JOURNAL OF INNOVATIVE TRANSPORTATION

The fifth mode of transportation: Hyperloop

Kemal Armagan[a,*]

[a]Department of Civil Engineering, Karamanoglu Mehmetbey University, Karaman, Turkey

Highlights

- Hyperloop as the fifth mode
- New transportation opportunities are still undiscovered
- High velocities in transportation

Abstract

Hyperloop has proposed as a mode of passenger and freight transportation. The concept was about a vactrain that provides very-high-speed rail transportation which was invented two centuries ago. This old high-speed transportation idea in evacuated tubes has become popular again. Ellon Musk has proposed Hyperloop as a system that reduces the travel time between Los Angeles to San Francisco cities (563 km/350 miles) down to 35 minutes with a very high speed in 2012. To improve the idea an open-source design of the Hyperloop pod has released by the Tesla and Space X teams and some competitions held. Many ideas have come out at those competition in 2015 to 2019. Elon Musk himself described hyperloop as "a cross between a Concorde, a railgun, and an air hockey table" within the time in those competitions. For the competitions a trial test track of a 1-mile tube adjacent have built in Los Angeles city by Space X and the experimental work for trying to ensure the capabilities of the fifth mode of transportation. With recent innovations, Hyperloop can be described as a sustainable, self-powered, high speed, safe and a promising transportation mode for future, but its deficiencies will have to lead some changes and improvements for Hyperloop in future.

Information

Received: 30.06.2020

Received in revised: 06.07.2020

Accepted: 06.07.2020

Keywords: *hyperloop, vactrain, fast transportation*

1. Introduction

Defined as The Fifth Mode of Transportation, Hyperloop (HL) is a new mode of transportation after road, air, water and rail. HL is a structure composed of a capsule within a partly vacuum shield, the capsule is centred on the maglev concept and thus does not touch any section of the shield. It's just like a high altitude, low-pressure aircraft. A single pod can hold 28 passengers on a single travel. Each pod has its own front and end compressors that creates a vacuum. By this vacuum the drag can be minimized during the travel. Nowadays a test field for several researches were being built in Nevada with the collaboration of Hyperloop Transportation Technology Inc., SpaceX and Hyperloop Technologies [1].

The Hyperloop travel experience is expected to be more likely an airplane travel on a train. Musk is reported this as an initial acceleration can feel at first place and once the pod is at a constant speed the passenger wouldn't feel the speed due to smooth ride, so this travel experience can feel like a fluent, quiet and without any turbulence or disturbances. He also affirmed that HL is targeted at high travelling routes by less than 1,500 km. More than this distance, a supersonic aircraft with a low acoustic profile can be more predictable [2].

In 2013, Musk proposed a hyperloop design that envisions a world in which transport between cities takes place inside enclosed tunnels, with passenger pods traveling as quickly as 760 miles an hour while floating on a thin air cushion. He came up with the concept as a quicker, affordable solution to a high-speed rail project with $68 billion value in California. For this purpose, SpaceX has launched open competitions targeted at individual innovation teams and university students to develop and create new pod designs. And SpaceX have supplied the test track of a 1-mile tunnel adjacent to the company's headquarters in Hawthorne, Los Angeles County [3].

*Corresponding author: kemalarmagan@kmu.edu.tr (K. Armagan), +90 338 226 2000-5459

2. Literature Review

2.1. History

The first announcement of Hyperloop as "fifth mode of transport" was at a PandoDaily event in California in July 2012 by Ellon Musk [4]. Hyperloop name has selected on purpose to define the travel in a loop with a very high speed. He wants modern travel modes to be able to travel at hypersonic speed [5]. Musk described the HL as a "cross between a Concorde and a railgun and an air hockey table" In May 2013 [6].

But, looking at the working concept of HL, he defined it as a vactrain. And the vactrains, like in the gravity train, can use gravity to help in their acceleration. When these trains achieve the expected speeds, they would overtake the air transportation as the quickest means of mass transport in the world [7].

The knowns researches on this principle starts in 1799, by George Medhurst from London. He addressed the concept of transporting goods pneumatically through cast iron pipes and, in 1812, suggested blowing passenger carriages into a tunnel. He also developed and patented an atmospheric railway which has a capability of conveying people or freight through pressurized or evacuated tubes [8].

