HYPERLOOP: TECHNICAL RISKS AND PROSPECTS

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ABSTRACT

The article is devoted to the technical analysis of Hyperloop high-speed land transport project, interest in construction of which has increased significantly recently. The basic technologies are briefly considered, with the help of physical calculations the basic design characteristics are specified. Technical risks are identified, some of which may affect the initial configuration of the project, while others call into question the very possibility of its implementation. The carried out researches allow to give the conclusion about expediency of the further work on creation of high-speed transport system Hyperloop and to formulate a list of priority research tasks which are necessary to be realized for the project becomes successful.

<u>Keywords:</u> Hyperloop, vacuum overpass, shuttle, high-speed transport, transport systems of the future, new technologies, technical risks.

Background. *The growth of population of the Earth inevitably leads to aggravation of various kinds of problems, including transport problems. The search for solutions to these problems occurs both through modernization of the existing transport infrastructure and creation of new systems.*

In this vein, the Hyperloop project is of great interest in many countries of the world, where geographical conditions require further development of transport, availability of the most accessible and high-speed system for moving cargo and passengers, which significantly improves interconnectedness of regions and individual territories within state territorial entities.

Objective. *The objective of the authors is to consider technical risks and prospects of Hyperloop project.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, mathematical apparatus.*

Results.

Brief background of the project

The Hyperloop project was introduced by Elon Musk in 2013 and was originally proposed for implementation in the State of California (USA). It is based on an original combination of technical solutions involving pipeline transport, aerospace technologies and an alternative source of energy – solar radiation.

It should be noted that the idea of pipeline cargo-and-passenger transport (in other words, a transport using a sealed long pipe with discharged air as a shell of a path for moving objects between two points of communication) is not new. It arose at the end of 18th century and found its embodiment in the form of pneumatic mail, which exists to this day, for example, in the Russian State Library, as well as in various prototypes, including:

– Thomas Rammell pneumatic railways (London, 1864) and Beach Pneumatic Transit (New York, 1870);

– Vacuum trains on magnetic cushion of H. Kemper (Germany, 1934) and N. Ozawa (Japan, 1969).

By 20th century, the development of technology has made it possible to introduce new components into the idea of pipeline transport, which gives us grounds to talk about Hyperloop as of a new form of transport, and, according to Musk himself, as of a revolutionary breakthrough in transportation organization (Pic. 1).

Below is the technical analysis of the project. The basis is preliminary concept of Hyperloop [1]. Most of the key characteristics are rechecked.

Analysis of technology readiness

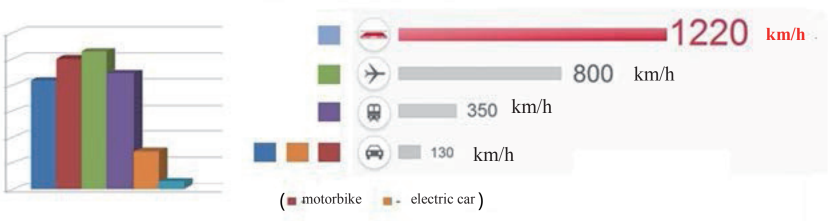
Hyperloop is a high-speed cargo and passenger transport system consisting of the following main parts.

Overpass: steel cylindrical pipes with a diameter of 2–3 m and a wall thickness of 2–2,5 cm welded in two pipelines (one for movement «there», the other for «back» movement) and mounted on concrete supports with a height of 6–30 m (Pic. 2). Inside the pipes the shuttles with passengers move from station to station with a declared frequency of 2 minutes. The technology of construction of loaded pipelines has long been worked out, for example, in the oil and gas industry, and no special difficulties are foreseen in this.

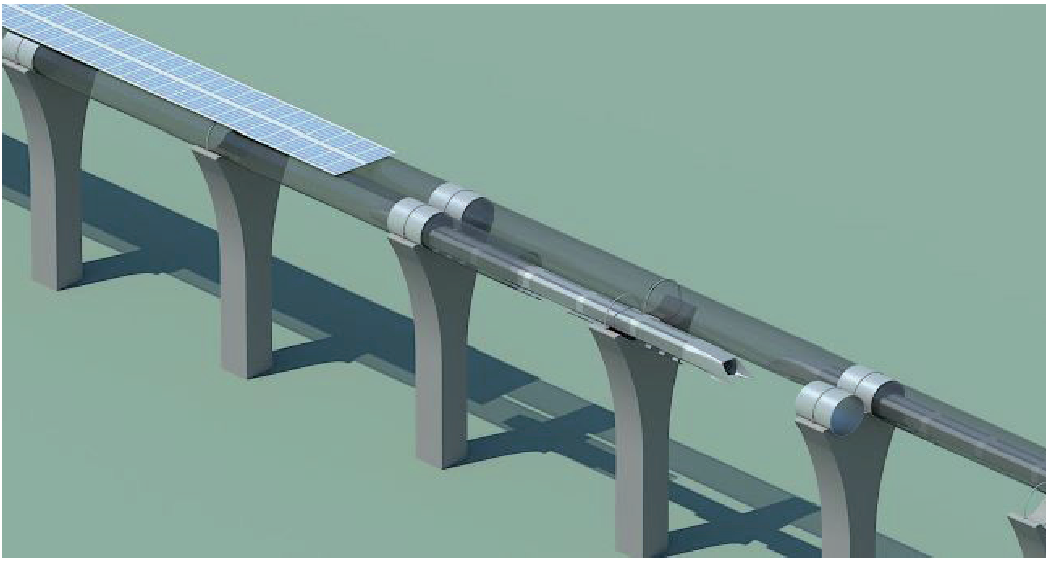
Low vacuum system in the overpass: a set of vacuum pumps with which a pressure of 100 Pa is created and maintained inside the sealed pipes, the so-called forvacuum. This system is quite easy to be implemented, since modern industrial vacuum pumps are of moderate cost, have high reliability and sufficient capacity (~1 m^3/s at the indicated outlet pressure).

