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DESIGN ANALYSIS AND CHARACTERISTICS OF THE VACUUM TRANSPORT SYSTEM

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ABSTRACT

The given paper proves that the key factors governing the design of the vacuum magnetic levitation transport system are the competitiveness of the new transport system and the safety of passenger transportation. This article draws attention to the similarities of the engineering problems when designing the passenger compartment of the vacuum vehicle equipped with the life support system and the aircraft. It allows using the aviation system design experience for development of a vacuum transport system. As the most similar prototype, the Japanese JR-Maglev high-speed system is considered. The assumption is made that the adaptation of JR-Maglev traction levitation system to the aviation technologies can become one of the directions to design a vacuum magnetic levitation transport system. For justification of this assumption, the layout diagram of the vacuum transport system adapted to the aviation fuselage is provided. The assessment of the energy consumption for the route is given. The vacuum transport system is compared with the airbus A320 in terms of specific energy consumption. The estimate calculations performed under the identical comparison conditions have shown that the vacuum transport system is much more effective than the aviation system.

Keywords: vacuum maglev, vacuum transport technology, linear motor, superconducting magnet, vacuum tunnel.

1. INTRODUCTION

Due to the increasingly stringent requirements for the freight and passenger running speed, new solutions in the high-speed land transport engineering are being searched. The main obstacles in further train speed increasing are the “wheel-rail” system and the aerodynamic resistance. The use of the magnetic field ensuring the contactless vehicle movement is the solution of the first problem [1, 2].

The decreasing of aerodynamic resistance to the movement is reached by creation of the vacuum environment in the transport tunnel. Nowadays there are two approaches to implement the contactless vehicle movement in the vacuum environment. One of them is Hyperloop [3-6] which is designed as a hovercraft train moving in the vacuum. The second one is Vactrain [7] designed as a train with magnetic suspension moving in the vacuum.

At the current development stage of the new technical system, the designers tend to prove the advantages which the vacuum transport system could provide. The top priority is the justification of the system performance specifications, whereas the questions of restrictions caused by operation, safety, standard and legal regulations as well as sales opportunity are not discussed. Trying to show the best advantages of the new transport technology without taking into account the restrictions, the designers present significantly overestimated possibilities of the system. So the dominating concept of the system development is a car-capsule design with the capacity from 4 to 6 passengers moving in the vacuum tunnel with an interval from 2 to 200 capsules per minute [8, 9]. It is obvious that the given system cannot ensure the safety of passenger transportation.

The next stage of the transport system development should involve more realistic approaches to the system design with account of restrictions, among which the safety control is the priority. In this regard, there is a need to identify the key factors governing the design of the vacuum transport system, to specify its main components parameters as well as to compare its energy efficiency with the closest analogues.

2. MATERIALS AND METHODS

2.1 Factors determining the transport system design

The main factors determining the magnetic levitation vacuum transport system design are competitiveness and operating safety. Taking this into consideration, the following design objectives can be defined:

- the system should be able to compete with current vehicles;
- the system should ensure the safe, efficient and reliable passenger and freight transportation.

According to the expert assessment [10], the appropriate target speed for the development of the vacuum levitation transport systems is the speed of 1000 km/h.

The rational scope of application for this kind of transport, providing that a passenger travel for 2.5 h (150 min), is the routes up to 2000 km long.

The competitive growth of the new passenger transport, moving at the directions with range to 2000 km, depends on the route choice having a high passenger traffic flow. The routes rating of the passenger

transportation at the internal Russian air lines shows that the greatest passenger flow is observed in the south direction. As the example, let us consider the Moscow - Sochi route having the passenger flow of 2677 thousand passengers per year. The scheme of the route going along existing tracks is shown in Figure-1.