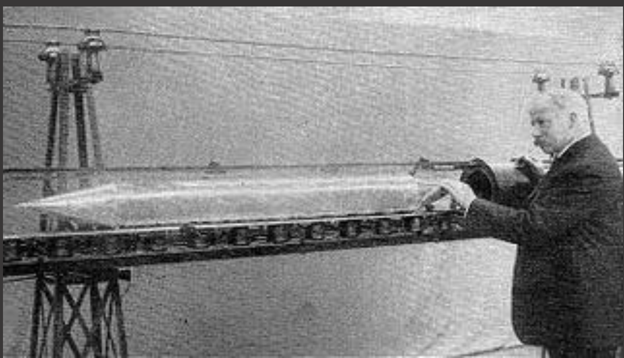

Figure 1. Illustration of the article called "The SciFi Story Robert H. Goddard Published 100 Years Ago" [9].

The vactrain itself was discovered by Robert Goddard in 1904 as illustrated in Figure 1. Goddard then perfected the concept in "The High-Speed Bet" short story in 1906, which was condensed and reported in the 1909 Scientific American editorial, “The Limit of Rapid Transit”. Five years after Goddard's death in 1950, his wife Esther, was granted a US patent for the vactrain [9,10].

Historically, many HL-like pneumatic and maglev trains were suggested at conceptional stage, mainly with a view to significantly reducing travel time relative to current types and are thus implemented in the transport network. In 1910, for example, Robert Goddard engineered a moving train on track with magnets in a vacuum tube that could achieve 250 miles an hour between New York and Boston cities in 10 minutes. RAND suggested that a very high-speed transit (VHST) system embedded in deep evacuated tubes powered by electromagnetic waves might be theoretically viable and reach east to west in the United States nearly 21 min in 1972 [11,12].

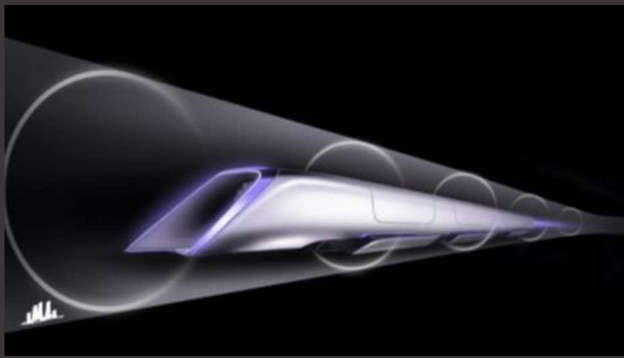

Figure 2. Hyperloop passenger transport capsule conceptual design rendering [11, 13].

High-speed aircraft, combined with relatively low fares, in especially those provided by low-cost carriers, have led to increasingly challenging travel requirements, contributing to a burden on high-quality service delivery modes, especially in terms of reduced travel times with cheap prices. Moreover, transport's environmental impact has created that concern, contributing to a growing discussion regarding the continued domination of air travel and the need for more environmentally friendly, more effective alternatives to travel. With innovations, incremental but not drastic changes have been made on a permanent basis. Radical new innovations like HL, illustrated in Figure 2, could deliver considerably improved performance, but these innovations are still rare and have not yet been able to reach the transport market successfully [11]. Figure 3 shows where the HL developments come, the interior design of the pod have opened for visiting in World Energy Congress [14].

Figure 3. Interior design of Virgin Hyperloop Projects pod [14]

2.2. Working Principles

The developments in high-speed land transport is lack of improvement due to lack of “wheel-rail” network. Rather, numerious newly invented vehicle suspension types for levitation systems are summarized as: air bearing suspension [13], Electrodynamic Suspension (EDS) and Electromagnetic Suspension (EMS). These systems can be used together as a hybrid electromagnetic suspension.

The elimination of heat energy losses is one of the problems with high-speed vacuum transport (HSVT) operating under vacuum conditions. The hybrid electromagnetic suspension reduces the energy consumption that is required for the production of the levitation force. Consequently, the amount of heat losses can be minimized. Another issue is that the integrated electric suspension is unreliable. Another concern is that the hybrid electromagnetic suspension hasn't got a predictable mechanism and for this reason the system needs a rapid response control mechanism for monitoring the negativities of the system [15-19].