Stations: facilities, inside which embarkation / disembarkation of passengers, recharging of

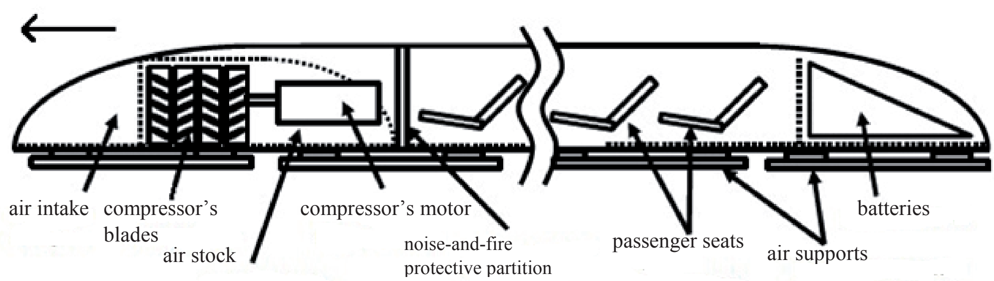
Costs of transportation of 1 passenger (con. units) and speed of movement for different modes of transport



Pic. 1. The declared technical and economic characteristics of Hyperloop [1].



Pic. 2. General view of the Hyperloop path fragment.



Pic. 3. Schematic structure of the passenger shuttle Hyperloop.

cooling system and storage batteries of transport shuttles take place. Unlike ordinary landing stations they are characterized by the presence of a system of high-speed locks at the junction with the main overpass.

Freight-passenger shuttles: a fleet of vehicles of the same type, each of which has a cylindrical shape, a length of about 30 m and a cross-sectional area of about 1,4 sq. m. The shuttle is structurally close to fuselages of modern aircrafts. The movement of shuttles inside the pipeline on the main part of the route takes place according to the principle of an air-cushion vessel (ACV), that is, without the use of wheels (Pic. 3). Air to the supports of the air support is fed with a frontal air intake and an axial compressor, powered by on-board batteries.

Acceleration and deceleration system of shuttles: built on the principle of electromagnetic induction for linear rotor and stator, while the stator is attached to the walls of the overpass, and the rotor – under the bottom of the shuttle. Acceleration takes place on a section about 10 km long, adjacent to the station, then the shuttle moves by inertia (which is permissible under forvacuum conditions with minimal energy losses), and braking occurs in the same way. The acceleration / deceleration time, provided that the passenger is relatively comfortable to carry a horizontal acceleration of 0,5 g, is about 1 minute. In spite of the fact that electromagnetic induction is used everywhere in all areas where electric motors or electric generators are used, in the described configuration – linear rotor and stator – the named physical principle is just beginning to be approved. However, its successful feasibility has already been proved in the military field (the electromagnetic catapult EMALS of the aircraft carrier «Gerald R. Ford» [2], electromagnetic guns).