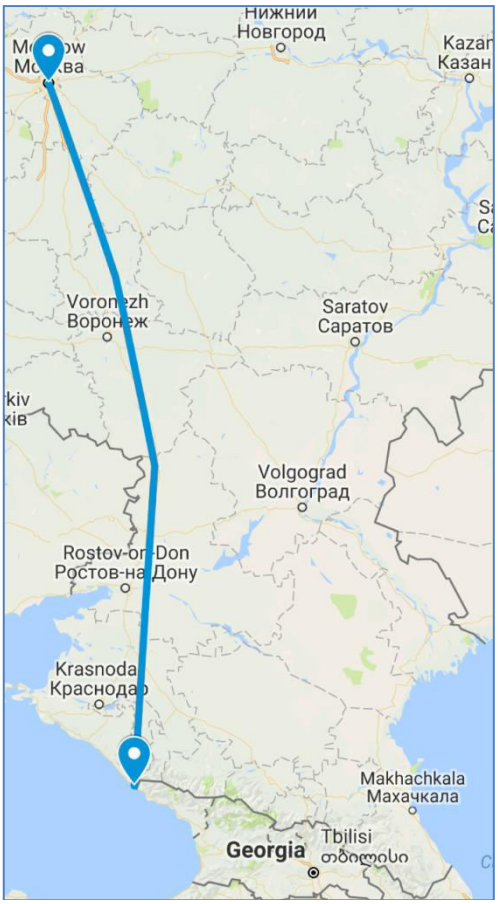

Figure-1. The Moscow - Sochi route.

The main operational characteristics of the high-speed vacuum transport system at the Moscow – Sochi route is presented in Table-1.

Table-1. Operational characteristics of the Vacuum Transport System.

Characteristics	Value
Passenger traffic flow, th. pass	2677
Distance, km	1620
Speed (commercial), km/h	810
Running interval, h	0.5
Annual service life of the vacuum tunnel, h	7200
Number of trips per year	14400
Load of the vehicle per trip, passengers	186

The determining factor of the transport system design is the passenger load per one trip. In the case under consideration, the passenger load should be not less than 186 passengers. It is obvious that the passenger loading of the vacuum vehicle per one trip is closed to the cabin capability of the narrow fuselage passenger aircraft of A320-200 type (refer to Table-2).

Table-2. Airbus A320 parameters.

Characteristics	Value
Length, m	37.5
Fuselage, m	3.95
Speed, km/h	840
Limit passenger capacity, pass	190
Operating empty weight, kg	41800

It is obvious that the designing issues of a passenger compartment of the high-speed vacuum vehicle equipped with the life support system are similar to the issues of aircraft development. It suggests an idea of possible application of aviation technologies when designing a new transport system. The presence of baggage-cargo compartments of rather high capacity can be used for the placement of the traction levitation equipment.

The equipment structure and configuration in the updated plane fuselage should be defined with providing the safety requirements during the operation of a high-speed vacuum transport system.

2.2 Emergency analysis

The major hazards during operation are:

- the vacuum environment where the passenger transportation is;
- the high running speed;
- the closed space (transport tunnel).

These hazards can lead to emergencies involving:

- the vehicle integrity damage;
- the transport tunnel integrity damage;
- the forced stop.

The initial assumption is the fact that emergency can occur in any place of the transport tunnel. All actions have to be aimed at preventing of harm to the passengers health and minimizing the emergency consequences. The algorithm of emergency elimination in the least favorable cases should provide for the following actions:

- the vehicle stop;
- localization of the transport tunnel section in the place of the accident;
- depressurization of the localized section;
- disassembling of the transport tunnel in the place of a stop;
- passengers evacuation;
- extraction of the damaged vehicle out of the tunnel;
- transport tunnel reconstruction.

It is assumed that the transport tunnel is divided into the railway hauls separated from each other by vacuum gates. It allows localizing the section of the transport tunnel where the damaged vehicle located. When the localization is completed, the valves have to be opened to equalize the pressure in the localized section with the atmospheric pressure. Besides, the processing equipment for partial dismantling of the vacuum tunnel and the damaged vehicle extraction is supposed.

Thus, to ensure the safety requirements during the operation of the high-speed vacuum transport system at least two conditions should be fulfilled: the vehicle design should provide the possibility for the fast extraction of the damaged vehicle out of the tunnel and the design of the vacuum tunnel should ensure its disassembling in any place of the vacuum tunnel.

2.3 The system design features

The application of the aviation technologies in the design of the magnetic levitation vacuum transport system makes it possible to regard the Japanese JR-Maglev [11] system of high-speed trains with a magnetic suspension designed by Japan Railway Technical Research Institute as the closest prototype. So far, it is the most high-speed system.