The EMS and EDS systems have the same major characteristics as secure high-speed transport, low emissions due to electrical control, low maintenance and high ability to handle rising traffic production but are technologically somewhat different. The EMS system 's efficiency is focused at enticing magnetic forces whereas the EDS technology works with repulsive magnetic forces. Across the EDS method, pod is levitated between 10 mm and 100 mm off the path using permanent magnets or superconducting magnets. Instead, the pod is levitated between 10 mm to 20 mm above the path utilizing electromagnets in the EMS method [20].

EDS is based at the repulsive force generated with induced eddy currents in a rail track, a magnetic excitation system and a relative speed between the magnetic field and the track. As the excitation mechanism is realized as a Halbach array of permanent magnets and placed on a moving pod, the necessary lift can be produced to levitate the pod and no more mechanical suspension is needed. EDS's popularity is increasing in high-speed transport technologies as in the Hyperloop concept, which is mainly powered by the SpaceX firm. Electrodynamic fields and forces were studied widely in the literature; nevertheless, the difficulty and/or restricted acceptability of theoretical techniques or FEM / numeric methods computational requirements render them unrealistic for the conceptual development of EDS systems [21,22].

Although HL is comparable with other Vacuum Tube (VacTrain) designs, soft vacuum is a significant distinguishes. Air bearings require a source of pressurized air supplied by an on-board battery-powered compressor. Because Hyperloop runs at transonic speeds in a low-pressure setting, the design of the pod compression mechanism can be related to the design of the compressor for aircraft turbomachinery. In comparison, aerodynamic problems resulting from restricted flow via the tube are prominent in the construction of inlets and nozzles of aero engines, and the whole system encounters significant weight and volume constrains. Of such purposes, the simulation methodology can be close to the approaches used for aircraft scale and turbine engine cycle calculations [23].

The Virgin Hyperloop One project test site as seen in Figure 4 at Nevada is one of the test sites to eliminate these problems [24].

Figure 4. Virgin Hyperloop One Test site in Nevada [24].

Musk's Hyperloop plan was one of the most comprehensive, postulating its existence of Hyperloop pod levitation air bearings, as well as fans capable of moving and compressing the ambient air being used for levitation. A conceptual pod design to levitate belongs to Musk's HL pod is shown in Figure 3. Within the simple principles, the planned Hyperloop design would achieve the technological advantage over conventional types of transport by mitigating two main resources of friction: (a) aerodynamic drag might be reduced or removed by pushing the pod through the tunnel and reducing the atmospheric pressure by pumping; (b) Rolling and interaction friction can be minimized by the use of air bearings or other levitation methods [25,26].

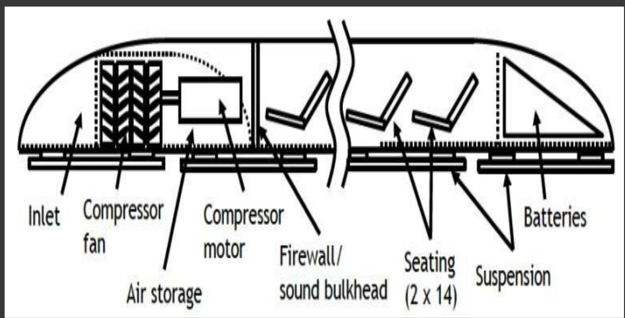

Figure 3. Conceptual structure and configuration of the HL framework [26]

All open-air systems face a simple problem: aerodynamic drag. If Maglev is considered, a lot of drag need to consider as speed increases. When the velocity of the object doubles, the drag forces become quadruple and, eight times the power requires to overcome that drag forces to increase its speed. Therefore, drag reduces the maximum speed for ground-based open-air structures. Hyperloop has been planned to solve this issue. Through working in a low-pressure area that requires a greater air level, the device reduces the amount of drag it will experience to begin with. It combined with a passive levitation mechanism to reduce pressure and a turbine to funnel the air in front of the capsule as seen in Figure 3 and to energize it to the back to produce additional power. The compressor is powered by an electric motor that is powered by rechargeable DC batteries in the pod. In order to reach extremely high speeds, the use of a linear induction motor (LIM) seems to be the most effective way to generate a frictionless thrust capable of overcoming aerodynamic drag [20].

