

EVOLVING TOWARD A SCALABLE HYPERLOOP TECHNOLOGY:

Vacuum Transport as a Clean Alternative to Short-Haul Flights

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INTRODUCTION: The future transformation of transportation is set to fundamentally shape our modern civilization in reducing the global energy consumption from travel and the time needed to move. In the European Union's (EU's) future climate vision, 90 percent of travel-related emissions is omitted by 2050. In order to achieve this optimistic goal, one of the EU's strategically proposed solutions is the vacuum train concept, called out as the Hyperloop transportation system (HTS) in 2013¹. The Hyperloop is currently viewed as the fastest way to cross the surface of the earth². It employs fully electric propulsion, and thus, it is seen as a clean option. The optimal routes that are relevant for implementation are found in traffic-intense intercity regions, which would generate sufficient throughput to pay back its infrastructure investment. Another driver is that European countries (e.g., France and Germany) have already proposed banning short-haul domestic flights where travel by rail is an option. Such policies could accelerate the push for new Hyperloop projects as a promising alternative to rail. In this article, a technical path for affordable Hyperloop development and implementation is presented.

The long-forgotten idea of vacuum trains, or vactrains, was already patented decades ago³.

Following the closure of the Swissmetro vactrain project in 2009, the key idea of a low-pressure

¹ COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - Sustainable and Smart Mobility Strategy – putting European transport on track for the future
<https://ec.europa.eu/transport/sites/transport/files/legislation/com20200789.pdf>, European Commission, 9. Dec. 2020.

² J. K. Nøland, "Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review", *IEEE Access*, vol. 9, pp. 28439-28458, February 2021, <https://ieeexplore.ieee.org/document/9350309>.

³ E. C. Goddard, "[Vacuum tube transportation system](#)", U.S. Patent No. 2,511,979, June 1950.

tube was rebranded as the Hyperloop in an open-source design paper in 2013⁴. In its core principle, passenger or freight capsules are propelled inside an airless vacuum tube at nearly the speed of sound. Hyperloop is still at the early stage of development, as no fully operational systems exist, and many engineering challenges are left open. In Figure 1, a conceptual HTS is depicted, including magnetic lift and drag for suspension, air losses, and forward thrust. Here, the capsules generate their own propulsion, driven by linear motors and powered by batteries onboard. As a result of recent marketing hypes about the technology, not enough explanation of its functionality has been provided, which is the goal of this article.

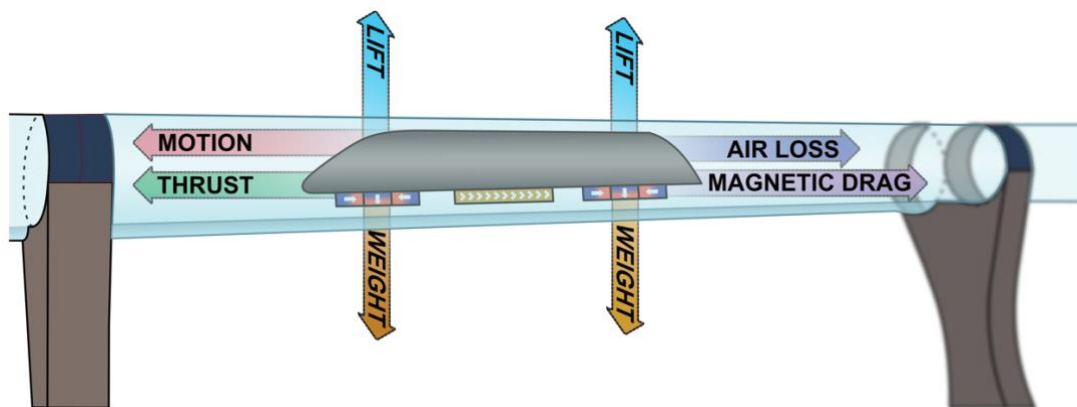


Figure 1 This figure shows a conceptual illustration of the Hyperloop transportation system (HTS) configured with magnetic levitation and electric propulsion. A free-body diagram of arrows indicating the different forces acting on the capsule is depicted.

TECHNICAL DRIVERS OF HYPERLOOP DEVELOPMENT

The key benefits that are promoting the development and implementation of Hyperloop are as follows. By removing the air from the tube, the advantage is dramatically reducing the air losses and the associated drag, thus enabling ultra-efficient transportation means. The feasible cruising speeds are rivaling the fastest airplanes, with an energy consumption per passenger (PAX) per kilometer (or revenue passenger-kilometer, RPK) that are very close or inferior to those of trains and comparable to those of electric cars. For longer routes, the energy

⁴ E. Musk, "[Hyperloop Alpha](#)" (white paper), Hawthorne, 2013.

consumption per revenue passenger-kilometer can be reduced further. This is because a larger share of the tube will be utilized for the cruising speed.

In many ways, Hyperloop can be seen as a symbiosis between the aviation and rail industries. It is a subsonic train that experiences high-altitude atmospheric pressure levels and must cope with safety certification standards similar to or stricter than those of airplanes. The impacts of Hyperloop on humans are a significant reduction in delay and travel times, and that transits can happen much closer to the big city centers. Benefits will be further explained in the following.