The U-shaped track structure is used for train running. The side walls of the track structure are equipped with traction and levitation windings shown in Figure-2.

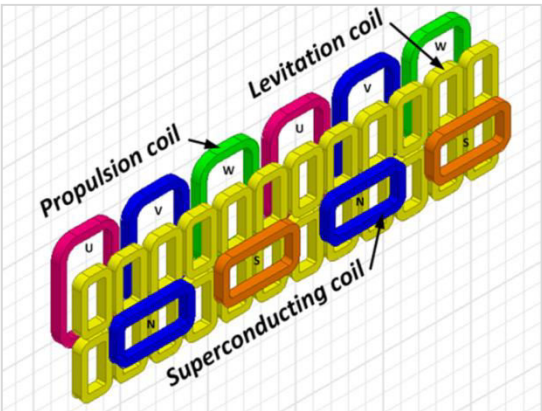

Figure-2. Coil arrangement.

The traction effort is generated by currents interaction in the traction windings with superconducting electromagnets placed at the train bogies. The levitation force is generated by the interaction of the superconducting electromagnets and currents induced in the levitation windings while the train running.

One of the directions for development of the high-speed vacuum transport system can be the adaptation of JR-Maglev traction levitation system to the aviation technologies.

Considering the fact that the vehicle moves in the vacuum under the low aerodynamic resistance, the traction system can be divided into two subsystems: a start-up subsystem operating at the acceleration (braking) section and an independent traction subsystem operating at the section of the cruise running mode. In this case, at the acceleration section the traction windings should be integrated into the tunnel structure and supplied by the fixed railway substation. Unlike the prototype, the traction windings are laid in the track only at the acceleration (braking) section, which allows us to reduce significantly the materials consumption of the system.

As the example, Figure-3 shows the layout scheme of the vacuum transport system adapted to an aviation fuselage.

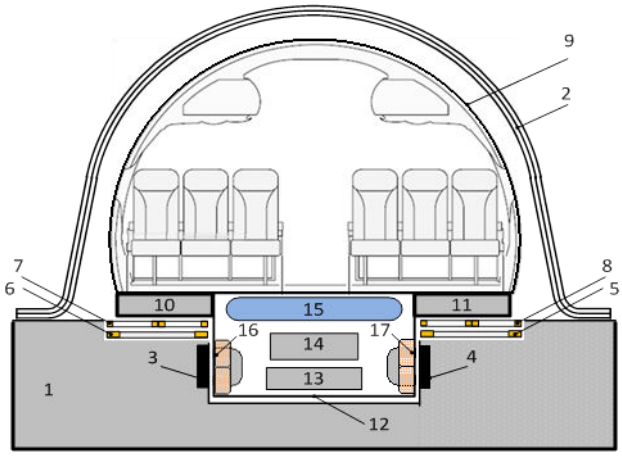

Figure-3. The layout scheme.

In the scheme presented the safety requirements are ensured by the fact that the vacuum tunnel is formed by U-shaped pipeline 1 and removable sections of the semi-cylindrical duct 2 covering it from above, which allows the fast disassembling of any part of the vacuum tunnel to provide the passenger evacuation. In addition, the aircraft fuselage design includes a pressurized compartment 12, where the independent traction drive system is placed. Moreover, the pressurized compartment is connected with the fuselage bottom 9 and placed in the duct of the U-shaped pipeline with a gap from its surface, which ensures the easy extraction of the vehicle from the tunnel.

In the scheme presented, the traction windings at the start–up section and the levitation windings at the whole length of the pipeline are located horizontally along the edge of the pipe-line. It makes possible to arrange the superconducting magnets horizontally under the bottom of the passenger compartment. The independent traction system operating at the section of the cruise running mode is located in the duct of the transport tunnel.

