

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

UDC 625.57:621.311

S. V. RAKSHA^{1*}, O. S. KUROPYATNYK^{2*}, O. L. KRASNOSHCHOK^{3*}

^{1*}Dep. «Applied Mechanics and Materials Science», Dnipro National University named after Academician V. Lazaryan, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (056) 373 15 18, e-mail raksha@ukr.net, ORCID 0000-0002-4118-1341

^{2*}Dep. «Applied Mechanics and Materials Science», Dnipro National University named after Academician V. Lazaryan, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (050) 674 26 44, e-mail kuropyatnick@gmail.com, ORCID 0000-0001-5581-3883

^{3*}Dep. «Applied Mechanics and Materials Science», Dnipro National University named after Academician V. Lazaryan, Lazaryana St., 2, Dnipro, Ukraine, 49010, tel. +38 (098) 706 27 43, e-mail sasha96.08.20@email.ua, ORCID 0000-0002-0140-5179

JUSTIFICATION OF CRITERIA FOR ROPEWAYS ENERGY EFFICIENCY

Purpose. The article is aimed to form and justify the energy efficiency indicators of ropeways of traditional design and ropeways with self-propelled wagons based on the determination and comparison of their values. The substantiation of the energy efficiency criteria of ropeway wagons allows us to determine fully the direction of further research in the field of development of alternative transport mode. **Methodology.** To obtain initial data, the authors reviewed the world trends in the development of ropeway wagons, proposed analytical formulas for determining criteria for ropeways` energy efficiency used to compare traditional ropeways and ropeways with self-propelled wagons. Herewith, we took into account the influence of the loading degree and rated power on the electric motor efficiency. In order to take into account the energy dissipation in the haul rope through its elastic properties, the concept of the efficiency coefficient of the haul rope was introduced. **Findings.** The authors formed a methodology for calculating the efficiency of ropeways, developed formulas for determining energy efficiency. We assessed the influence of the ropeway characteristics on their calculated values; constructed dependence graphs of the self-propelled ropeway efficiency coefficient on the rated electric motor power and the efficiency coefficient on the ropeway drive loading, as well as compared general efficiency coefficients for ropeways with self-propelled wagons and for ropeways of traditional design. The results are based on the averaged values of the electric motors parameters at their different loads. **Originality.** The authors first proposed and justified the energy-efficiency criteria for ropeways that make it possible a comparative analysis of traditional ropeways and those with self-propelled wagons. We determined the dependence of these indicators on the ropeway parameters. **Practical value.** The results of the comparative analysis of traditional construction of ropeways and the ropeways with self-propelled wagons, based on the proposed energy efficiency indicators, can be used to substantiate the feasibility of using certain type of ropeways for the implementation of individual transport processes. The construction diagram of a self-propelled wagon can be used in the development of energy efficient passenger ropeway projects.

Keywords: ropeway; energy efficiency; self-propelled wagons; alternative transport; specific energy consumption; efficiency coefficient

Introduction

Throughout the world, ropeway is called the transport of the future. Modern transport complexes must fully meet the urban needs of passengers

and freight traffic. Aerial ropeway for any terrain has low construction and operation costs. Ecological cleanliness, safety, movement speed, considerable carrying capacity – these factors have become decisive for the use of ropeway transport not only

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

for tourist entertainment, but also for passenger transportation along with the traditional transport modes – by cars, railways, trams and so on. The use of aerial ropeways helps to reduce the traffic load on automobile roads. The ropeways can have a long distance between supports, pass over houses, settlements, forest stands, and overcome long-range water obstacles.

Aerial ropeways are a versatile transport mode that has significant advantages over existing transport that provide transportation of goods and people. The volume of construction and maintenance costs for ropeways is much lower than the corresponding values that characterize other modes of transport [6].

The use of modern technologies has made it possible to create reliable transport systems integrated into the urban environment. Economic efficiency is one of the main indicators of ropeway transport [15]. The use of rope haulage is explained by the lower power consumption due to the combination of end (and intermediate) destination points over the shortest distance. There is also a possibility to adjust the number of cars on the route depending on the line congestion and the possibility of work automation on the sections between the city districts. When designing a ropeway, one searches for an optimum-compromise solution that meets the requirements of economic efficiency, manufacturability and safety.

Comparative evaluation of the effective introduction into operation of wagons and energy-saving technologies, productivity and economic efficiency of machines and units is carried out using the operating and reduced costs [12].

The rules for the construction and safe operation of aerial ropeways of the Labor Safety Laws and Regulations 60.2-1.02-14 set safety requirements for the equipment of ropeways for transportation of passengers and apply to economic entities regardless of ownership and organizational and legal forms involved in its manufacture, installation, dismantling, adjustment, operation, repair, maintenance and modernization [9].

Let us compare the types of passenger ropeways by the number of ropes.

In single-rope ropeways, the rope performs both traction and carrying functions at the same time. When passing the pick-up and drop-off zones, it is possible to stop the wagons; at the same time, the system has high carrying capacity. Single-rope ropeways are becoming more widespread in today's urban mobility. The main characteristics of this type of ropeway are as follows [1]:

- carrying capacity – up to 4,500 people/hour;
- wagon movement speed – up to 6 m/sec;
- wagon capacity – up to 10 people.

Two- and multi-rope ropeways have one haul rope and move along one or two carrying ropes. Ropeways of these types allow changing the number of wagons on the track. They also have high capacity, guarantee extraordinary stability of movement in case of significant increase in wind speed [7]. The main features of this type of ropeway are as follows:

- carrying capacity – up to 6,000 people/hour;
- wagon movement speed – up to 8.5 m/sec;
- wagon capacity – up to 35 people.