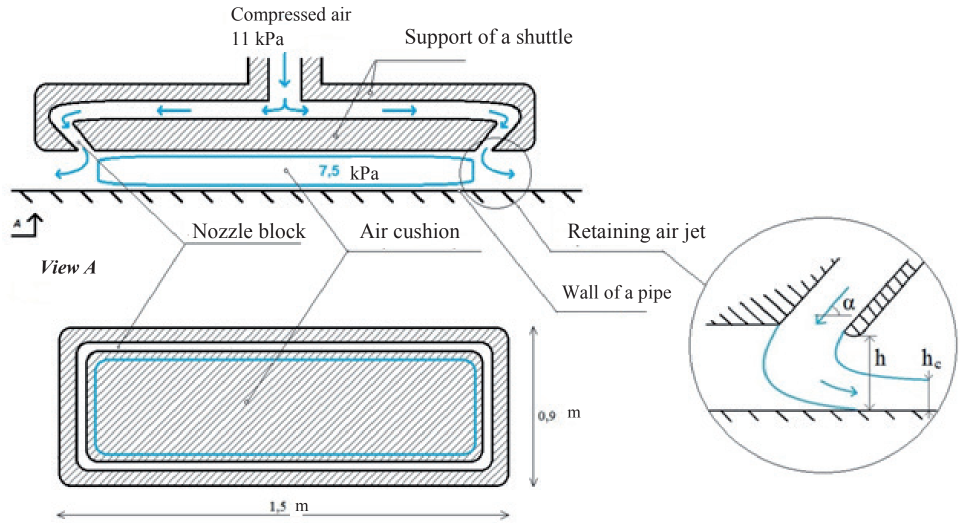
Power supply system: rows of solar batteries mounted above the tracks. The projected capacity, generated by such batteries, is 120 W / sq. m, which gives a total capacity of up to 285 MW at the peak of solar activity, or 57 MW in the average daily calculation, and this completely covers the energy needs of Hyperloop of 21 MW [1]. The excess of absorbed solar energy and the energy converted into electric energy during the deceleration of the shuttle are stored in stationary storage batteries, which allows achieving the declared energy balance characteristics.

Analysis of technical risks

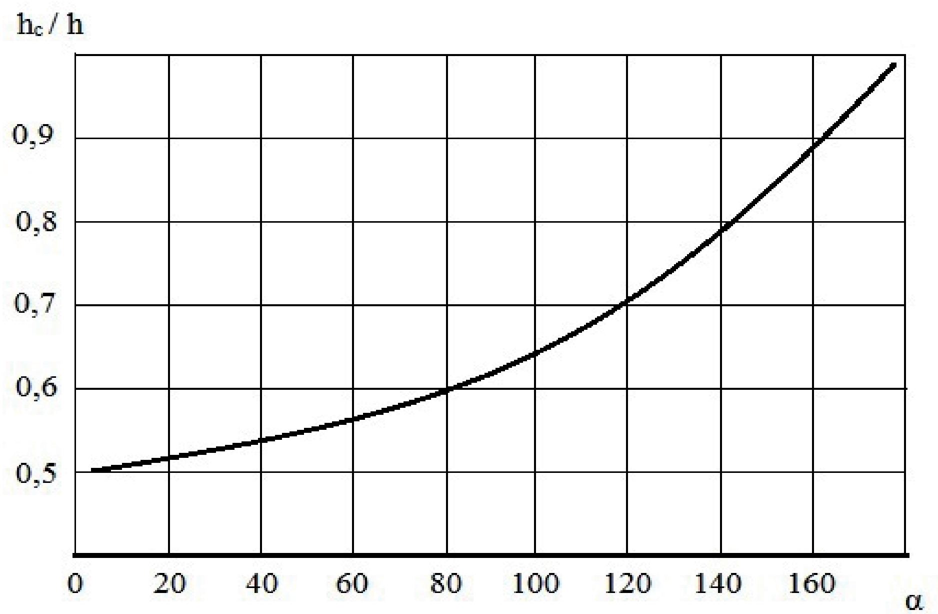
As you can see, the project is a combination of previously known and to some extent mastered technologies. However, the apparent simplicity should not be misleading: at the junction of these technologies some new technical solutions are born that require serious research before the construction of the Hyperloop route.

1) Stability of the supporting air cushion in forvacuum.

The main differences between the Hyperloop air cushion from other areas in which ACV technology is used are high speed and the presence of forvacuum as an environment instead of the usual atmosphere.



Pic. 4. Arrangement of the air support of the shuttle Hyperloop.



Pic. 5. The relationship between the parameters of the nozzle block of the air support.

Unfortunately, the concept [1] does not contain a detailed description of air supports, but only individual technical details of the design and characteristics of the air cushion. Therefore, we assume that the most optimal variant, taken from real ACV, is the nozzle circuit with peripheral rigid nozzles (Pic. 4).

The weight of the Hyperloop shuttle is maintained by the air pressure in the air cushions created under 28 supports of 1,35 sq. m each. The total area of the supports in the projection to the horizontal plane is approximately 32 sq. m, and they are mounted in pairs along the entire length of the shuttle (14 pairs).

