы V2V и предоставляет информацию водителю о корректировке скорости с целью проведения безопасного маневра в местах слияния автомобильных потоков. При этом также анализируются расстояние между транспортными средствами и их скорости движения. Данная работа представляет результаты, подтверждающие эффективность применения этой системы в случае слияния автомобильных потоков. Ранее сконструированный и испытанный интерфейс интегрирован в мобильное устройство, которое прошло тестовые испытания в реальных условиях вождения и установлено внутри транспортного средства.

Ключевые слова: слияние, человеческий фактор, вспомогательные системы, поведение водителя, когнитивная нагрузка

Для цитирования: Проверка эффективности вспомогательные системы для маневрирования в местах слияния автомобильных потоков в режиме реального вождения автомобиля / С. Санчес-Матео [и др.] // *Наука и техника*. 2019. Т. 18, № 6. С. 525-531. https://doi.org/10.21122/2227-1031-2019-18-6-525-531

Introduction

Reducing the number of traffic accidents is an issue that has been a social concern for quite some time. Today, thanks to the new technologies implemented in the automotive sector, it has been possible to alleviate the number of fatal accidents on the roads, but traffic accidents are still considered one of the leading causes of death worldwide according to recent studies by the World Health Organization [1].

According to the latest study carried out by the National Highway Traffic Safety Administration in 2018 [2], 94 % of serious accidents are due to human errors related to the decision, such as performing illegal maneuvers, driving too fast, overconfidence or misjudgment of another car.

The increasing development of Advanced Driver Assistance Systems (ADAS) technologies helps to improve these situations because they assist the driver in making decisions in risky situations and suggest actions that favor not only the safety of the driver himself but also that of those around him.

However, some complex scenarios such as highway merging, which is the subject of this study, involve a high mental load for the user due to the large amount of information that must be processed while performing the merging maneuver. Timely decision making is crucial in this context since if it takes too long to enter the main road, the driver will reach the end of the acceleration lane without speed, assuming a risk of entering at a low speed on the highway.

That is why in previous studies [3, 4] a driver assistance system was proposed for the merging maneuver on highways. The following study is a continuation of the same one, in which the system design and its validation in real driving are presented.

State-of-the-art

ADAS offers great potential for further improving road safety, in particular by reducing driver error. Examples include adaptive cruise control (ACC), which permits maintaining a constant speed in accordance with road conditions and keeping a predetermined safety distance, pedestrian protection systems (PPS), capable of alerting the driver and acting autonomously to reduce the hit speed, and blind-spot detection (BSD), which indicates the existence of another vehicle or object in a blind spot in the rear detection area.

However, there are still many complex scenarios where human error is present due to the high amount of information that the driver has to process while making the right decision for the maneuver. Merging situation is one of the most critical scenarios that occur on the road because to perform a safe maneuver, the driver depends not only on the variables of his vehicle and the environment but also on the relative speed and position of adjacent vehicles.

Several authors have dedicated their studies to this situation, such as [5] which studied accidents in situations of lane change and merging, [6] which analyzed the time needed to perform a merging maneuver between young and elderly drivers or [7], which performed a realistic multi-driver merging simulation, where several driving simulators were connected to each other in order to have a more naturalistic behavior. This last study compares an ADAS cooperative system for merging situations in two conditions, single-driver simulation and multi-driver simulation, in which all drivers are warned of the maneuver that the ego vehicle is going to perform.

However, most of the studies carried out are in the field of simulation and very few in real driving, due to the cost and risk involved in performing tests, especially if there is dense traffic. In the study carried out by [8], real driving tests were carried out with 10 subjects, analyzing the effect of traffic density on the state of the driver's eye. From the results, he supported the need for a driving assistant that could suggest to the driver to accelerate or decelerate the vehicle depending on the gap necessary for merging. A study that serves as a precedent to ours is [9], which developed a merging system on highways, which provided a visual warning on a Google map on a smartphone, verified in real driving. Unlike ours, this article had three vehicles connected, indicating the need to accelerate, brake or enter the gap by means of three sentences according to the calculations of the algorithm until the end of the lane, in addition to being a more complex algorithm than ours.