Recreating the Outer Atmosphere

The main advantage of the Hyperloop concept is the opportunity to achieve a high-altitude low-pressure environment at the surface of the earth. In reality, airplanes have to consume a lot of energy to reach the 10-kilometer altitude, where the pressure level is 75 percent lower. Approximately 27 kWh of potential energy is needed to lift every ton of mass from sea level to 10 kilometers above the ground. In addition, one would also have to displace a distance where drag forces must be met as well. These energy needs come on top of the kinetic energy needed for an airplane to accelerate to 900 km/h, which constitutes about 9 kWh per ton of mass. The kinetically stored energy is more difficult to regenerate on an airplane (i.e., regenerative soaring), which is in a non-constrained environment, opposite to the Hyperloop.

In order to keep a medium vacuum on the earth, vacuum pumps must be operated along the tube. The concept can be made economically viable and more energy-efficient than airplanes, given that the number of capsules utilizing the tube environment generates enough throughput in the system. A steady passenger flow and easy embarking must be kept as long as the tube is operated. In fact, the high amount of energy needed to depressurize the tube favors operating

the tube at low pressure continuously for day and night and as long as possible, in order to justify the energy consumption needed to depressurize². One attractive solution would be to allow freight transport during the night and more passenger-related travel during the day, in order to maximize your revenue as much as possible. This synergy might be important, as the freight market is usually much bigger than passenger needs. A passenger-only transportation system would be rarely profitable, and might need governmental subsidies to operate.

Energy is also needed to compensate for the leakage of air into the tube (i.e., concrete's air leak). This is another good reason for the importance of keeping the tubes operated continuously. By lowering the tube pressure as much as possible, the higher are the gains in reduced air loss. However, the desire for a low-pressure environment must be weighed against its safety concerns. It is also worth noting that a hard vacuum would be too expensive. On the extreme end, the Hyperloop concept could be designed with a 99.9 percent lower pressure than at sea level, i.e., as low as it would recreate the atmosphere experienced closer to the outer space, implying a massive reduction in energy consumption.

A Dramatic Reduction of the Air Resistance

The density of air is approximately proportional to the pressure where it exists. As a result, the air density inside the tube is only 1/1000 of atmospheric air with a 99.9 percent lower pressure. The aerodynamic drag will then be reduced with the same portion, i.e., 0.1 percent of the air resistance experienced at atmospheric pressure (i.e., 1 atm). In addition, the ideal gas law states that any heat accumulated inside the tube will cause a temperature rise that reduces the air loss further. Figure 2 illustrates how the power consumption due to air resistance is reduced by lowering the pressure, as well as increasing the temperature. The power consumption is presented for two cruising speeds, 1000 km/h and 1235 km/h, respectively. Compared to sea

level and aerospace altitudes, the aerodynamic power consumption in the Hyperloop environment seems insignificant in Figure 2.

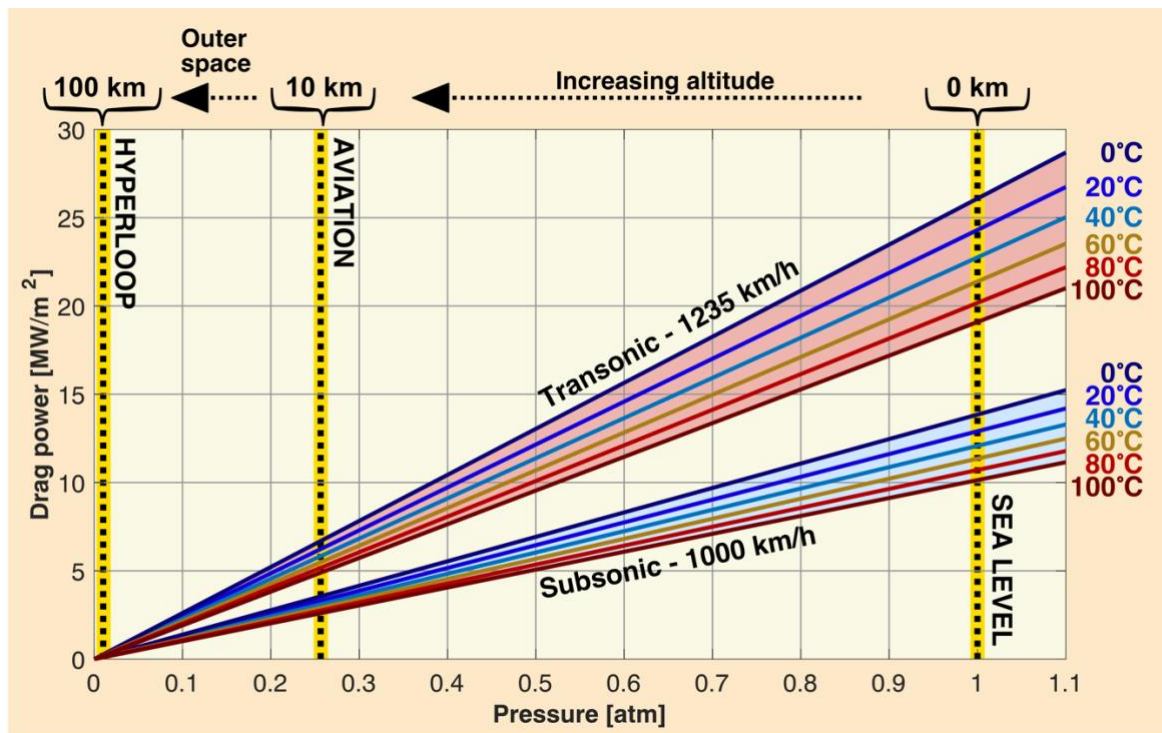


Figure 2 The drag power is plotted per frontal surface area of a capsule moving at subsonic (1000 km/h) and transonic (1235 km/h), respectively. The projections are calculated from the drag equation ($F_d = 0.5C_d\rho Av^2$), where the drag power (or air loss) is the drag force (F_d) times the speed (assuming a unitary drag coefficient, $C_d = 1$). Ideal gas law ($p = RT\rho$) is used to obtain the air density (ρ) as a function of both pressure (p) and temperature (T), where $R = 287.05$ J/kgK.