The ropeway classification by wagon types is presented in Fig. 1 [8].

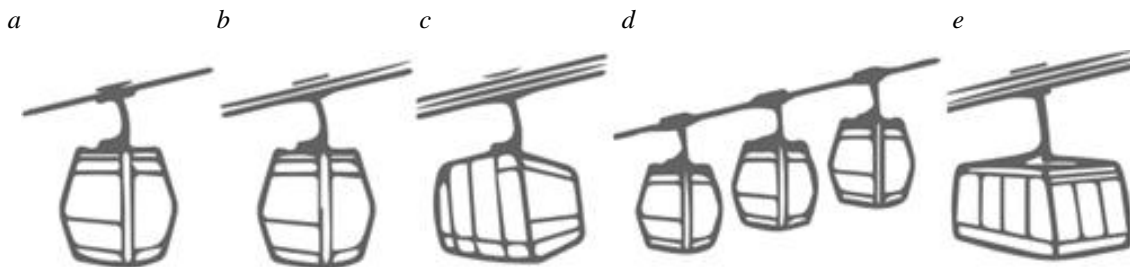


Fig. 1. Passenger ropeways by types of wagons:
a) single-rope dismantlable; *b)* two-rope dismantlable,
c) multi-rope dismantlable; *d)* group reversible wagons; *e)* aerial tram

The advantages of ropeways over other transport modes are as follows:

1. Small capital investment and operating costs. The cost for implementing the ropeway system is about half the cost for the tram and about 1/10 of the cost for underground [16].

2. Constant transportations – ropeways guarantee uninterrupted travel time, do not impede the traffic of other transport modes.

3. Fast creation – ropeways can be built in a short period of time, immediately after ordering. This is mainly due to the use of modular structures.

4. Low space requirements – when designing ropeways, the location of all possible obstacles is considered, which is particularly relevant in densely populated urban areas. Supports and stations occupy a relatively small space, and cable lines are conveniently integrated into the cityscape.

5. Environmentally friendly – ropeways have no harmful emissions because the type of system drive is electric.

6. Separate track that does not cross the existing transport routes.

7. Insignificant dependence on terrain and elevation differences – ropeways can run on steeper slopes than any land roads and are suitable for use in any terrain [1].

8. Architecture – architects and designers have many creative possibilities for designing stations, supports and interiors and exteriors of ropeways.

Given the benefits of ropeways, it is obvious that they can be widely used to solve the transport problem of metropolitan areas.

Purpose

The main purpose of the article is to formulate and substantiate the energy efficiency indicators of ropeways of traditional design and those with self-propelled wagons based on comparison of their values.

Substantiation of energy efficiency indicators of ropeways allows determining in full the direction of further research in the field of development of alternative mode of urban transport.

Methodology

The concept of energy efficiency was introduced in the draft Law of Ukraine «On Energy Efficiency» and is formulated as follows: energy ef-

iciency is the ratio between the volume of produced benefits (results of activity (functioning), products (goods, works, services) and energy) and the volume of energy used for production of such benefits [11]. A similar concept is presented in the current Law of Ukraine «On Energy Efficiency of Buildings,» which states that the energy efficiency of a building is a property of a building, characterized by the volume of energy required to create the proper living and/or life conditions of people in such a building [4]. It should also be noted that it is advisable to compare the structures of different size according to specific indicators – the ratio of absolute values to the basic design indicator (for example, productivity). Considering this, we will assume that the energy efficiency of ropeway is a property of the road, which is characterized by the volume of energy required to carry out the transport process.

To compare the ropeways, it is necessary to determine the energy efficiency parameters for each type.

To obtain the initial data, an overview of the world trends in the ropeways development was conducted. Analytical formulas are proposed to determine the energy efficiency indicators by which traditional ropeways design and the ropeways with self-propelled wagons are compared. Herewith the effect of the load degree and rated power on the motor efficiency coefficient was taken into account. In order to take into account the energy dissipation in the haul rope due to its elastic properties, the concept of efficiency coefficient of the haul rope was introduced.

Findings

Instead of the traditional ropeway design, we propose the use of ropeways with self-propelled wagons as one of the possible solutions to the transport problem of large cities. The following advantages are expected from the use of such a transport system: high mobility, reduced energy costs due to the use of electric motors of lower power than in traditional ropeways, and the design of a fundamentally new wagon drive structure with modern electric motors.

The use of modern software systems for engineering calculations and the creation of models with high reliability of the obtained results allow

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

us to confirm the expediency of using innovative ideas, as well as to clearly present the results of engineering and design solution. During the modeling of the self-propelled system design, the engineers used the principle the simpler the system, the higher the reliability, as well as the principles of partial and complete interchangeability.

The task of the research is to compare two ropeway designs: traditional (with haul rope) and self-propelled wagons, based on the need to minimize the reduced energy costs. Unlike traditional ropeways (with haul or load-haul rope), decentralized haul ropeways have self-propelled wagons or a group of locomotive-driven trolleys. A distinctive feature of such roads is also the horizontal or gently inclined, mainly rail ropeway, as well as the ability to equip self-propelled cars with lifting mechanisms. These ropeways have electric traction [1].

A self-propelled vehicle is a vehicle equipped with a propulsion device that enables it to move itself without the external forces, in the presence of batteries – devices for the accumulation of energy for its further use.