The operation of the traction levitation system involves the following stages. When the power is supplied from the railway substation to the traction windings 7, 8 laid in the pipeline 1 at the acceleration section, there is a force interaction between them and superconducting magnets 10, 11 fixed at the vehicle 9, as the result, the traction effort is generated and the vehicle moves fast along the pipeline 1 by means of wheels mechanism. When the certain running speed is reached, there is a force interaction between the superconducting magnets 10, 11

and levitation windings 5, 6 laid in the pipeline 1 along its length; as the result, the lifting effort is created which transfers the vehicle in the levitation state. After achievement of the specified running speed at the acceleration section, the vehicle switches into the running mode with the steady speed in the self-driven mode. The vehicle design includes the pressurized compartment 12 located in the duct of a U-shaped pipeline with a gap from its surface. The compartment is connected with the vehicle bottom and equipped with the source of power 13, the electronic converter 14, and the cooling system 15. The linear electric motors 16, 17 are installed at the side walls of the compartment in the way that their poles could interact with ferromagnetic track elements 3, 4 embedded in the internal side walls of the pipeline 1 along its length through the air gap.

2.4 Assessment of energy consumption needed for vacuum creation

The vacuum tunnel structure is supposed its division into hauls which can be separated from each other by a vacuum gate. Each haul is equipped with an emergency lock and in addition, the transport locks are foreseen at the beginning and end of the tunnel.

The passenger transportation technology includes the following operation:

- the vehicle transportation to the station,
- the passenger loading at the station,
- the passenger compartment pressurization,
- the vehicle movement to the transport lock,
- the vacuum gate closing
- the air pumping in the transport lock up to the specified pressure,
- the connection of the transport lock with the transport tunnel,
- the vehicle start.

In order to ensure the specified passenger traffic flow, the processing steps should not exceed the time of train running interval. At the same time, the air pumping in the transport lock should take the part of the train running interval time. This determines the requirement to the air pumping speed. The data provided by vacuum pumps manufactures makes it possible to define the dependence of the pumping capacity on the pumping time to reach the specified pressure in the given capacity. As the example, let us consider the two-rotor vacuum pump RNVB 27-20, which has a great action speed. The pumps of this model are used for pumping of large-sized vacuum systems. Figure-4 shows the dependence of the pumping speed on the pumping time up to pressure p = 50 Pa for the transport lock capacity of V = 795 м3.

The Table-3 demonstrates the calculation results of the vacuum pipeline parameters.

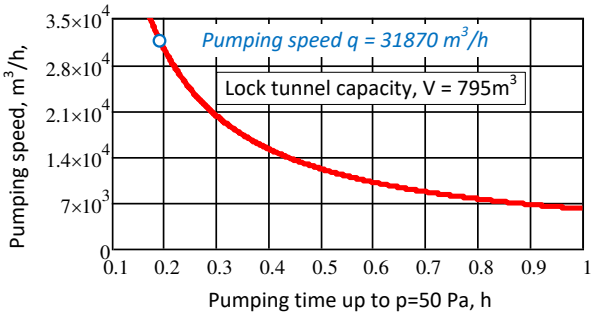

Figure-4. The dependence of the pumping speed on the time up to pressure p = 50 Pa for the volume of the tunnel of V = 795 м3.

Table-3. The calculation results of the vacuum pipeline parameters.

Specification	Value
Total length of vacuum tunnel, km	1620
Cross section area, m^2	15.9
Length of vacuum span, m	5000
Length of the lock tunnel, m	50
Operational pressure in the tunnel, Pa	50
Pumping speed, m^3/h	15555
Power of a pump drive, kW	30
Number of vacuum pumps, Gt.	324
Time creating of vacuum in the tunnel, h	19.48
Energy consumption for creating a vacuum, kW·h	378691
Time creating of vacuum in the lock, h	0.19

The energy consumption required for maintaining the vacuum in the transport tunnel is composed of the energy consumed for vacuum creation and leakage compensation. The coefficient with account of leakages is taken as $k_{al} = 1.1$.

The specific energy consumption needed for vacuum maintain in the transport tunnel is:

$$W_{sp1} = \frac{k_{al} \cdot W_1 \cdot N_1 \cdot 3.6}{P_f \cdot L}. \quad (1)$$

Where

W_1 = energy needed for vacuum creation

N_1 = annual service life

P_f = annual passenger traffic flow

L = route length

2.5 Assessment of the route energy consumption

The estimate calculation is performed under the following assumptions:

- the travel is carried out along the straight train section;
- the running start (braking) is performed with steady acceleration;
- the efficiency factor when acceleration has a fixed value;
- the energy of regenerative braking is assumed to be 40% from the energy consumed when acceleration;
- the aerodynamic resistance coefficient does not depend on the speed.