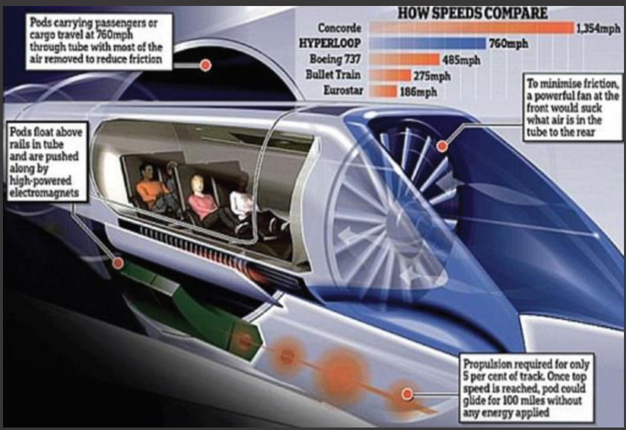

Fig. 3. Hyperloop's main properties [27].

2.3. Comparison Between Similar Transportation Modes

In the Table 1, the comparison of transportation systems of high-speed rail, Maglev and HL. The maximum predicted speed of HL is nearly twice as Maglev and considering this speed it has nearly half minimum horizontal curve to construct. But seating capacity of HL is very low then the others, so it can carry too less passenger one at a time. This cause expensiveness and unfeasibility for the HL. Maybe using more pods can lower this negativity.

Table 1: Comparison of high-speed transportation systems [28].

Basic specifications of	High-speed rail	Maglev system	Hyperloop
Current maximum speed	380 km/h	431 km/h	387 km/h
Speed record	TGV (2007) 574.8 km/h	YMTL1 (2015) 603 km/h	Virgin Hyperloop One 387 km/h
Maximum design speed	402 km/h	604 km/h	1,223 km/h
Maximum seating capacity	1500	824	28 per capsule
Minimum horizontal curve	7.6 km	9.1 km	4.8 km
Maximum gradient	4%	not applicable	not applicable
Technology maturity	mature	almost mature	infant

A comparison is shown in Table 2 for the performances of the HP(Hyperloop), APT (Air Passenger Transport) and HSR (High Speed Rail) systems. As seen, the HL system would only perform better than its APT and HSR counterpart in terms of indicators such as technical productivity and total travel time under certain conditions [22]. Also, in this comparison total in vehicle and station to station times can be reduced by HL.

Table 2: Some estimations of the HL system and its counterparts-APT and HSR at operational performance indicators [11].

Indicator	HL	APT[4]	HSR[4]
Maximum service frequency (dep/h)	10[1]	3	12
Infrastructure capacity (veh/h)1)	10[1]	-	12
Vehicle capacity (seats/veh)	28	130	1000
Transport capacity (pax/h)2)	224[2]	312	9600
Technical productivity (pax-km/h)3)	273280[3]	258968[5]	3360000[6]
Length of line (km)	600	600	600
Average operating speed (km/h)	965	407	264
In-vehicle time (minutes)	37,3	88,5	136,4
Schedule delay (min)7)	3	10	2,5
Total station-station travel time (min)	40,3	98,5	138,9

1) At the maximum speed of 1220 km/h and maximum deceleration rate: a- = 1m/s2; At the maximum load factor: ϴ= 0,8; 3) At the maximum service frequency and speed, and load factor; 4) Taylor et al., 2016; 5) Average speed: v = 830 km/h; 6) Average speed: v = 350km/h;

As can be seen in the Figure 4, the drag resistance of the levitated Hyperloop pod, decreases with altitude, while the drag resistance of conventional transportation systems increases. The EDS device displays lower drag resistance relative to commercial aircraft at high speeds (> 200 m / s), while it can run far outside the operational range of traditional high-speed trains [21,27].