The basis for the creation of a new system of alternative transport (ropeway with self-propelled wagons) is its following advantages:

1. compactness of vehicles;
2. movement interval of 50 meters;
3. automated control system;
4. self-propelled movement principle;
5. separate path integrated into complex urban development.

The purpose of using a self-propelled aerial transport system instead of traditional ropeway is to increase energy efficiency and the degree of automation of the transport process.

Low energy costs can be achieved through the use of a self-propelled transport system:

- innovative technical solutions;
- individual drive for each wagon;
- energy recovery during braking;
- possibility of using renewable energy.

The ropeway design with self-propelled wagons involves the use of drive motors on each unit of rolling stock instead of a single centralized drive located at one of the stations.

To improve the safety of transportation, passenger comfort and energy efficiency in a funda-

mentally new design of the passenger wagon of the ropeway, air conditioning systems, regenerative braking, energy storage, automatic control of wagon movement, temperature control inside and outside the cabin, and air speed, as well as integrated security system (cabin return to the station in case of any emergency) are provided.

The following basic parameters of the self-propelled system are provided: maximum wagon movement speed, diameter and type of rope, maximum operating temperatures of the rope system, maximum wind speed, maximum carrying capacity (number of passengers carried per hour), specific energy consumption, capacity of the battery section, power consumption, loading factor, the track length in the plan, reduced wagon movement resistance factor.

The new self-propelled wagon scheme (Fig. 2) contains accumulator batteries for the subsequent accumulation of energy during the journey from the initial station to the destination.

While moving the car down (descent), it is possible to accumulate energy – recharging the battery, which is realized through the use of regenerative braking. Full charging must occur at the station.

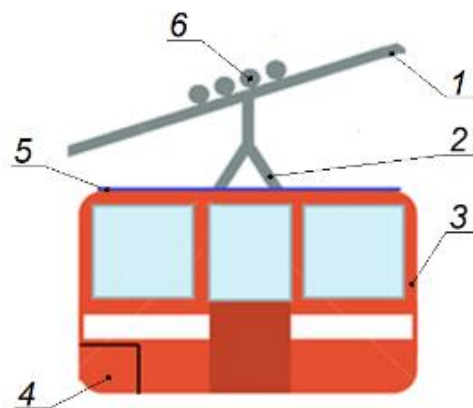


Fig. 2. Construction diagram of self-propelled wagon:

- 1 – carrying rope; 2 – cabin fastening to the running equipment; 3 – cabin; 4 – accumulator batteries; 5 – solar panel; 6 – drive wheels

The ropeway with self-propelled wagons is provided a single-rope type; herewith the rope is not haul but only load one. The individual drive of the self-propelled wagon gives the cabin movement relative to the support rope, and the cabins move in the desired direction.

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

It is provided recharging the batteries from solar energy, as well as to store it for future use.

A significant advantage of this scheme is the ability to stop one wagon at a pick-up and drop-off station.

The utility model «Aerial over-ground transport system» by E. M. Kublanov (Fig. 3) was taken as a prototype of the aerial self-propelled transport system (Fig. 3) [10].

Indicators of the ropeway efficiency are the specific energy consumption and the increase of the efficiency coefficient.

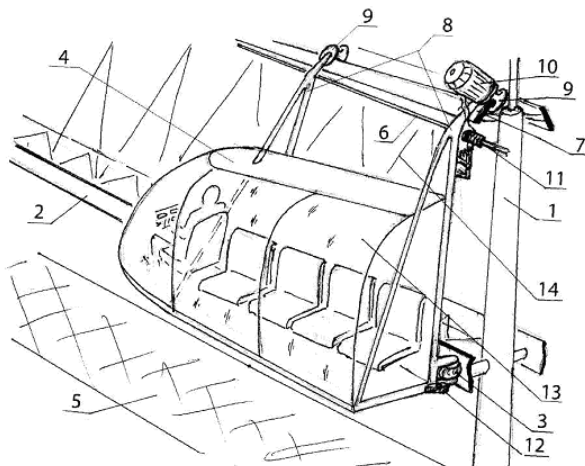


Fig. 3. Aerial over-ground transport system:
1 – support; 2 – lower rail; 3 – moving element of transverse movement confinement; 4 – wagon,
5 – platform; 6 – live cable; 7 – upper rail; 8 – power component; 9 – rollers;
10 – electric motor; 11 – current collector,
12 – clutch elements; 13 – foldaway doors;
14 – power struts

Specific energy consumption is the amount of energy consumed by a ropeway for transporting a unit of a transported cargo (or one person for a ropeway) [2].

The specific energy consumption of the ropeway can be defined as the ratio of the output power of its drive to the ropeway performance (carrying capacity):

$$e = \frac{D}{P},$$

where e – energy consumption; D – drive output power; P – ropeway productivity (carrying capacity).

Such a criterion allows us to estimate the energy costs for transporting passengers and cargo (by weight, volume, quantity, etc.) [6].

Drive output power:

$$D = 2 \cdot (m_0 + m_1) \cdot g \cdot L \cdot v \cdot w' \cdot \lambda,$$

where m_0 – wagon weight (empty); m_1 – total weight of passengers with luggage; g – acceleration of gravity; L – track length in the plan; v – wagon movement speed; w' – reduced wagon movement resistance factor; λ – wagon hanging spacing.