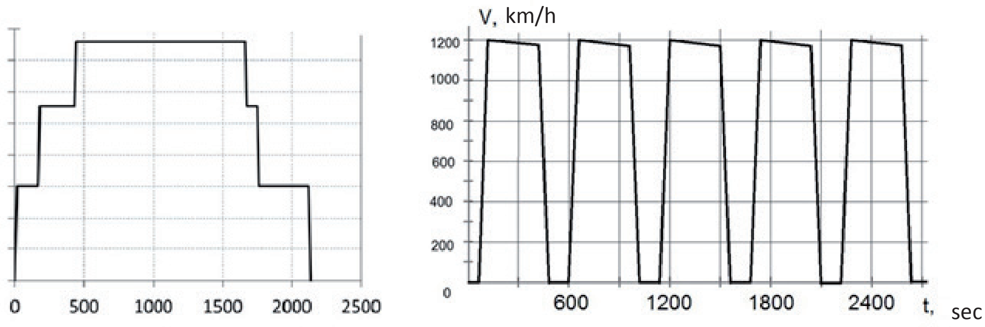
According to the terminology of ACV [3], the gap between the support and the wall of the tube h is called the hover height, and it is fundamentally different from the thickness of the retaining jet h_c flowing into the surrounding space. It is indicated in [1] that h ~0,9 mm, and the reasons for choosing such a hover height are not indicated, although it is additionally noted that at a shuttle speed of 1200 km / h (or ≈ 330 m / s) and an ambient forvacuum pressure of 100 Pa air in the amount of 0,49 kg / s enters the inlet of the shuttle air intake, and 0,2 kg / s is sufficient to hold the air cushions under all 28 supports.

One of the factors determining the hover height is precisely the thickness of the retaining jet h_c. The relationship between h and h_c is determined by the choice of the angle of inclination of the nozzle α and is determined by means of the graph (Pic. 5) [4].

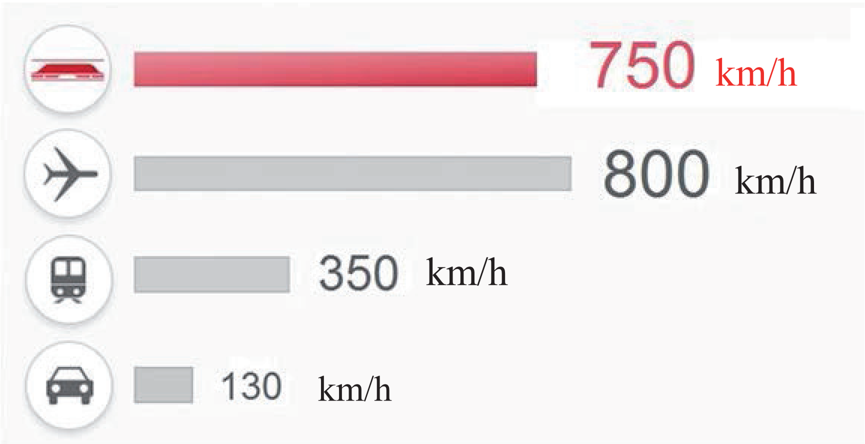
In the subsequent calculations we shall simplify to assume that h_c ~ 0,5 h.

The equation of the balance of the incoming and outgoing air masses gives the thickness of the jet

$$h_c = \frac{m_{ext}}{V_c L_{per} \rho_c N_{\sup}}, \qquad (1)$$



Pic. 6. Advertising [1] and real shuttle speed charts on the Los Angeles–San Francisco section, S = 550 km.



Pic. 7. Real comparison of the speeds of Hyperloop and other transport modes.

where V_c is speed of the air jet flow, ρ_c – air density of the jet, N_{sup} is the number of air supports, L_{per} is the perimeter of the air cushion (~ 3 m).

Since the flow of the jet occurs in the forvacuum, at the exit from the air support, the speed of flow V_c reaches the critical value V. Assuming that the air channels leading from the compressed air cylinder to the air supports are optimally designed, from the experience of the ACV design this gives a pressure loss of the order of 30 % [3]. Also assuming that the gas flow is laminar (a necessary condition for a stable air cushion retention) and viscous (which on the average slows down the jet by a factor of 2, $V_c \approx 0{,}5V^*$), using the hydrodynamic equations of the flow of a compressible gas, we find that $V_c \approx 170$ m/s, $\rho_c \approx 0{,}035$ kg/m^3, and from (1): $h_c \approx 0{,}001$ m, or $h \approx 0{,}002$ m (2 mm).*

It would seem that the average hover height of the shuttle can be more than doubled. In fact, the determining factor for the laminar flow of such a retaining jet is the Reynolds number:

$$\mathrm{Re} = \frac{\mathrm{Vc}\bullet\mathrm{hc}}{\nu}, \qquad (2)$$

where V_c is average flow speed of the jet, h_c is characteristic linear dimension, in our case – jet thickness, $\nu \sim 0{,}0006$ m^2/s is the kinematic coefficient of viscosity of the air in the jet with the parameters described in [1].

For flows with the closest geometric configuration, the critical value $Re_{cr} \sim 420$ [5]. Then it follows from (2): for the flow of the retaining jet to be laminar, it is necessary to reduce the gap between the support and the wall by at least 2 times, that is, up to the value h ~ 0,9 mm given in [1]. And this restriction is immutable.