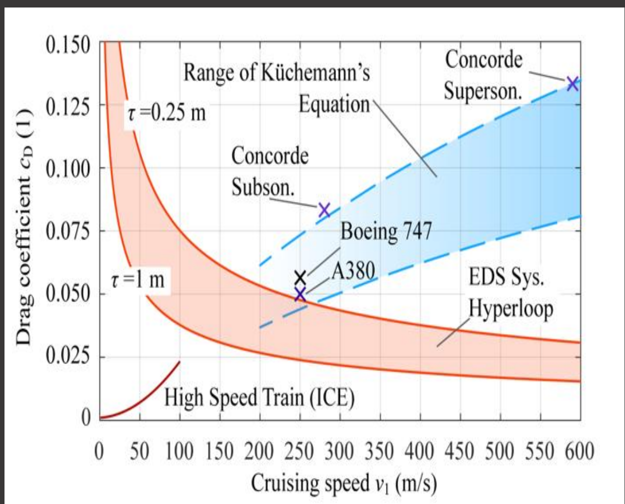

Figure 4: Comparison of the drag coefficient of a levitated Hyperloop pod with EDS and other high-speed transportation systems [21].

2.4. Advantages and Disadvantages of Hyperloop

The Hyperloop 's planned operations are somewhat close to those of a subway network, with a distinction being that the latter line requires more stations. Whereas a subway regularly pauses, it is anticipated that a standard Hyperloop would make one stop at a station in a city. And then take passengers from the stop to the terminal in the destination area. As for flying from the beginning to the end with no delays in between, it's like a straight airline flight. While Hyperloop is like the subway and operating aircraft, this invention 's capability would greatly differ from those two conventional modes of transport [29].

Advantages of Hyperloop Technology

- Extremely efficient transportation potential on large scale
- Very fast transportation opportunity like twice of an aircraft
- Can use mostly or entirely renewable energy. If only powered by solar and wind power, the emission values become practically zero.
- Power consumption is very low
- In long period it provides a low-cost transportation. Needs very less ground space for construction and needs very less energy for transporting the pods comparing the conventional trains.
- Not effected from bad weather conditions.
- Resists to earthquakes.
- Safer transportation mode.
- Less civil engineering work with less noise or no direct emissions comparing with railways.
- Maximum longitional slope is more than conventional
- Lower tunnel costs due to smaller diameter of tunnel need
- Minimum radius of curbs is lower than conventional railroads
- %20-50 Smaller Right of way requirement than high speed rail [13,27]

Challenges or Disadvantages of Hyperloop Technology

- Speed of the pods may cause dizziness on passengers due to vibration and jostling within the pod
- Initial costs are very high.
- More technical skills become necessary for longer vacuum tube manufacturing. Also, the costs and maintain risks become higher with longer tubes.
- Land use rights will be concern for deployment of the project.
- Death risk is very high if something goes wrong in the system.
- Very limited space for passengers to move freely in the pod.
- In Hyperloop system steel is using for track and by the temperature changes steel can change the shape or expand. This can cause serious problems so it should consider at designing and constructing periods [13,27].

2.5. Costs

The Alpha document which have published by Elon Musk in 2013, formed the foundation principles for the Hyperloop project. The article described the vacuum tube and the design of the pod within the tube. The report measured the expense of a one-way ride as $20 / passenger for an approximate 7.4 million passengers between Los Angeles and San Francisco per year with an annual cost of $6 billion over 20 years [13,30].

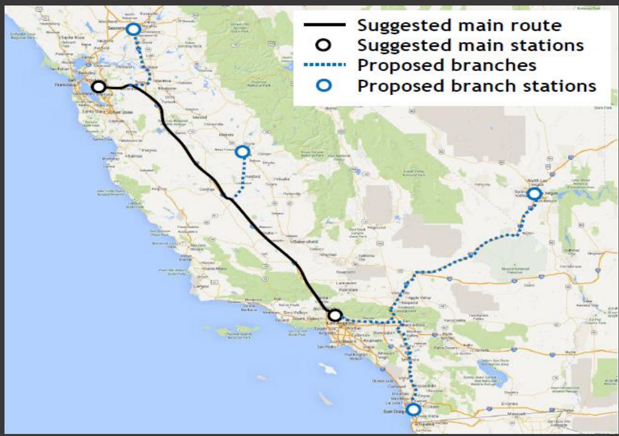

Figure 5. Suggested main route and branches of HL project [13].