Carrying capacity of the passenger ropeway:

$$P = \lambda \cdot m_1 \cdot v,$$

Then the energy consumption of the drive:

$$e = 2 \cdot (1 + k_m) \cdot g \cdot L \cdot w'.$$

The analysis of the obtained dependence shows that the factors that influence the specific energy consumption are:

- track length in the plan L ;
- wagon loading coefficient

$$k_m = \frac{m_0}{m_1};$$

– reduced wagon movement resistance factor w' .

Specific energy consumption for traditional design (with haul rope):

$$e_{HR} = 2 \cdot \left(1 + k_m + \frac{q_T \lambda}{m_1} \right) \cdot (f \cdot L + H) \cdot g,$$

where f – resistance factor of wagon movement and haul rope; q_T – distributed load taking into account the weight of rope and wagons.

Specific energy consumption for self-propelled wagons (without haul rope):

$$e_{w/HR} = 2 \cdot (1 + k_m) \cdot g \cdot L \cdot w'.$$

Since the factor f takes into account the movement resistance of wagons and haul rope and the coefficient w' – only the wagon movement resistance, it can be stated that:

$$e_{w/HR} = 2 \cdot (1 + k_m) \cdot g \cdot L \cdot w' < 2 \cdot (1 + k_m) \cdot g \cdot L \cdot f$$

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

Let us transform the expressions to determine e_{HR} to bring it to correspondence with the formula for $e_{w/HR}$:

$$e_{HR} = 2g \cdot [(1+k_m) \cdot f \cdot L + H(1+k_m) + \frac{q_T \cdot \lambda}{m_1} \times (fL + H)];$$

$$e_{HR} = 2(1+k_m) \cdot g \cdot f \cdot L + 2g \cdot [(1+k_m)H + \frac{q_T \cdot \lambda}{m_1} (f \cdot L + H)].$$

Let $w' \approx f$, then:

$$e_{HR} = e_{w/HR} + \Delta e,$$

where Δe – excess specific energy consumption caused by the energy consumption for lifting wagons and moving the haul rope for a ropeway of traditional design;

$$\Delta e = 2 \cdot g \cdot \left[(1+k_m) \cdot H + \frac{q_T \lambda}{m_1} \cdot (f \cdot L + H) \right].$$

The last expressions show that the specific energy consumption for ropeways of traditional design (with haul rope) exceeds that for ropeways with self-propelled wagons.

The absence of traction rope will reduce the specific energy consumption. However, the use of an individual drive leads to an increase in the wagon weight (m_0), which can cause increase in reduced energy consumption.

As it is known, the efficiency coefficient of a mechanical system is the product of all the components of efficiency coefficient that are part of this system [3]. Let us consider the schematic diagrams of drives of a self-propelled wagon (Fig. 4) and aerial ropeways of traditional design (Fig. 5).

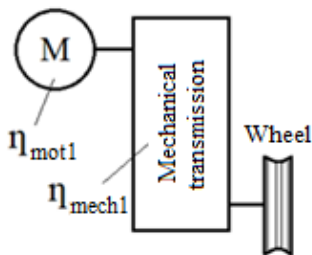


Fig. 4. The drive scheme of self-propelled wagon

Overall drive efficiency of the self-propelled wagon:

$$\eta_{ov1} = \eta_{mot1} \cdot \eta_{mech1},$$

where η_{mot1} – efficiency coefficient of electric motor of self-propelled wagon; η_{mech1} – efficiency coefficient of mechanical transmission.

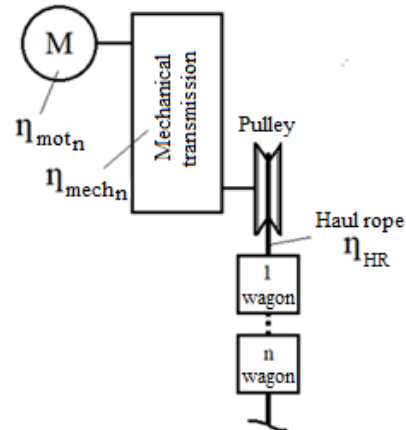


Fig. 5. The drive scheme of the traditional type of ropeways

The overall efficiency of traditional ropeways:

$$\eta_{ovn} = \eta_{motn} \cdot \eta_{mechn} \cdot \eta_{HR},$$

where $\eta_{mot.n}$ – efficiency coefficient of electric motor of traditional ropeway; $\eta_{mech.n}$ – efficiency coefficient of mechanical transmission; η_{HR} – efficiency coefficient of haul rope – a value that characterizes energy dissipation due to the damping properties of the rope.

The efficiency coefficient concept of the haul rope was introduced conditionally to take into account its energy dissipation properties during transportation.

Let us find the increase in efficiency coefficient:

$$\Delta \eta = \eta_{ov1} - \eta_{ovn}.$$

If $\Delta \eta > 0$, then the ropeway with self-propelled wagons is more energy efficient than that of traditional design.

The motor efficiency coefficient may vary depending on the following parameters:

- 1) rated power;
- 2) loading degree;
- 3) rated shaft speed.

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

The dependence of the motor efficiency coefficient on the rated power can be represented in the form of a graph (Fig. 6), based on the analysis of efficiency coefficients of motors of different rated power in the catalogs of their manufacturers [5].