This paper validates an application of merging assistance in real driving, based on cooperative systems, which have already been used in previous studies applied to the merging maneuver as for example [10] and [11]. Thanks to this technology the vehicles share internal variables of position and speed, proposing a more affable and safe environment.

Assistance system design

Previous work

In previous studies [3, 4] the influence of the merging situation on the cognitive behavior of the driver depending on traffic density was analyzed. The tests, carried out with several subjects in real driving using an eye-tracking system, confirmed that pupil diameter is a sensitive indicator of this type of situations. The fixations were also analyzed, whose duration was affected during the maneuver due to the amount of information to be processed in a single glance to the rear-view mirror. The frequency of mirror looks was also increased by 30 % with respect to the baseline in normal driving. In [12] the fixations were also analyzed by means of heat maps, noting that there was a common hot zone in both rear-view mirrors when the merging maneuver was performed in most driving tests. This area, located in the upper-inner part of the rear-view mirror, is considered adequate for the placement of the assistance system to be developed later.

System development

The proposed assistance system uses cooperative systems (C-ITS) based on Vehicle-to-vehicle (V2V) communication, where vehicles share information on speed and position. This technology used in several experiments such as [13, 14] makes the environment safer and less hostile to adjacent vehicles, thanks to knowing the internal variables of the vehicles.

The variables of speed and position are the inputs of the mobile application that supports the assistance system. For the system interface, a simple bar design has been chosen (Fig. 1), based on previous ADAS development studies [15], where an intelligent speed adaption system was developed. The bars show in qualitative terms, how much to brake or accelerate once the vehicle starts to merge to the main road, guiding it to acquire an optimal speed.

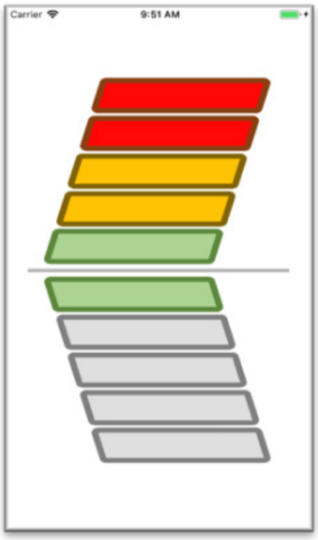

Fig. 1. Bar interface design

The main premises in the algorithm are:

1) the safety margin between vehicles must not be less than two seconds;

2) the maximum speed of the road in the acceleration lane must not be exceeded in any case;

3) the assumed acceleration and deceleration limits to reach are 2 and 4 m/s^2 respectively [16, 17].

The reason for defining a safety margin in terms of time is because more speed requires more distance to brake. Numerous studies report that a driver reacts, in the worst case, with a reaction time of 1.5 s to a surprise event, as an object that moves suddenly on the driver's route [18]. This is why in a conservative way two seconds of time is chosen as the safety margin, so this variable can be applied to any scenario due to its dependence on speed and space.

On the algorithm are shown two main conditionals, the vehicle merge in front of the vehicle that is already in the main road, if safety conditions permit, or the vehicle merge behind the vehicle of the main road, either because it exceeds the maximum speed of the road or because the acceleration need is excessive.

The algorithm used, which is based on motion equations, is more intuitive and simple than the one presented in [19], where a decentralized algorithm for highway merging system was developed, which only indicated the need to accelerate, brake or enter.

The code written generically with the variables is attached below, as well as a flowchart (Fig. 2) to improve understanding:

```
if a1 < amax & vf1 ≤ vmax  #acceleration loop
     if a1 > 0
     level = round (a1/amax)
else                        #brake loop
     if t1 > t2 + T
     if v1 < v2
     level = 2
else
     level = round (dec1/decmax)
```

d1 = distance from vehicle 1 merging to the lane end point

d2 = distance of vehicle 2 from the road to the end of lane

t2 = time it will take for vehicle 2 to reach end of lane

tfront = Time limit for vehicle 1 to pass in front

tbehind = Time limit for vehicle 1 to pass behind

T = safety time, used 2 s

v1, v2 = velocities of both vehicles

level = amount of acceleration or braking

vmax = Maximum track speed in m/s

amax = Maximum acceleration, using 2 m/s^2

decmax = Maximum deceleration, using 4 m/s^2

a1 = Instantaneous acceleration of 1

dec1 = Instantaneous deceleration of 1.