Figure 2 is realistic given that the drag scales linearly with the air density. The drag equation predicts that the total drag experienced by a body submerged in air is proportional to the dynamic pressure ($0.5\rho v^2$), the frontal surface area of the body (A), and the drag coefficient (C_d). The premise for a low air resistance relies on the realism of a low drag coefficient inside the tube. This only holds if the tube's volume surrounding the capsule can be assumed infinitely large, relative to the vehicle. Normally, the walls of the tube are much closer to the capsule. Inevitably, we are dealing with an internal aerodynamic problem, where a violation of the so-called Kantrowitz limit could potentially increase the drag, and thus, deuterate the benefits of the Hyperloop concept. Let us have a look at how this concern can be mitigated.

The hyperloop capsule resembles a subsonic or near-sonic wind tunnel, where choked flows and shock waves at the tail easily occur. The flow around the capsule will accelerate and create choked flows if the blockage ratio is high (i.e., the capsule's cross-sectional area is large relative to the tube). In these cases, the sides of the capsule are too close to the tube. Elon Musk's white paper from 2013 proposed that a huge compressor in the front of the capsule could release the flow and prevent the pressure build-up by mitigating the twisted flow around the pod. However, the required compression ratios were several times higher than the current jet engines. Consequently, it is perceived that this solution rather complicates the pod design.

It is, in fact, possible to deal with the increased drag by approaching other options instead. For a cruising speed of 1080 km/h, it has been identified a non-linear relationship between the drag coefficient and the blockage ratio². This ratio describes the ratio of the cross-section frontal area of the capsule to the inner tube area. A 25 percent ratio means that the diameter of the capsule is about half of the inner diameter of the tube. Hence, more depressurization energy is needed to fill the tube, but it can significantly reduce the drag, as more space is available around the capsule. The violation of the so-called Kantrowitz limit then reduces. A feasible drag coefficient could be as low as a factor of 2 times the unity drag coefficient². As a result, the penalty applied to the estimated drag power in Figure 2 (i.e., with unity drag factor) is significantly lower than the reduced air resistance due to the reduction in the pressure level.

As seen above, a better path forward might be optimizing the aerodynamic performance of the capsule or increasing the tube volume. It might also be more fruitful to deal with any additional extra drag by strengthening the propulsion system instead of adding compressors onboard. Still, it is an open design question to minimize global energy use.

Feasibility of Shorter Travel Times

Another major benefit of the Hyperloop is its dramatic reduction in travel time. However, due to the acceleration needed, the travel time depends strongly on the length of the route where it is built. There is always a needed trajectory time and length before the capsule reaches the desired cruising speed. As a result, the travel time does not improve significantly beyond 1000 km/h for routes in the range between 250 and 500 km. This effect can be observed in Figure 3, where the travel time is plotted as a function of the cruising speed.