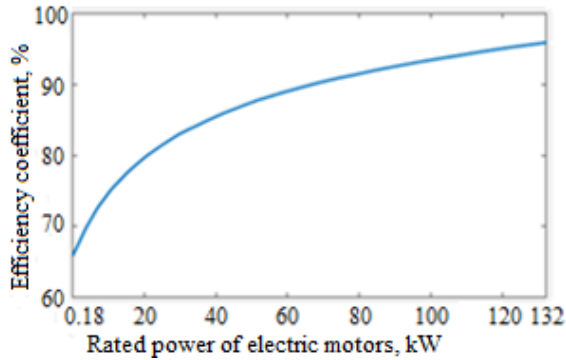


Fig. 6. The dependence of efficiency coefficient on the rated power of electric motor

The dependence of the efficiency coefficient on the motor loading is presented in Fig. 7. In case of overload of electric motor, the efficiency coefficient is lower than the design value [13].

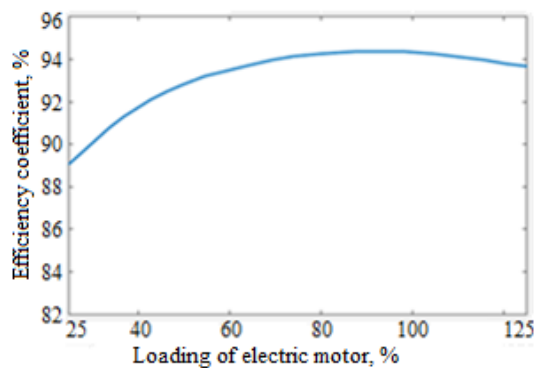


Fig. 7. The dependence of efficiency coefficient on the loading of electric motor

The analysis showed that the effect of the rated shaft speed on the motor efficiency coefficient is negligible (within 0.5%).

The power range of motors for traditional type of ropeways is 20... 250 kW. Efficiency of motors of corresponding power is 0.91... 0.93. For self-propelled cars, the capacity of the engines is 3...10 kW. The efficiency of these engines varies significantly: 0.81... 0.87.

The range of power levels of electric motors for traditional ropeways is 20...250 kW. Efficiency coefficient of motors of corresponding power is 0.91... 0.93. For self-propelled wagons, the power

is 3... 10 kW. The efficiency coefficient of these motors varies significantly: 0.81... 0.87.

Since the transmission mechanisms in both cases (self-propelled wagon, traditional ropeway type) are structurally composed of the same components, we will assume their efficiency coefficients are the same.

Let us consider the case when a traditional ropeway motor is loaded at 25% power. Such a case is possible if 75% of the wagons are removed from the track due to their underload. At the same time, for self-propelled wagons, the electric motor is 100% loaded. In both cases, we believe that the wagons remaining on the track are fully loaded.

The increase in the efficiency coefficient is defined as:

$$\Delta\eta = \eta'_{\text{mot1}} \cdot \eta''_{\text{mot2}} \cdot \eta_{\text{mech1}} - \eta'_{\text{motn}} \cdot \eta''_{\text{motn}} \cdot \eta_{\text{mechn}} \cdot \eta_{\text{HR}}$$

where η'_{mot1} , η'_{motn} – the values that take into account the effect of electric motor power on its efficiency coefficient for a self-propelled wagon and a ropeway of the traditional type; η''_{mot1} , η''_{motn} – values that take into account the effect of the loading of electric motor on its efficiency coefficient for a self-propelled wagon and a ropeway of the traditional type, respectively;

Then the haul rope's efficiency coefficient can be defined as:

$$\eta_{\text{HR25\%}} = \frac{\eta'_{\text{mot1}} \cdot \eta''_{\text{mot1}} \cdot \eta_{\text{mech1}}}{\eta'_{\text{mot25}} \cdot \eta''_{\text{mot25}} \cdot \eta_{\text{mech25}}} = \frac{\eta'_{\text{mot1}} \cdot \eta''_{\text{mot1}}}{\eta'_{\text{mot25}} \cdot \eta''_{\text{mot25}}} = \frac{0.94 \cdot 0.84}{0.83 \cdot 0.89} \approx 1.07 > 1.$$

Efficiency coefficient cannot be greater than one, which means that in case of 25% loading of both ropeways, the ropeway with self-propelled wagons has an advantage over the overall efficiency of the system.

Let us consider the case when a motor of the traditional ropeway is loaded at 100% power. At the same time for self-propelled wagons, the electric motor remains loaded at 100%. Under the following conditions, the haul rope efficiency is as follows:

$$\eta_{\text{HR100\%}} = \frac{\eta'_{\text{mot1}} \cdot \eta''_{\text{mot1}}}{\eta'_{\text{mot100}} \cdot \eta''_{\text{mot100}}} = \frac{0.94 \cdot 0.84}{0.94 \cdot 0.89} \approx 0.94.$$

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

The haul rope's efficiency coefficient is less than one, which means that there is a limit value of the number of wagons n_{lim} , for which the total ropeway efficiency coefficient of traditional ropeway and self-propelled wagons is the same, despite the relatively low motor efficiency of the latter.

To check the accuracy of the calculation, let us draw up a mathematical block diagram of finding the efficiency coefficient of the haul rope, depending on the loading of electric motors (Fig. 8).

The data given above we take as the output, as well as take the efficiency coefficient of transmission mechanisms 0.9 [14]. For the efficiency coefficient of traditional ropeways, depending on the loading (25-100%), we form the matrix of the initial data. The haul rope efficiency matrix is obtained as a result of mathematical actions.

As a result of mathematical actions, it follows that in the case of loading of traditional ropeway motor of less than 50% self-propelled wagons will be guaranteed an advantage, despite the low efficiency coefficient of electric motors of relatively low power. This indicates that there are certain conditions in which the use of ropeways with self-propelled wagons instead of traditional ropeways is appropriate and justified in terms of energy efficiency.