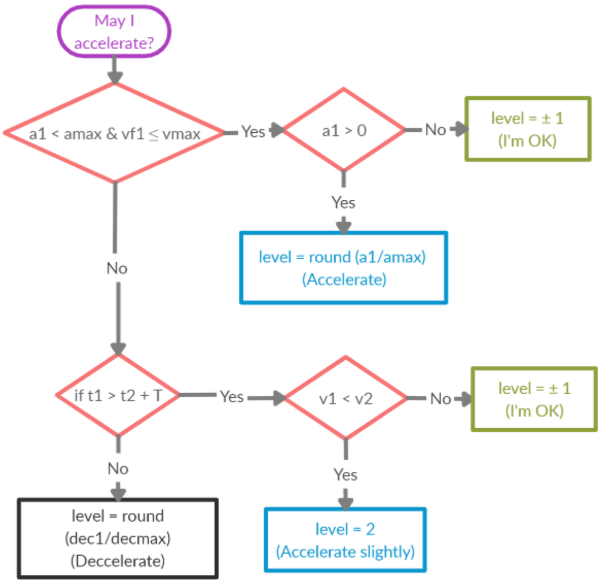

Fig. 2. System operation schematic

System validation in real driving

Three merging maneuvers were carried out along the M-45 highway in Madrid, Spain. Two On-Board Unit (OBU) G5 communication modules embedded in each of the vehicles, send information to the application through the wireless network, which generates only visual warnings based on the speed information and the positioning collected by the Global Navigation Satellite System (GNSS) on a digital map (Fig. 3).

Fig. 3. Interface of merging assistance system

The GNSS is an integrated satellite navigation receiver GLONASS + GPS + GALILEO + SBAS, whose sampling frequency for the position and speed values of each vehicle is 200 m/s and which are the inputs to the control algorithm of the merging assistance interface (Fig. 4).

Fig. 4. Communications module and GNSS

The communication modules are connected to two external antennas each one located on the roof of the vehicle, 2.4 and 5.0 GHz bandwidth (Fig. 5). The GNSS receiver are also fixed to the vehicle roof in order to obtain the best signal possible.

Fig. 5. Vehicles equipped with communications modules and GNSS

The driver will perform the three merging maneuvers supported by the visual warnings provided by the assistance system. The cognitive load of the task is studied examining the pupil diameter and the fixations by means of an ocular tracking system.

Results

Considering the environmental difficulties involved in performing a real driving test, the results obtained in the merging maneuvers have been satisfactory. The position, velocity and acceleration values for each maneuver were analyzed, as well as the levels shown in the application. A total of 13 subjects between the ages of 25 and 45, instrumented with an eye-tracking, performed the circuit. The fixations can be seen in a heat map below, performing a merging maneuver (Fig. 6).

Fig. 6. Heat map of the merging maneuver

As you can see, the driver looks mainly at the road and the merging assistance application, as well as the vehicle and control panels. Also shown in the following graph as an example, are the internal data with which the application works and the levels of warning it generates, the positive level is the need to accelerate and the negative, the need to brake.

In the graphs, it can see to the left the velocities of each vehicle and to the right the distances to the lane end. The level is a dimensionless measure that indicates in the positive part the need to accelerate and in the negative part, the need to brake. As can be seen in Fig. 7, vehicle 1 is warned of the need to accelerate because, although it is closer to the lane end than vehicle 2, at first it starts with a speed of less than 2, and they will probably end up at the lane end. In this case vehicle 1 passes in front of vehicle 2 in the merging. In Fig. 8, the merging maneuver is very similar to the maneuver in Fig. 7, observing how the application warns of the need to accelerate at first, as it gives time to pass in front of vehicle 2. There is a negative peak downward in a particular instant because the speeds of the vehicles are equalized and vehicle 1 must accelerate if he wants to maintain its position with respect to vehicle 2. In Fig. 9, it can see the warnings at first but due to acceleration by vehicle 2, the application suggests passing behind the vehicle.