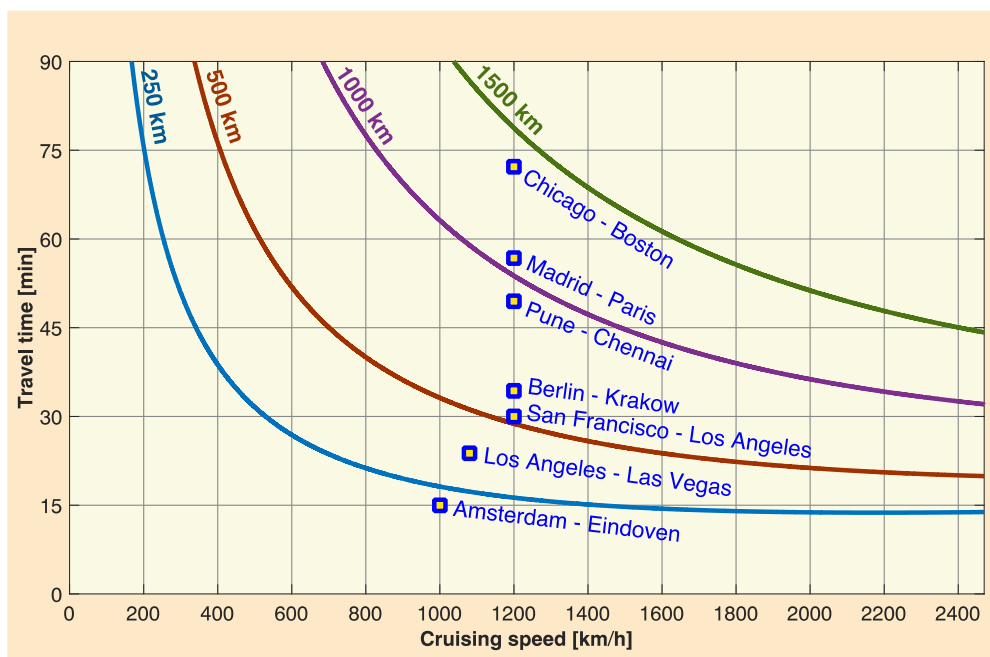


Figure 3 In this figure, the relationship between travel time (in minutes) and cruising speed (kilometers per hour) is shown for different journey distances, 250 km, 500 km, 1000 km, and 1500 km, respectively. Some example routes are also depicted. The impact of the acceleration trajectory is taken into account, with a mean acceleration of 0.1 G and a de-acceleration of 0.3 G. The G-force values were chosen based on the report by the Transportation Economics and Management Systems report, "Great Lakes Hyperloop Feasibility Study", December 2019, <https://www.glyperloopoutreach.com/feasibility-study>. The cruising time is calculated by dividing the cruising length by the cruising speed, and the acceleration and braking times are calculated by dividing the cruising speed by the mean acceleration or de-acceleration, respectively.

Figure 4 considers the impact of the acceleration, with a base thrust of 0.1 G (assumed in Figure 3) and with a final cruising speed of 1200 km/h. As the velocity profile develops, the propulsion power needed to accelerate increases linearly with speed (v). It also scales linearly with the normalized G-force, which is the ratio of the acceleration (a) to the gravitational constant ($g = 9.81\text{m/s}^2$). The acceleration power (P_{acc}) can be calculated from the following expression:

$$P_{acc} = mg \left(\frac{a}{g} \right) v,$$

where the mass of the capsule (m) could be taken as 1000 kilograms to identify the acceleration power needed per ton. A similar relationship applies to the deceleration process as well. The maximum power needed will strongly influence the dimensioning of the capsule's propulsion system (either onboard or external). One solution is to restrict the acceleration when the vehicle has reached a certain speed level and then speed up toward the desired cruising velocity.

Figure 4 illustrates the strong non-linear relationship between the maximum acceleration power and the distance needed to accelerate. Firstly, it can be observed that a reduction of 25 to 50 percent has less effect on the distance needed, while restricting further has a much stronger impact. The maximum power rating should, therefore, be chosen carefully. One would be less interested in over-dimensioning the power reservoir onboard the capsule if the acceleration distance does not get significantly reduced. It would be a worthless investment. Moreover, it has been shown that high acceleration performance increases the capsule's overall mass, as well as the energy consumption per passenger-kilometer⁵. Figure 4 suggests that partial restrictions in the acceleration do not have detrimental effects on the overall performance. For instance, at 1 G force, the acceleration length needed to reach 1200 km/h would be only 5.6 kilometers, one-tenth of what is needed at 0.1G. However, it would be a less comfortable experience for the passengers. In the extreme case, where maximum acceleration power is reduced by 75 percent, the speed profile is restricted when the capsule has reached 300 km/h. Due to the limited acceleration from 300 km/h to 1200 km/h, the trajectory profile toward cruising gets significantly longer. Even though it downrates the propulsion system, the tube trajectory needed to accelerate gets about two and a half times longer. Increasing the capsule's trajectory traveled at lower speeds also influences the feasible travel time.

⁵ D. Tudor & M. Paolone, "Optimal Design of the Propulsion System of a Hyperloop Capsule", *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, Dec. 2019, URL: <https://ieeexplore.ieee.org/document/8892514>.