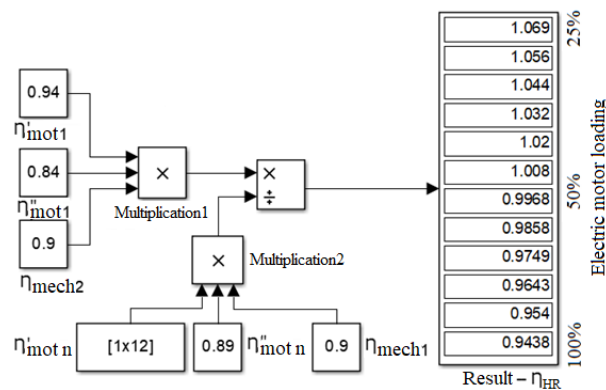


Fig. 8. Mathematical block diagram of determining the efficiency coefficient of the haul rope in the Simulink software application

Under real conditions, the efficiency coefficient of the haul rope is always less than one.

Originality and practical value

The authors first proposed and substantiated energy efficiency indicators that allow for a comparative analysis of ropeways of traditional ropeways with self-propelled wagons. The dependency of these indicators on the ropeway parameters was determined.

According to the proposed indicators of energy efficiency, the results of the comparative analysis of traditional ropeways with those containing self-propelled wagons can be used to justify the feasibility of using certain types of ropeways for implementing certain transport processes.

The developed design scheme of the self-propelled wagon can be applied during the development of energy efficient projects of passenger ropeways.

Conclusions

Specific energy consumption for traditional ropeways (with haul rope) exceed those for the ropeways with self-propelled wagons. The absence of haul rope will reduce the specific energy consumption. However, the use of an individual drive leads to increase in the wagon weight, which can cause an increase in reduced energy consumption.

Using a specific example, the traditional ropeways were compared with self-propelled wagons by the criterion of increasing energy efficiency. The concept of the efficiency coefficient of the ropeway's haul rope, which takes into account energy dissipation, was introduced. There is no haul rope's efficiency coefficient for calculating ropeways with self-propelled wagons, since the rope is a supporting one.

It is established that the total efficiency coefficient of traditional ropeway can be comparable to the efficiency coefficient of a ropeway with self-propelled wagons due to the expedient loading of the electric motors of the latter.

LIST OF REFERENCE LINKS

1. Банько, В. Г. Будівлі, споруди та обладнання туристських комплексів : навчальний посібник / В. Г. Банько. – 2-ге вид, перер. та доп. – Київ : Дакор, 2008. – 325 с.
2. ДСТУ 2420-94. Енергоощадність. Терміни та визначення. – Київ : Державний Стандарт України, 1994. – 13 с.
3. Жемеров, Г. Г. Энергоэффективность системы электроснабжения метрополитена с рекуперацией электроэнергии при торможении / Г. Г. Жемеров, Д. С. Крылов, А. В. Машура // *Електротехніка і електро-механіка*. – 2019. – № 5. – С. 25–31. doi: 10.20998/2074-272X.2019.5.04
4. Закон України № 2118-VIII від 22.06.2017 р. «Про енергетичну ефективність будівель» / *Відомості Верховної Ради (ВВР)*, 2017. – № 33, ст. 359.
5. Каталог электродвигателей АИР [Electronic resource]. – Available at: <https://systemax.ua/elektrodvigateli/trehfaznye-obshepromyshlennye-elektrodvigateli/air/> – Title from the screen. – Accessed : 27.11.2019
6. Куроп'ятник, О. С. Обґрунтування шляхів підвищення енергоефективності канатних доріг / О. С. Куроп'ятник // *Modern methods, innovations, and experience of practical application in the field of technical sciences : Conference proceedings (Radom, Republic of Poland, December 27–28, 2017)*. – Radom, 2017. – P. 159–162.
7. Малыбаев, С. К. Специальные виды промышленного транспорта / С. К. Малыбаев, А. Н. Данияров. – Караганда, 2011. – 211 с.
8. Матеріали інтернет-сайтів виробників підвісних канатних доріг [Electronic resource]. – Available at: www.doppelmayr.com; www.skado.ru; www.poma.net; www.leitner-ropeways.com/ – Title from the screen. – Accessed : 27.11.2019
9. НПАОП 60.2-1.02-14: Правила будови і безпечної експлуатації підвісних канатних доріг [Electronic resource]. – Available at: https://dnaop.com/html/32423/doc-%D0%9D%D0%9F%D0%90%D0%9E%D0%9F_60.2-1.02-14 – Title from the screen. – Accessed : 27.11.2019
10. Пат. 54262 Україна, МПК51 В61В 3/00, В61В 13/00. Підвісна надземна транспортна система / Кубланов С. М. ; заявник та власник патенту Кубланов С. М. – №u200814870 ; заявл. 24.12.2008 ; опубл. 10.11.2010, Бюл. № 21. – 3 с.
11. Проект Закону України «Про енергетичну ефективність» [Electronic resource]. – Available at: https://sae.gov.ua/sites/default/files/Draft_EE_18_09_2017.docx – Title from the screen. – Accessed : 27.11.2019
12. Ракша, С. В. Обоснование способов снижения энергопотребления подвесных канатных дорог / С. В. Ракша, О. С. Куроп'ятник, А. О. Курка // *Наука та прогрес транспорту*. – 2014. – № 1 (49). – С. 125–131. doi: 10.15802/stp2014/22677
13. Формула КПД электродвигателя [Electronic resource]. – Available at: https://electric-220.ru/news/formula_kpd_ehlektrodvigatelja/2016-10-19-1090 – Title from the screen. – Accessed : 27.11.2019
14. Шейнблит, А. Е. Курсовое проектирование деталей машин : Учеб. Пособие / А. Е. Шейнблит. – 2-е изд., перераб. и дополн. – Калининград, 2002. – 454 с.
15. Frequency analysis of vehicle drive with cable traction / S. Raksha, O. Kuropiatnyk, P. Anofriev, D. Onoprychuk, I. Kovalov // *MATEC Web of Conferences*. – Vol. 230, No. 01010. – P. 1–8. doi: 10.1051/mateconf/201823001010
16. The urban cable transport magazine international [Electronic resource]. – Available at: http://www.siurban.com/media/files/urban2__englisch_web.pdf – Title from the screen. – Accessed : 27.11.2019