The full energy consumption during the route is calculated by the following equation:

$$W_t = W_A + W_C - W_B + W_V. \quad (2)$$

Where

W_A = energy consumed when the vehicle acceleration;

W_C = energy consumed during the cruise mode

W_B = energy consumed when braking

W_V = energy consumed for vacuum maintenance per one trip

The energy consumed during the vehicle acceleration mode:

$$W_A = \frac{(m \cdot a + F_x + F_{ed}) \cdot v_{\max} \cdot t_a}{2 \cdot \eta_a}. \quad (3)$$

Where

m = vehicle weight

a = acceleration

F_x = aerodynamic resistance force

F_{ed} = electrodynamic resistance force

$v_{\max}$ = maximum speed

t_a = acceleration time

The aerodynamic resistance is calculated as:

$$F_x = 0.5 \cdot c_x \cdot S_v \cdot \rho \cdot v^2. \quad (4)$$

Where

c_x = vehicle shape coefficient

S_v = fuselage cross sectional area

ρ = air density in the pipeline

v = vehicle running speed

The electrodynamic resistance is calculated as:

$$F_{ed} = 0.5 \cdot \left(k_1 + \frac{k_2}{v} + \frac{k_3}{v^{1.5}} \right). \quad (5)$$

Where

k_1, k_2, k_3 = the coefficients obtained by extrapolation of the experimental data given in [12] at the speed range from 500 to 1000 km/h

The acceleration time is calculated by:

$$t_a = \frac{v_{\max}}{a}. \quad (6)$$

The energy consumed in the cruise mode is defined as the equation:

$$W_C = \frac{(F_x + F_{ed}) \cdot v_c \cdot t_c}{\eta_c}. \quad (7)$$

Where

vc = cruise running speed

tc = running time at the cruise speed

ηc = the efficiency coefficient in the running mode at the cruise speed

The energy consumed when regenerative braking is assumed as 40 % from the energy consumed when acceleration:

$$W_B = 0.4 \cdot W_A. \quad (8)$$

The energy consumed for vacuum maintenance per one trip is calculated as the following equation:

$$W_V = W_{sp1} \cdot L \cdot n_1. \quad (9)$$

Where

W_{sp1} = specific energy consumption for vacuum maintenance (calculated by the equation (1))

n_1 = passenger number per one trip

The initial data is given in Table-4 and the calculation results are presented in Figure-5.

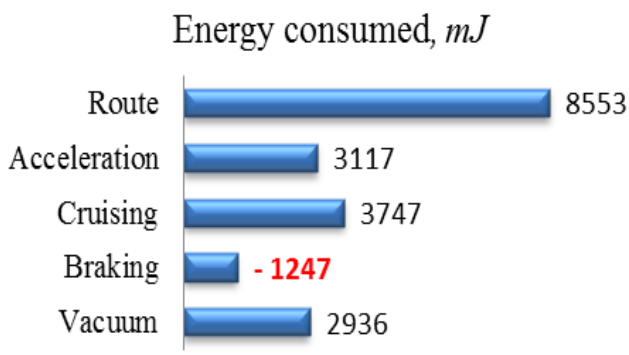

Figure-5. Energy consumption structure

Table-4. The initial data.

Parameter name	Symbol	Unit	Value
Energy to create a vacuum	W_1	**kW·h**	**378691**
Length of vacuum tunnel	L	km	1620
Passenger traffic	P_f	th. pass.	2,677
Annual operating time	N_1	h	7200
Coefficient of air leakage	k_{al}	Per-unit	1.1
Vehicle mass	m	kg	56575
Acceleration of motion	a	m/s^2	1.0
Maximum speed	v_{max}	m/s	233
Cruising speed	v_c	m/s	233
Vehicle shape factor	c_x	oe	0.5
Frontal area	S_v	m^2	12.57
Gas density	ρ	kg/m^3	$6.388 \cdot 10^4$
Cruising time	t_c	s	9000
System efficiency (cruising mode)	η_c	per-unit	0.9
System efficiency (overclocking mode)	η_a	per-unit	0.5
Passenger capacity	n_1	pass	186
Extrapolation coefficient	k_1	No Units	-1.36
Extrapolation coefficient	k_2	No Units	4554
Extrapolation coefficient	k_3	No Units	-21119

3. RESULTS

3.1 Systems comparison in terms of energy efficiency

In order to compare the energy efficiency of the vacuum transport system and the airbus A320 in terms of the specific power consumption under the identical routing and passenger number, the systems are compared.