We recall that the above theoretical calculations are based on a number of assumptions that determine the stability of the air cushion. Moreover, the NASA report [6] on the Hyperloop problem notes that it is the presence of forvacuum that contributes to formation of a steady flow of air under the air support, and the flow does not break up into separate movements of individual molecules. The movement of the support relative to the wall of the pipe only leads to curvature of the cushion by frictional forces in the direction opposite to the direction of motion, but again does not lead to destruction of the cushion [1].

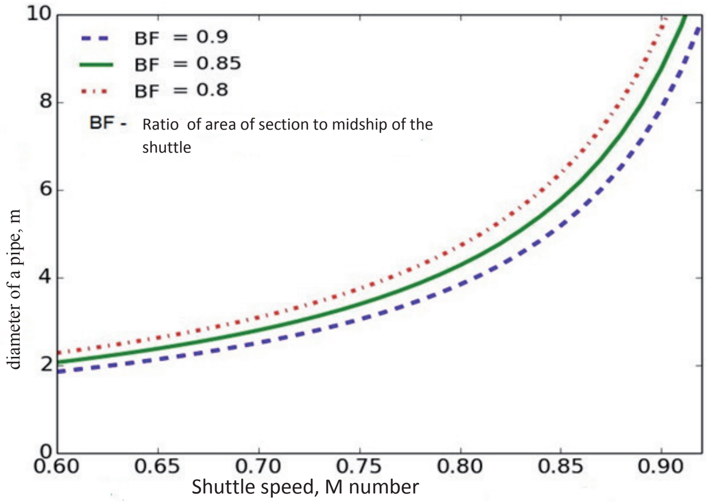
To verify the correctness of these statements, not only reliable numerical simulation is needed, but also a series of experiments in forvacuum with moving ACV, which is new in science and technology.

2) Autonomous cooling system.

Since the shuttle moves in an environment close to the vacuum state, and various units and systems operate on the shuttle, an on-board autonomous cooling system is required.

The task of creating such a system is noteworthy, because previously on all passenger vehicles the heat transfer has been lead to the environment.

The fact is that during the shuttle movement a large amount of heat is released (about 100 MJ per 100 km of the track), which should be removed from compressors, air cushion supports, air conditioners and other operating units, otherwise they will be heated to temperatures of 700°C. Since the shuttle moves in the forvacuum, then it is extremely



Pic. 8. Dependence of the number M, achievable by the shuttle, on the diameter of the pipe in which it moves (preliminary calculations [6]).

problematic to realize heat transfer to the environment, firstly, the total heat capacity of the forvacuum is small, and secondly (even if the first was possible), the second shuttle going beyond the first would move in an unbalanced mode – in preheated to more than 100°C forvacuum. And so the increase will be observed cumulatively for the third, fourth, fifth... shuttle.

To avoid the cumulative heat effect, a single network of heat exchangers is installed on the shuttle, through pipelines connected to the central heat exchanger, in which there is a water supply m_{water} = 290 kg.

The design of the cooling system in the initial configuration presupposes the heating of water to 100°C, steam generation and further heating of the steam to 125°C. The total heat capacity of such a system:

$$Q_{sh} = m_{water}(C_{water}\Delta T_1 + C_{steam} + C_{p\ steam}\Delta T_2), \quad (3)$$

where C_{water} = 4180 J/(kg K) is specific heat capacity of water;

ΔT_1 = 75 K – change in water temperature when heated to 100°C;

C_{steam} = 2260 kJ/K is specific heat of steam formation;

$C_{p\ steam}$ = 2020 kJ /(kg K) is specific heat capacity of water steam;

ΔT_2 = 25 K is change in steam temperature when heated to 125°C.

Calculation of the heat capacity of such a cooling system gives Q_{sh} = 760 MJ, and this is sufficient to ensure the movement of the shuttle in a 660 km non-stop section (comparable to the distance from Moscow to St. Petersburg). And the reserve is set for safety in case of emergency situations, when shuttle traffic stops and passengers wait for evacuation in shuttles much longer than planned, and the life support system (air-conditioning) must work without failures.

However, [1] does not explicitly state that water as a coolant passes from a liquid state to a steam state, although the word «steam» is used. In order for the cooling system to work in this case, it must be divided into subsystems: in one there is heating of the cooling water, in the other – cooling by evaporation, in the third – heating of water steam. At present, there are no aggregates of this level of complexity; it is much easier to increase the pressure in the system and the amount of coolant without converting it to another state.

In addition, as rightly noted [6], containers with superheated steam would increase the length of the shuttle by several tens of meters.

Therefore, in order to simplify the functioning of the transport system in the light of the cooling problem of a moving shuttle, intermediate stations are mandatory, and they are envisaged by the project at every 110 km. In one such section of the path, up to 100 MJ is released, and this amount of heat can be completely absorbed by this water supply without evaporation.

When stopping at these stations, the cooling system must be recharged: an empty water tank and a hot water tank are replaced respectively with a full cold water tank and an empty tank.