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

С. В. РАКША^{1*}, А. С. КУРОП'ЯТНИК^{2*}, А. Л. КРАСНОЩОК^{3*}

^{1*}Каф. «Прикладна механіка і матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (056) 373 15 18, ел. пошта raksha@ukr.net, ORCID 0000-0002-4118-1341

^{2*}Каф. «Прикладна механіка і матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (050) 674 26 44, ел. пошта kuropyatnick@gmail.com, ORCID 0000-0001-5581-3883

^{3*}Каф. «Прикладна механіка і матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (098) 706 27 43, ел. пошта sasha96.08.20@email.ua, ORCID 0000-0002-0140-5179

ОБОСНОВАНИЕ ПОКАЗАТЕЛЕЙ ЭНЕРГОЭФФЕКТИВНОСТИ КАНАТНЫХ ДОРОГ

Цель. Основной целью статьи мы ставим формирование и обоснование показателей энергоэффективности канатных дорог традиционной конструкции и дорог с самоходными вагонами основе сравнения их величин. Обоснование показателей энергоэффективности канатных дорог позволяет в полном объеме определиться с направлением дальнейших исследований в области развития альтернативного вида городского транспорта.

Методика. Для получения исходных данных проведен обзор мировых направлений развития канатных дорог. Предложены аналитические формулы для определения показателей энергоэффективности, по которым выполнено сравнение канатных дорог традиционной конструкции и дорог с самоходными вагонами. При этом учтено влияние степени загруженности и номинальной мощности на коэффициент полезного действия электродвигателя. С целью учета рассеяния энергии в тяговом канате из-за его упругих свойств было введено понятие коэффициента полезного действия тягового канату. **Результаты.** Сформирована методика подсчета коэффициента полезного действия канатных дорог. Разработаны формулы для определения энергоэффективности и оценено влияние характеристик канатной дороги на их расчетные значения. Построены графики зависимости коэффициента полезного действия самоходной канатной дороги от номинальной мощности электродвигателя и коэффициента полезного действия от загруженности привода подвесной канатной дороги. Также сравнены общие коэффициенты полезного действия для канатных дорог с самоходными вагонами и для дорог традиционной конструкции. Приведенные результаты основываются на усредненных значениях параметров электродвигателей при их разной нагрузке. **Научная новизна.** Авторы впервые предложили и обосновали показатели энергоэффективности, которые позволяют осуществлять сравнительный анализ канатных дорог традиционной конструкции и дорог с самоходными вагонами. Определили зависимость этих показателей от параметров канатной дороги. **Практическая значимость.** Результаты проведенного сравнительного анализа канатной дороги традиционной конструкции с дорогами, которые используют самоходные вагоны, по предложенным показателям энергоэффективности могут быть использованы для обоснования целесообразности применения определенных видов канатных дорог с целью реализации отдельных транспортных процессов. Разработанную конструктивную схему самоходного вагона можно применять при разработке энергоэффективных проектов пассажирских канатных дорог.

Ключевые слова: канатная дорога; энергоэффективность; самоходные вагоны; альтернативный транспорт; удельные энергозатраты; коэффициент полезного действия

С. В. РАКША^{1*}, О. С. КУРОП'ЯТНИК^{2*}, О. Л. КРАСНОЩОК^{3*}

^{1*}Каф. «Прикладна механіка і матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (056) 373 15 18, ел. пошта raksha@ukr.net, ORCID 0000-0002-4118-1341

^{2*}Каф. «Прикладна механіка і матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (050) 674 26 44, ел. пошта kuropyatnick@gmail.com, ORCID 0000-0001-5581-3883

^{3*}Каф. «Прикладна механіка і матеріалознавство», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (098) 706 27 43, ел. пошта sasha96.08.20@email.ua, ORCID 0000-0002-0140-5179