The specific energy consumption of the vacuum transport system is:

$$W_{Vactrain} = \frac{W_t}{L \cdot n_1} = \frac{8553}{186 \cdot 1620} = 0.0284 \frac{mJ}{pass \cdot km}. \quad (10)$$

The specific energy consumption of the A320-200 airbus is:

$$W_{A320} = P_{A320} \cdot q_{A320} = 0.0191 \cdot 43.1 = 0.8232 \frac{mJ}{pass \cdot km}. \quad (11)$$

Where

P_{A320} = specific fuel consumption A320-200 (P_{A320} = 0.0191 *kg/pass·km*)

q = Specific heat of jet kerosene (q = 43.1 *mJ/kg*)

The energy efficiency coefficient is:

$$k_{EE} = \frac{W_{A320} \cdot \eta_{Tpp}}{W_{Vactrain}} = \frac{0.8232 \cdot 0.35}{0.0284} = 10.15. \quad (12)$$

Where

η_{Tpp} = the efficiency coefficient of the thermal power plant.

Therefore, the estimate calculation performed under the identical comparison conditions allows us to assume that in terms of energy criteria the vacuum transport system is much more effective than the aviation system.

3.2 Assessment of electrotechnical systems parameters

The installed power capacity of the traction converter is:

$$P_{IPC} = \frac{(m \cdot a \cdot + F_x + F_{ed}) \cdot v_{max}}{\eta_a} \quad (13)$$

The power of the autonomous drive system in the cruise running mode is:

$$P_{ADS} = \frac{(F_x + F_{ed}) \cdot v}{\eta_{ADS}} \quad (14)$$

The minimal rated capacity of the battery charger per trip is

$$H_{AB} = \frac{P_{ADS} \cdot t_c}{U_{AB} \cdot k_4}. \quad (15)$$

Where

U_{AB} = battery charger voltage;

k_4 = the coefficient of the permissible discharged depth

The battery charger weight is:

$$m_{AB} = \frac{W_c}{W_{AB}}. \quad (16)$$

Where

W_{AB} = specific energy of the battery charger by weight

The calculation results performed under W_{AB} = 0.378 mJ/kg, k4 = 0.8, η_{ADS} = 0.9, U = 640 V is shown in Table-5.

Table-5. The calculation results.

Parameter name	Symbol	Unit	Value
The installed power capacity of the traction converter	P_{IPC}	kW	26762
The power of the autonomous drive system	P_{ADC}	kW	442
The Capacity of the battery	H_{AD}	A·h	1725
The battery mass	m_{AB}	kg	9920

The analysis of the results obtained shows that the drive system at the acceleration section and the autonomous electric drive system are physically realizable.

4. CONCLUSIONS

The key factors determining the vacuum transport system design are the competitiveness of the new transport type in the sphere of passenger transportation and the safety during the operation.

The emergency analysis has shown that to ensure the safety requirements during the operation at least two conditions should be fulfilled: the vehicle design should provide the possibility for the fast extraction of the damaged vehicle out of the tunnel and the vacuum tunnel construction should ensure its disassembling in any place of the vacuum tunnel.

One of the directions for vacuum transport system development could be the adaptation of the JR-Maglev traction levitation system to the aviation technologies.

In order to reduce the material consumptions, the traction system can be divided into two subsystems: a start-up subsystem operating at the acceleration (braking) section and an independent traction subsystem operating at the section of the cruise running mode. The parameters assessment of the electro technical systems has shown that the drive system at the acceleration section and autonomous electric drive system are physically realizable. The comparison of the vacuum transport system and the airbus A320 in terms of the energy consumption performed under the identical comparison conditions has proved that the vacuum transport system is much more effective than the aviation system.

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