However, let's see how this will affect the characteristics of the shuttle's motion (Pic. 6).

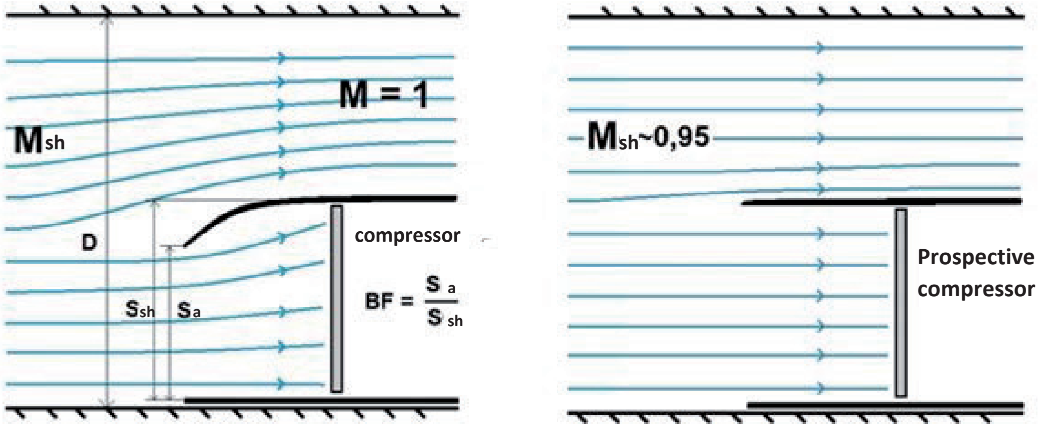
In both cases, the total area under the curve gives a path of 550 km. At the same time, as can be seen, the need for intermediate stops significantly reduces the average speed of the shuttle movement – up to 750 km / h. And then the real comparison of speeds, in contrast to the advertising one (Pic. 1), should correspond to Pic. 7.

Thus, Hyperloop does not have a revolutionary gain in the speed of transporting passengers, as stated in the concept [1], and the constant acceleration and braking is extremely detrimental to the comfort of the trip.

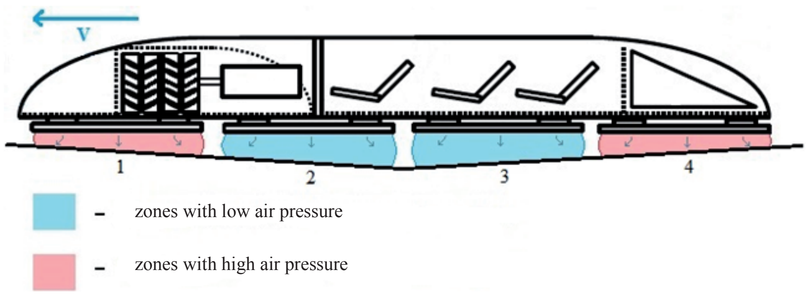
However, it should be noted that the shuttle can be redesigned to ensure non-stop traffic. In this case, its mass will increase by about 10 %, which will lead to a slight change in other parameters and characteristics of the movement and significantly complicate the technique of recharging the cooling system (instead of a tank with water of 290 kg, a tank with 1500 kg of water will be installed, also heated during the process up to almost temperature of boiling water).

3) Transonic movement of bodies in a channel with a compressible medium.

Long-term movement of the body in a pipe with a compressible medium at a speed close to the speed



Pic. 9. Adaptation of Hyperloop existing axial compressors and the required advanced compressor.



Pic. 10. Formation of air cushions when the shuttle moves along a curved trajectory (example No. 1).

of sound (the speed of propagation of disturbances) is a new technical problem, which was not previously required to be solved, since there are no transport systems that include such a movement.

In [1] it is stated that in the version with purely passenger shuttles the pipe has an internal diameter of 2,23 m (or a cross-sectional area of 3,9 sq.m), while the shuttle is about 1 m (1,4 sq. m is respectively shuttle maximum cross-section).

This ratio of the shuttle diameters to the pipe is optimal for the transonic motion of a piston of diameter d in a hollow cylinder with a wall diameter D filled with a compressible medium (conditionally, the «syringe» problem). Let us consider the qualitative aspect of this phenomenon.

When the piston moves in a compressible medium, it experiences additional resistance associated with the effect of the walls: $X = X_a + X_{add}$, where X is the total resistance, X_a is the aerodynamic and viscous resistance of the medium, X_{add} is the additional resistance caused by the influence of the pipe walls.

If d/D ~ 1, then there are two solutions for X_{add} to obtain the optimum piston speed: the piston moves at a speed much lower than the speed of sound in this medium, and the piston moves with supersonic speed. In the first case, the medium flows smoothly around the piston. In the second case, perturbations from the motion of the piston do not propagate upstream. At intermediate values of speed, however, the contribution of additional resistance is quite weighty: the piston is forced to «push» most of the compressible medium ahead of itself according to the principle of a syringe. This phenomenon can be observed, for example, in the metro: when a train arrives at the station, a very long and intense wind blows from the tunnel first.