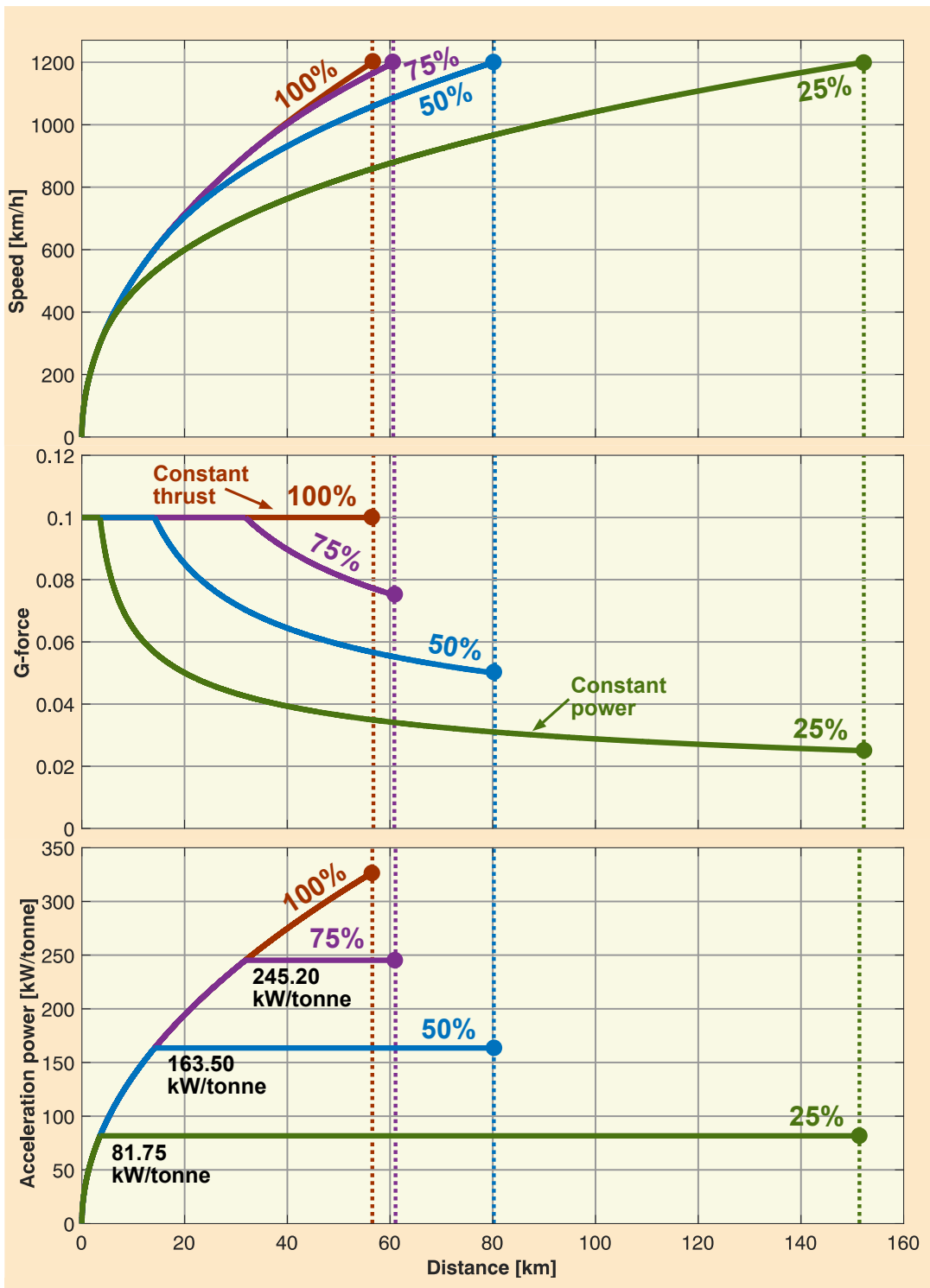


Figure 4 The figure shows the impact of restricting the acceleration power by constraining the g-force during the acceleration trajectory distance for a capsule with 0.1 G in initial acceleration and a final cruising speed of 1200 km/h. The calculation is based on Newton's second law of motion ($\Sigma F = ma$), the accumulation of velocity ($v = \int a dt$), as well as the accumulation of distance ($s = \int v dt$). The acceleration power is the product of the thrust and the instantaneous speed ($P_{acc} = \Sigma Fv$), and the G-force acceleration is normalized with the gravitational constant ($g = 9.81 \text{ m/s}^2$).

An Environmentally Friendly Alternative to Conventional Rail

Finally, another environmental advantage of Hyperloop over railways is that the tube can be built above the ground on pylons with pre-fabricated sections. The supporting pillars might be installed for every 30 meters on average and tall enough to cause reduced disruption of farmland. It also emits less noise from its operation since it can contain its sound inside the tube. Moreover, the tube infrastructure is a perfect synergy for solar harvesting that lowers the occupation of the environment. In fact, one of the major challenges with solar energy is the occupation of land areas. It can be estimated that a solar roof on top of the tube can make the Hyperloop net energy positive. Based on the California climate, a two-way tube of 4.25-meter width can provide an electric power capacity of 510 kW per kilometer of the tube at peak solar activity (assuming 120W/m^2) or an annual average of 75.5 kW per km (i.e., 16.78 W/m^2).

THE HYPERLOOP PROPULSION CONCEPTS

This section takes the technical drivers on board to explore the realization of different Hyperloop propulsion solutions. Even though everything has not yet been settled, most major companies now agree to use linear electric motors for propulsion and employ magnetic levitation for suspension and guidance. Moreover, the typical target for the pressure levels inside the vacuum chamber is in the range between 1/1000 of the atmospheric pressure (1 atm) to the pressure levels where aviation has been certified to fly, i.e., 1/10 of sea level.

Design for a Scalable Low-Infrastructure Solution

Currently, the scalability of Hyperloop's core technology is a major concern for its implementation in the short-haul flight segment. It is well known from high-speed rail and classical maglev projects that the infrastructure could be as high as 95 percent of the total investment costs. Therefore, the possibility to design the capsule energy-autonomous is viewed

as a very promising option. Otherwise, one would have to electrify the whole tube, where active rails for propulsion lead to a rapid increase in extra components. Complex safety-critical systems along the track favor the option of minimum infrastructure for the propulsion. You are less interested in adding even more costs on top of the vacuum-proof low-pressure solution. It will also affect the environmental footprint, the need for resources, the manufacturability, and the utilization of active components. Moreover, it is vital to make the infrastructure as affordable as possible to ensure profitability. Thus, the self-propelled pods are economically the best alternative, as they maximize your returns from invested building costs.

In general, there are four alternatives for the Hyperloop propulsion system.