As seen in Table 3 and Table 4 HL system investment costs have shown for transportation for 2015. As seen in table one pod weight is 15 tons and total value of a pod costs 1,35 million dolars. And a total cost of a HL system for San Fransisco to Los Angeles is 6 billion dolars.

Table 3. Crew capsule weight and cost breakdown [13]

Vehicle Component	Cost ($)	Weight (kg)
Capsule Structure & Doors:	$ 245,000	3100
Interior & Seats:	$ 255,000	2500
Propulsion System:	$ 75,000	700
Suspension & Air Bearings:	$ 200,000	1000
Batteries, Motor & Coolant:	$ 150,000	2500
Air Compressor:	$ 275,000	1800
Emergency Braking:	$ 50,000	600
General Assembly:	$ 100,000	N/A
Passengers & Luggage:	N/A	2800
Total/Capsule:	$ 1,350,000	15000
Total cost for Hyperloop	$ 54,000,000	

The main route and proposed branch routes from Ellon Musk in HL project is seen in Figure 5. As seen San Diego, Sacramento and Las Vegas can be connected to this system.

3. Conclusion

Hyperloop is an old transportation idea with a new cover that claims to be a competitive and sustainable alternative to either high-speed trains or air transportation. The total costs have calculated for 40 pods and besides very high speed for travel and the other benefits the investment value is very high for transportation system. Safety, Earthquake and weather resistance are good benefits. But, besides all the benefits, the cost of project remains expensive because of low passenger number at a one-time travel. However, with the evaluated passenger needs due to globalization, fast travel needs of passengers, increased value of time, supersonic logistic needs.

Table 4. Total cost of the Hyperloop passenger transportation system [13].

Component	Cost (million USD)
Capsule	54 (40 capsules)
Capsule Structure & Doors	9.8
Interior & Seats	10.2
Compressor & Plumbing	11
Batteries & Electronics	6
Propulsion	5
Suspension & Air Bearings	8
Components Assembly	4
Tube	5,410
Tube Construction	650
Pylon Construction	2,550
Tunnel Construction	600
Propulsion	140
Solar Panels & Batteries	210
Station & Vacuum Pumps	260
Permits & Land	1,000
Cost Margin	536
Total	6,000

4. Discussion

The method itself is open to improvements and can be a good alternative transportation mode in near future. And some of the benefits of HL system needs more researches. But especially for now within the economic crisis all over the world this HL system is an expensive transportation mode.

Declaration of Interest Statement

The author declare that he have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement

K. **Armagan:** Investigation, Supervision, Validation, Visualization, Draft writing, Review&Editing

References

[1] Joshi, P. R. (2016). Hyperloop: The 5th Mode of Transportation?, Retrieved from: https://bit.ly/3gvxUbx

[2] Urban Transport. (2013). Musk announces plans to build Hyperloop demonstrator, Retrieved from: https://bit.ly/3dZj9vT

[3] Baker, D. R. (2015). Build your own hyperloop! SpaceX announces pod competition, Retrieved from: https://bit.ly/2NVRCB8

[4] Pensky, N. (2012). PandoMonthly Presents: A Fireside Chat with Elon Musk, Retrieved from: https://bit.ly/3iwYfrA

[5] Musk, E. (2016). Hyperloop Pod Award Ceremony, Retrieved from: https://bit.ly/2ZHm8UL

[6] Gannes, L. (2013). Tesla CEO and SpaceX Founder Elon Musk: The Full D11 Interview (Video), Retrieved from: https://bit.ly/2VOJZAU

[7] Anonymous. (2020). Vactrain. Retrieved from: https://bit.ly/3e3jjCK

[8] Anonymous. (2020). Atmospheric railway. Retrieved from: https://bit.ly/3e17Q6t

[9] Miller, R. (2014). The SciFi Story Robert H. Goddard Published 100 Years Ago. Retrieved from: https://bit.ly/2ZGK5eW

[10] Goddard, E. C. (1950). Vacuum tube transportation system, U.S. Patent No. 2,511,979. Washington, DC: U.S. Patent and Trademark Office.