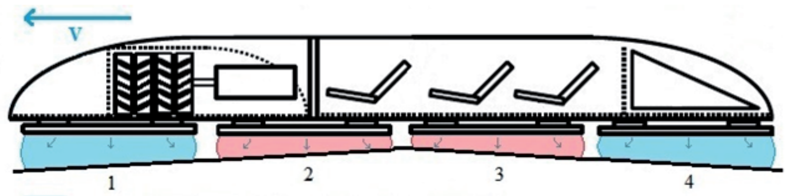
If, however, d/D<<1 (in the limit $D \to \infty$), then the effect of the walls on the piston is practically zero and normal flow around the body by the medium is observed.

Obviously, for d/D < 1 in our case, there is an intermediate conditional relation d/D separating the flow according to the principles the «wall effect is present» and the «wall effect is practically absent». In [1] it is indicated that this intermediate value can be obtained from the theoretical work of Arthur Kantrowitz. For Hyperlooop, d/D ≈ 0,6 at a pipe pressure of 100 Pa.

This ratio of diameters should be observed to minimize the effect of compressibility and frictional forces that arise from interaction of walls of the track and the shuttle, even despite forvacuum.

In [6] they refer to their own calculations, which show that for real air intakes where air retardation is required in front of the compressor, the pipe diameter should be increased to at least 4 m provided that the shuttle achieves a speed corresponding to the Mach number M = 0,8 (~1000 km/h, Pic. 8).

The above NASA calculations are based on the assumption that the air intake is built on the principle of a diffuser, and the compressor is axial, so it is necessary to slow the flow of air before its first stage. This is due to the fact that existing axial compressors, due to structural and other requirements, have a limitation on the number M of the incoming flow M < 0,75. At the same time, compressors of a different type (for example,



Pic. 11. Formation of air cushions during the movement of the shuttle along a curvilinear trajectory (example No. 2).

centrifugal ones) are able to work stably at large numbers M of the incoming flow. Moreover, the question is whether it is possible to create principally new compressors designed for highly specialized conditions in Hyperloop (Pic. 9).

Thus, to answer the question about which d/D ratio is to be chosen, and what is the dependence of achievable M on the diameter D, additional experiments, including experimental design, are required. Without this, the average speed of the shuttles will be even lower than 750 km/h.

4) Stability of shuttle hovering.

The most difficult technical problem to be solved when creating Hyperloop, is the stability of shuttle hovering.

The characteristics of the shuttle, given in [1] and other sources, were calculated assuming that the shuttle moves rectilinearly over a flat surface, and its weight is evenly distributed over all 28 supports.

Let us consider the real case of the motion of the shuttle, namely, motion along a curved trajectory. This can be the descent, lifting, turning of the pipeline or the natural curvature of the pipes under the influence of their own weight, due to thermal expansion, subsidence under the concrete supports, fatigue failure or deformation of concrete supports and pipe fastenings to these supports against multiple impact of a 15 ton impact load while shuttle is moving, pipe vibrations and other causes.

Let the considered section be the lifting of the shuttle (or the deflection of the pipe downwards). For simplicity, we assume that there are 4 supports. When the shuttle moves, regardless of whether the bend of the pipe is smooth or stepped, as in Pic. 10, there is a redistribution of air pressures under the supports.

Without going into the complicated equations of motion of the shuttle, let us explain the qualitative aspect of the phenomenon. The shuttle overcame the straight section, and it needs to start shifting upwards. To give the shuttle vertical acceleration, air pressure should increase in air cushions due to air compression, in the example shown – under supports 1 and 4. This compression occurs due to reduction in thickness of the gap between the pipe and the support. At the same time, the gap between the supports 2–3 and the wall increases, and the gas pressure below them decreases.

That is, at a certain moment the following pattern is observed: the pressure under supports 1 and 4 increases and blocks the flow of compressed air from the cylinder under these supports, at the same time the pressure under supports 2 and 3 decreases.

In other words, when moving on the curved section, only a part of the supports in which the further formation of the air cushion is blocked becomes holding or retaining, while the remaining supports lose their holding properties.

If the curvature of the trajectory does not disappear within the next 0,005 seconds (the time when the air support overcomes the distance equal to its length), the shuttle simply «goes down» from the air cushions 1 and 4 supporting it and touches the pipe wall with the support 1.

An estimate of the magnitude of the vertical displacement for the extreme supports, at which the intake of compressed air is blocked, gives 0,3 mm, or ~ 30 % of the mean value of the hover height of 0,9 mm. For a 30 m shuttle this corresponds to **an allowable track displacement of 1 mm per 100 m of track***, or a trajectory displacement of 0,011^o (in another way, the radius of curvature of the trajectory is about 150 km).*

A similar picture can be seen when the pipe is bent upwards (Pic. 11).