- 1) The first concept from 2013 was to make active acceleration zones along the track, with the rest of the tube being passive with lower infrastructure needs. It also made the capsule free of active propulsion components. However, the shorter the length of the boosting zone, the larger is the power spikes, which will have a detrimental impact on the external bulk power system⁸.
- 2) A second alternative is to design the whole tube as an electric propulsor and tailor the needs for thrust along the track (i.e., less needed coils for cruising). It has the benefits of a lightweight vehicle, but the extensive need for active components with low utilization along the tube cannot be neglected. This option clearly shows that there are conflicting objectives in the overall Hyperloop design.
- 3) A third alternative is to combine the benefit of option 2) and apply some affordability to the solution. The capsules are accelerated externally over a shorter launch zone of the track, while the rest of the track is passive, with propulsion on board to keep the cruising speed until the capsule arrives at the destination.

- 4) Finally, the fully energy-autonomous option is only to have active propulsion components onboard the capsule, making the tube less infrastructure-intensive, the track fully passive, and thus, achieve the most affordable and scalable solution.

Option 1): Partially Electrified Tube with Booster Zones (Hyperloop Alpha - 2013)

The 2013 white-paper proposed air bearings for suspension based on the principle of aerodynamic lift. Even though this levitation principle is mature, it is not as simple as playing air hockey inside a tube. In the Hyperloop application, the manufacturing tolerances are much tighter, considering that airlift implies a low levitation height at very high speeds. Moreover, the propulsion power was intended to be external with 4 km sections of active stator coils along the track, estimated to be long enough to increase the speed from 480 to 1220 km/h at 1 G-force. However, rough calculations based on the acceleration equation (Newton's law of motion) show that a 5-km section would be a more realistic figure at 1 G-force. The propulsion concept was using long primary linear induction motors (LP-LIMs). It was proposed as a lightweight and less bulky solution for the capsule, which already had compressors onboard. On average, a periodic re-boost of the LP-LIM would be needed roughly for every 110 km (or 70 miles). As a result, less than 4 percent of the tube's overall length would need active electrification infrastructure. The kinetic energy injected during each spike is equivalent to the energy that one ton of batteries could hold (200 kWh). Table 1 presents the key metrics of the Hyperloop Alpha system (2013), and Figure 5 depicts the booster station schematically.

In order to relieve the burden on the power grid, battery reservoirs could be installed for each accelerator to be used for peak-shaving. This is because the stator segments of the LIM, including the converter and the power stations, experience huge power spikes for just a few seconds (i.e., 21 s). It affects the power grid with very sharp spikes in their highly pulsating

load profiles, and in the worst case, they are likely to induce voltage disturbances and fluctuations⁶. They are also likely to reduce a significant amount of the frequency stability reserves of the grid in high-stress situations. However, it strongly depends on the point-of-connection (PoC) to the local power grid and the voltage level of the transmission line, where costly substations of higher voltage levels might be required.

TABLE 1. The Hyperloop Alpha preliminary design (2013).

Cruising speed	1220 km/h (max.) – 798 km/h (mean) - 480 km/h (min.)
Acceleration	1 G-force (i.e., 9.81 m/s ²)
Tube pressure	0.0987 % of atmospheric sea level
Capsule's frontal area	1.4 m ² w/ dimensions 1.35 m x 1.10 m
Capsule's blockage	35.8 % capsule-to-tube area ratio
Capsule's capacity	28 passengers (PAX) – 2 000 kg – 13.33% of total capsule mass
Capsule's weight	15 000 kg including PAX
Energy storage onboard	4 000 kg - 26.67% of total capsule mass
Propulsion system	Long primary double-sided linear induction motor (LP-DB-LIM)
Suspension system	28 air bearings - 2 800 kg - 18.67% of total capsule mass

*Based on: https://www.tesla.com/sites/default/files/blog_images/hyperloop-alpha.pdf

⁶ A. Tbaileh, et. al., "Modeling and Impact of Hyperloop Technology on the Electricity Grid", *IEEE Transactions on Power Systems*, vol. 99, no. PP (early access), March 2021, URL: <https://ieeexplore.ieee.org/document/9382792>.