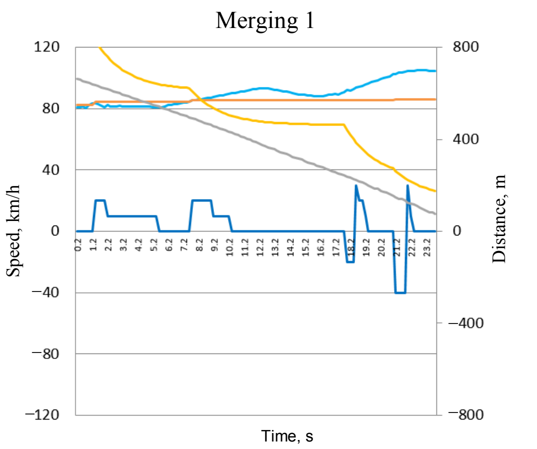

Fig. 7. Data in merging maneuver 1:
– level; – v1; – v2; – d1; – d2

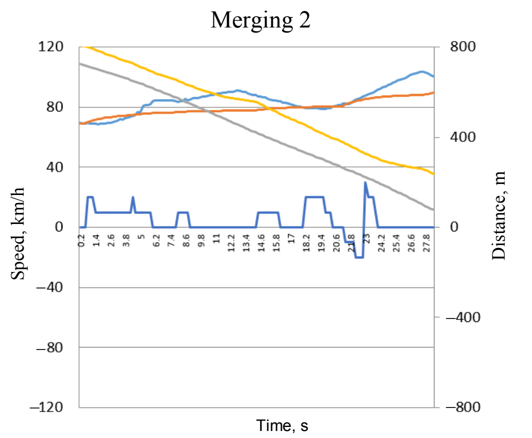

Fig. 8. Data in merging maneuver 2:
– level; – v1; – v2; – d1; – d2

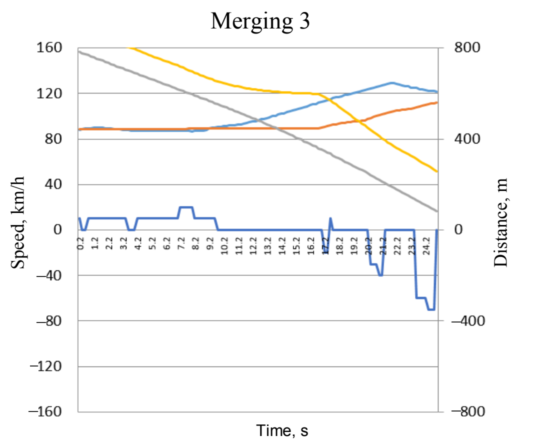

Fig. 9. Data in merging maneuver 3:
– level; – v1; – v2; – d1; – d2

In the Tab. 1 times and distances have been summarized, in which the application gives negative warnings, that is to say to brake and therefore pass behind the vehicle that is within the main road.

Table 1

Times and distances from the first negative warning to the lane end

	Merging 1	Merging 2	Merging 3
Distance, m	252.25	258.72	347.82
Time, s	9.2	10.4	10.6
Level	–20	–20	–20

These values are considered important, because if the driver does not react quickly and there is a situation of not having enough time to proceed to brake safely.

As can be seen from the results, there are no sharp level peaks, but the application suggests starting to brake gradually from level 20. Time and distance are values of similar range in all incorporations, which indicates that it would not show warnings to accelerate when the driver is in a critical situation near the lane end.

CONCLUSION

In this paper, a merging assistance system based on V2V communications has been developed with the aim of making the maneuver safer for the driver. In view of the results obtained, it can be concluded that the application has had a good performance in the real driving tests. In the heat maps, it has been observed that the system is the second point that has more fixations when the maneuver is carried out, behind the fixations to the own lane. This result is very coherent, given that for the driver the final point of the lane is the most important, and he has to arrive at this point with sufficient foresight to be able to merge. On the other hand, seeing the data shown in the graph above and the operation of the application, the merging assistance system is validated in real driving conditions. It has been proven that the system in no case would suggest the driver accelerate near the lane end, which makes it considered a conservative and reliable system in terms of safety.

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ТЕМАТИЧЕСКИЙ УКАЗАТЕЛЬ

Материалы 16-го Европейского автомобильного конгресса

МАШИНОСТРОЕНИЕ

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СТРОИТЕЛЬСТВО

ЭЛЕКТРОННЫЕ СИСТЕМЫ

ЭКОНОМИКА ПРОМЫШЛЕННОСТИ