Is it possible to create a track with strength characteristics that could ensure compliance with these requirements for the trajectory?

Let's consider two possible causes of curvature of a track as an illustration.

<u>The first reason.</u> We calculate the value of the maximum deflection y_{max} of a steel pipe of length L = 30 m (this value corresponds to the step of installing concrete supports) and a wall thickness of 2 cm lying on two supports [7]:

$$y_{max} = -\frac{5}{384}\frac{qL^4}{EJ},$$

where q ≈ 10,5 kg/cm is the distributed load during the passage of the shuttle;

E ≈ 2,1 • 10^6 kg/sq.cm is the modulus of elasticity of steel;

$J = \frac{\pi}{64}\left(D_{ext}^2 - D_{int}^2\right)$ *is moment of inertia of the pipe,*

where

D_{ext}, D_{int} are external and internal diameters of the pipe, respectively.

After substituting these numerical values, we get y_{max} = 1,2 cm, which is 40 times higher than the allowable trajectory deviation value – the tracks require multiple amplification.

<u>The second reason</u>. Short-term periodic and at the same time fairly strong vertical impacts on concrete supports that arise when a 15-ton shuttle pass, will lead to gradual ramming of the ground beneath them, which is not uniform due to the heterogeneity of the ground. In some cases, subsidence will also be difficult to be identified (the

situation is comparable with the deflection of rails under a moving train: at rest, the rails are straight, and when the train passes, they bend). In order to avoid the negative consequences of this factor, a larger backup tube strengthening will be required.

If we take into account another factor affecting the operation of transport, the expansion of bodies with heating, we get the following. The coefficient of linear expansion of concrete is 0,00001 m / (m • K). With a daily temperature variation of 10°C and a concrete support height of more than 10 m, this gives a daily change in its height, and hence a height difference of 1 mm.

Therefore, for laying of the Hyperloop route, it is necessary to provide much more complex engineering structures that could automatically ensure the deviation of the trajectory of the route by values not exceeding 1 mm / 100 m of the track at any time of the day of any season.

As stated above, the latter of these problems is critical for the system as a whole, since increasing the hover height is physically impossible due to the Reynolds number restriction. Therefore, a separate research of the very possibility of automatic control (ACS) by the shuttle is required when traveling along a curved trajectory. Elon Musk's report on creation of such a system, as well as the necessity of its existence, does not mention it.

At this stage of development of Hyperloop only the basic requirements that this ACS should satisfy can be formulated:

– accuracy of measuring the position of the shuttle in the vertical plane – no more than 0,2 mm;

– speed of measurement and supply of control actions to the control bodies– no more than 0,005 s.

Possible control bodies for the shuttle can be additional air supports capable of short-term, one-time increases in pressure below them. To do this, excess air after the compressor (0,29 kg / s) should be compressed significantly more than up to 11000 Pa, and be collected in a separate cylinder. Requirements to the curvature of the trajectory will not disappear, but will only decrease in proportion to the degree of compression of the additional air.

Another way to solve the problem would be magnetic levitation, used in trains on magnetic cushion (maglev). But then the Hyperloop project is reborn, in fact, into the same maglev, but over-complicated by the presence of pipes and everything related to providing forvacuum in these pipes, although it gives a gain in energy costs for the movement of shuttles. The speed of modern trains on magnetic cushion is far from 1000 km / h including due to the retention of the train on the trajectory. And if the cost of construction of the maglev route reaches 100 million USD / km, what will be the cost of the maglev in the vacuum pipe, and how feasible the project economy will be (according to Pic. 1) that is a question requiring a separate study.

Conclusion. *The analysis of the project Hyperloop outlines the range of technical problems that need to be solved before the construction of a full-fledged transport system. They include:*

– creation of reliable high-speed locks in the places of passage of the shuttle from station to track and back;

– checking the ability of a complex of vacuum pumps to effectively combat air leaks and maintain a working pressure of 100 Pa in an object with a total capacity of more than 2 cubic km;

– searching for stability of the supporting air cushion under forvacuum conditions, taking into account the high speed of movement;

– obtaining an experimental base for calculation of the critical Reynolds number for volume-symmetric flows with a configuration corresponding to the shape of the retaining jet;

– creation of a reliable autonomous cooling system, taking into account the requirement of its recharging at the station for the shortest possible time;

– adaptation of existing or development of compressors of a new type capable of stable operation with an inlet flow number M of not less than 0,95;

– study of fatigue strength characteristics of steel pipe and retaining supports under conditions of their short-term intensive periodic loading by mass of about 15 tons;

– confirmation of stability of hovering of a shuttle resting on an air cushion, while moving along a curved trajectory and under conditions of natural bending of the pipe.

Without solving these problems, the issue of feasibility of the Hyperloop project with the stated technical and economic characteristics will remain open for discussion.

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