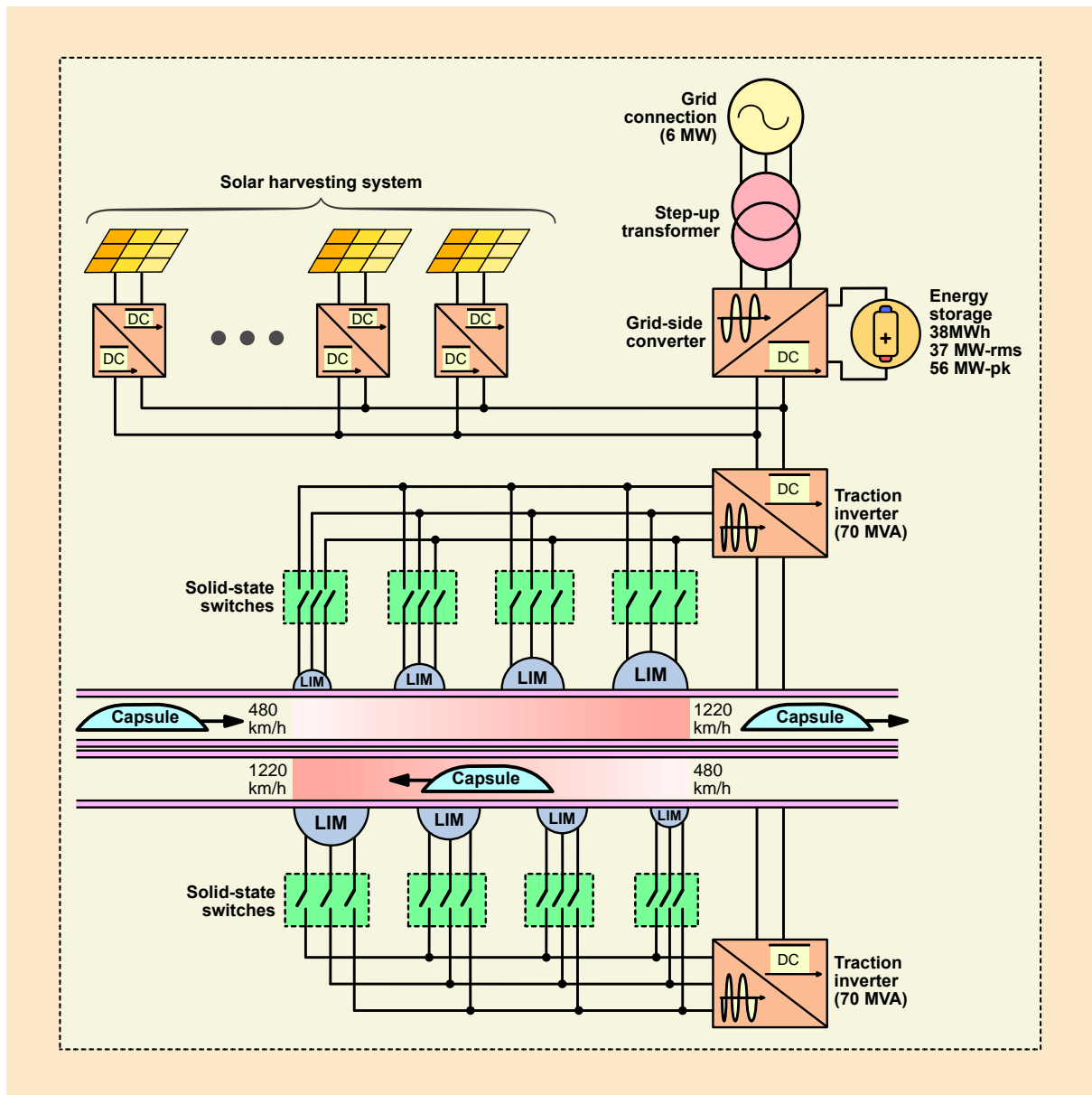


Figure 5 A schematic sketch of the acceleration booster concept (Hyperloop Alpha system) is shown in this figure. The details are taken from Elon Musk's white paper (https://www.tesla.com/sites/default/files/blog_images/hyperloop-alpha.pdf). The integration with the power system and the tube's harvesting of solar electricity is also depicted.

System optimization is an option for the power fluctuation problem, where the regenerative braking of capsules can be coordinated with the acceleration of others, but the inherent complexity of such a solution is inevitable. One would also need to have some grid-side compensation equipment (e.g., SVCs, STATCOMs, dynamic VAR devices, etc.) to handle the pulsating loads in active and reactive power. Alternatively, an energy storage system in between can be used to mitigate the highly stressful load profile, which might be one of the

most cost-effective mitigation strategies. It is also worth noting that the acceleration zones along the track require coils distributed for 4 to 5 kilometers, where switches can be used to energize fractions of the coils close to the capsule's position. This approach will improve the power factor experienced by the inverters, as depicted in Figure 5. The fluctuations in speed, G-forces, and propulsive power experienced by the capsule are plotted in Figure 6.