ОБГРУНТУВАННЯ ПОКАЗНИКІВ ЕНЕРГОЕФЕКТИВНОСТІ КАНАТНИХ ДОРІГ

Мета. За основну мету статті ми ставимо формування та обґрунтування показників енергоефективності канатних доріг традиційної конструкції та доріг із самохідними вагонами на основі порівняння їх величин. Обґрунтування показників енергоефективності канатних доріг дозволяє в повному обсязі визначитися з напрямом подальших досліджень у сфері розвитку альтернативного виду міського транспорту. **Методика.** Для отримання вихідних даних проведено огляд світових напрямів розвитку канатних доріг. Запропоновано аналітичні формули для визначення показників енергоефективності, за якими виконано порівняння канатних доріг традиційної конструкції та доріг із самохідними вагонами. При цьому враховано вплив ступеня завантаженості й номінальної потужності на коефіцієнт корисної дії електродвигуна. З метою врахування розсіювання енергії в тяговому канаті через його пружні властивості було введено поняття коефіцієнта корисної дії тягового канату. **Результати.** Сформовано методика підрахунку коефіцієнта корисної дії канатних доріг. Розроблено формули для визначення енергоефективності й оцінено вплив характеристик канатних доріг на їх розрахункові значення. Побудовано графіки залежності коефіцієнта корисної дії самохідної канатної дороги від номінальної потужності електродвигуна та коефіцієнта корисної дії від завантаженості приводу підвісної канатної дороги. Також порівняно загальні коефіцієнти корисної дії для канатних доріг із самохідними вагонами та для доріг традиційної конструкції. Наведені результати ґрунтуються на усереднених значеннях параметрів електродвигунів за умови їх різного завантаження. **Наукова новизна.** Автори вперше запропонували та обґрунтували показники енергоефективності, які дозволяють здійснювати порівняльний аналіз канатних доріг традиційної конструкції та доріг із самохідними вагонами. Визначили залежність цих показників від параметрів канатної дороги. **Практична значимість.** Результати проведеного порівняльного аналізу канатної дороги традиційної конструкції з дорогами, які містять самохідні вагони, за запропонованими показниками енергоефективності можуть бути використані для обґрунтування доцільності застосування певних видів канатних доріг з метою реалізації окремих транспортних процесів. Розроблену конструктивну схему самохідного вагона можна застосовувати під час розробки енергоефективних проектів пасажирських канатних доріг.

Ключові слова: канатна дорога; енергоефективність; самохідні вагони; альтернативний транспорт; питомі енерговитрати; коефіцієнт корисної дії

REFERENCES

1. Banko, V. G. (2008) *Budivli, sporudy ta obladnannia turystykykh kompleksiv: navchalnyi posibnyk (2nd ed.)*. Kiev: Dokor. (in Ukrainian)
2. *Enerhooshchadnist. Terminy ta vyznachennia.13 DSTU 2420-94 (1994)*. (in Ukrainian)
3. Zhemerov, G. G., Krylov, D. S., & Mashura, A. V. (2019). Energy efficiency of the subway electrical supply system with electrical energy recovery at braking. *Electrical Engineering & Electromechanics*, 5, 25-31. doi: 10.20998/2074-272X.2019.5.04 (in Russian)
4. Zakon Ukrainy № 2218-VIII (2017). *Vidomosti Verkhovnoyi Rady Ukrayiny*. (in Ukrainian)
5. Katalog elektrodvigatelay AIR. Retrieved from <https://systemax.ua/elektrodvigateli/trehfaznye-obshepromyshlennye-elektrodvigateli/air/> (in Russian)
6. Kuropiatnyk, O. S. (2017). *Obgruntuvannia shliakhiv pidvyshchennia enerhoefektyvnosti kanatnykh dorih, Modern methods, innovations, and experience of practical application in the field of technical sciences: Conference proceedings*. Radom. (in Ukrainian)
7. Malybaev, S. K., & Daniyarov, A. N. (2011). *Spetsialnye vidy promyshlennogo transporta*. Karaganda. (in Russian)
8. Materialy internet-saitiv vyrobnykiv pidvisnykh kanatnykh dorih. Retrived from www.doppelmayr.com; skado.ru; poma.net; leitner-ropeways.com (in English)
9. NPAOP 60.2-1.02-14: Pravyla budovy i bezpechnoi ekspluatatsii pidvisnykh kanatnykh dorih. Retrieved from https://dnaop.com/html/32423/doc-%D0%9D%D0%9F%D0%90%D0%9E%D0%9F_60.2-1.02-14 (in Ukrainian)
10. Kublanov, Ye. M. (2010). UA Patent No. 54262. Kyiv: Ukrainskyi instytut intelektualnoi vlasnosti (Ukrpatent). (in Ukrainian)

ЕЛЕКТРИЧНИЙ ТРАНСПОРТ, ЕНЕРГЕТИЧНІ СИСТЕМИ ТА КОМПЛЕКСИ

11. Proekt Zakonu Ukrainy «Pro enerhetychnu efektyvnist». Retrieved from https://sae.gov.ua/sites/default/files/Draft_EE_18_09_2017.docx (in Ukrainian)
12. Raksha, S. V., Kuropiatnyk, O. S., & Kurka, A. O. (2014). Substantiation of ways of decrease in power consumption of ropeways. *Science and transport progress*, 1(49), 125-131. doi: 10.15802/stp2014/22677 (in Ukrainian)
13. Formula KPD elektrodvigatelya. Retrieved from https://electric-220.ru/news/formula_kpd_ehlektrodvigatelja/2016-10-19-1090 (in Ukrainian)
14. Scheinblit, A. E. (2002). *Kursovoe proektirovanie detaley mashin: Uchebnoe Posobie*. Kaliningrad. (in Russian)
15. Raksha, S., Kuropiatnyk, O., Anofriev, P., Onoprychuk, D., & Kovalov, I. (2018). Frequency analysis of vehicle drive with cable traction. *MATEC Web of Conferences* 230(01010). doi: 10.1051/mateconf/201823001010.
16. The urban cable transport magazine international. Retrieved from http://www.siurban.com/media/files/urban2__englisch_web.pdf

Received: July 30, 2019

Accepted: Nov. 01, 2019