[11] van Goeverden, K., Milakis, D., Janic, M., & Konings, R. (2018). Analysis and modelling of performances of the HL (Hyperloop) transport system. European Transport Research Review, 10(2), 41. https://doi.org/10.1186/s12544-018-0312-x

[12] Salter, R. M. (1972). The Very High Speed Transit System. RAND Corporation, Santa Monica https://apps.dtic.mil/sti/citations/ADA032172

[13] Musk E (2013) Hyperloop Alpha. Retrieved from: http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf

[14] Virgin Hyperloop. (2017) One Project, Retrieved from: https://virginhyperloop.com/project/dubai

[15] Grebennikov, N., Kireev, A., Kozhemyaka, N., & Kononov, G. (2019). Hybrid electromagnetic suspension for high-speed vacuum transport. International Journal of Power Electronics and Drive Systems, 10(1), 74-82. https://doi.org/10.11591/ijpeds.v10.i1.pp74-82

[16] Kireev, A. V., Kozhemyaka, N. M., & Kononov, G. N. (2015). Potential development of vehicle traction levitation systems with magnetic suspension. International Journal of Power Electronics and Drive Systems, 6(1), 26-31. http://doi.org/10.11591/ijpeds.v6.i1.pp26-31

[17] Kireev, A. V., Kononov, G. N., & Lebedev, A. V. (2017). Starting Operating Mode of the Combined Traction Levitation System of the Vehicle Equipped with Magnetic Suspension. International Journal of Power Electronics and Drive Systems, 8(1), 176-183. https://doi.org/10.11591/ijpeds.v8.i1.pp176-183

[18] Virgin Hyperloop. (2016). How and Why We're Levitating the Hyperloop. Retrieved from: https://hyperloop-one.com/blog/how-and-why-were-levitating

[19] Jo, J. M., Han, Y. J., & Lee, C. Y. (2012). Design of the Miniature Maglev using Hybrid Magnets in Magnetic Levitation System. International Journal of Mathematical, Computational, Physical, Electrical and Computer Engineering, 6(2), 195-198. https://doi.org/10.5281/zenodo.1329408

[20] Santangelo, A., & Andrea, S. (2018). Hyperloop as an evolution of maglev. Transportation Systems and Technology, 4(4), 44-63. http://doi.org/10.17816/transsyst20184444-63

[21] ETH Zürich. (2017). Energy Efficiency of an Electrodynamically Levitated Hyperloop Pod. Retrieved from: https://esc.ethz.ch/news/archive/2017/11/energy-efficiency-of-an-electrodynamically-levitated-hyperloop-pod.html

[22] Flankl, M., Wellerdieck, T., Tüysüz, A., & Kolar, J. W. (2017). Scaling laws for electrodynamic suspension in high-speed transportation. IET Electric Power Applications, 12(3), 357-364. https://doi.org/10.1049/iet-epa.2017.0480

[23] Chin, J. C., Gray, J. S., Jones, S. M., & Berton, J. J. (2015). Open-source conceptual sizing models for the hyperloop passenger pod. In 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (p. 1587). https://doi.org/10.2514/6.2015-1587

[24] Virgin Hyperloop. (2017) One Project. Retrieved from: https://virginhyperloop.com/project/devloop

[25] Chaidez, E., Bhattacharyya, S. P., & Karpetis, A. N. (2019). Levitation Methods for Use in the Hyperloop High-Speed Transportation System. Energies, 12(21), 4190. http://doi.org/10.3390/en12214190

[26] Van Goeverden, C. D., Milakis, D., Janic, M., Konings, R. (2017). Performances of the HL (Hyperloop) transport system. Proceedings of the BIVEC-GIBET Transport Research Days, 29-43.

[27] Rana, V. (2020). Hyperloop the fifth mode of transport, Retrieved from: https://bit.ly/3e1kmCZ

[28] Gieras, J. F. (2020). Ultra high-speed ground transportation systems: Current Status and a vision for the future, Przeglad Elektrotechniczny. https://doi.org/10.15199/48.2020.09.01

[29] Virgin Hyperloop. (2019). Hyperloop One. Retrieved from: https://bit.ly/31Nd4QU

[30] Rajendran, S., & Harper, A. (2020). A simulation-based approach to provide insights on Hyperloop network operations. Transportation Research Interdisciplinary Perspectives, 100092. http://doi.org/10.1016/j.trip.2020.100092