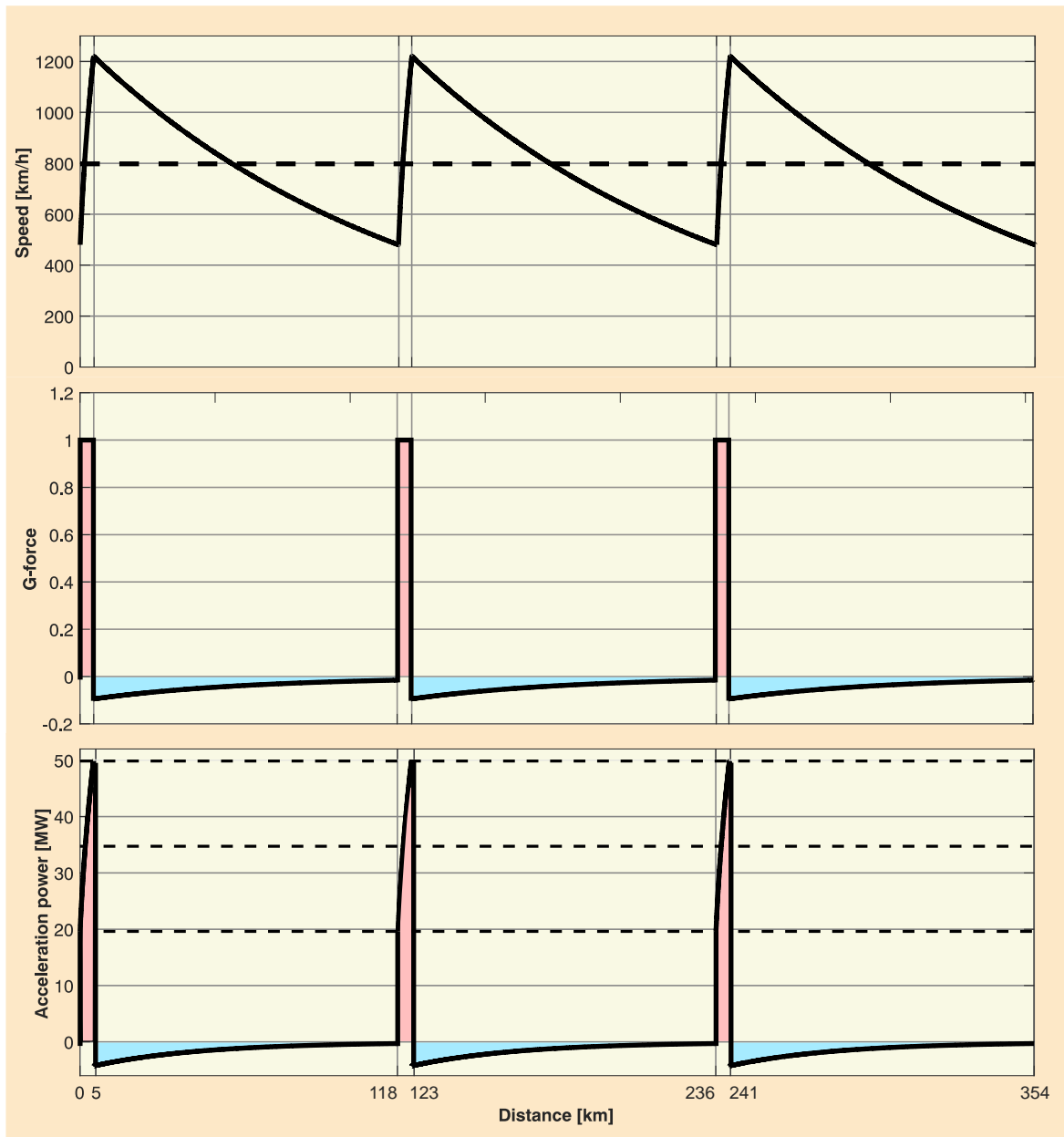


Figure 6 Speed profile, G-force, and acceleration power of the Hyperloop Alpha passenger capsule, with a total weight of 15 tons. Maximum and minimum speeds are 1220 km/h and 480 km, respectively. The acceleration force is 1 G over the boosting zone. In between the acceleration spots, aerodynamic forces are acting to de-accelerate the capsule, proportional to the square of the instantaneous speed. The mean electrical power absorbed during acceleration is 34.74 MW. The capsule uses approximately 21 seconds inside the boosting zone, and 9 minutes and 9 seconds in between. 202.2 kWh kinetic energy is injected under each spike, while discharged the same amount of energy in between due to natural air resistance and friction. The boosting interval repeats periodically through the whole cruising zone of the track.

The mean velocity for the cruising profile shown in Figure 6 is only 798 km/h, even though the maximum speed is 1220 km/h, yielding poor utilization of the track performance. Moreover, the repetitive spikes of 1 G also make the travel a less comfortable experience.

The Hyperloop Technical Transition from Option 1)

In the transition period between 2013 and 2018, the Hyperloop evolved toward a more traditional maglev approach, where classical magnetic levitation systems are placed inside a low-pressure tube. It allows a larger levitation gap than in air bearings, which is an important safety feature at subsonic speeds. In particular, Maglev has 50 years of developmental experience with actual systems working up to 600 km/h and practical lessons learned.

Currently, it is quite hard to know what is going on inside the commercial Hyperloop companies because they are not very forthcoming in delivering the technical details. Inspired by the SpaceX Hyperloop competition (starting in 2017), many companies initially considered a passive track with electro-dynamic suspension (EDS) and short-primary linear induction motors (SP-LIMs). In order to improve the primitive I-beam track employed in SpaceX, the Inductrack concept of track segmentation has been proposed to reduce the rolling magnetic drag (proposed in the year 2000: R. F. Post, “*Maglev: A New Approach*”, *Scientific American*, vol. 282, no. 1, pp. 82-87, Jan 2000). The Hyperloop Transportation Technologies (HTT) advertises this technology (<https://www.hyperlooptt.com/technology/>).

The EDS system is inherently stable and fail-safe in its physical nature. The levitation mass onboard the capsule is based on passive Halbach-array lift skirts with no energy requirement. However, the levitation is repulsive, which means that the capsule has to float over the track. In addition, auxiliary wheels must be employed for take-off and landing (i.e., no suspension

available at low speed). Moreover, the large levitation height of the Inductrack EDS makes it incompatible with linear propulsion, which means that the linear motor has to be separate and act over another track surface. If one decides to make the propulsion external instead of onboard the capsule, the linear synchronous motor (LSM) is considered the most energy-efficient solution. However, the LSM favors electro-magnetic suspension (EMS), as these technologies can be integrated with each other. This suspension concept relies on attractive levitation rather than the repulsive nature of the EDS. With EMS, the Hyperloop capsule could be hanging underneath the track inside the tube. It is postulated by the companies that a hanging capsule could improve cornering when it turns inside the tube. Still, the radius of curvature would need to be much higher for the Hyperloop than classical rail to restrict the centrifugal G-force experienced by passengers (e.g., a 0.2 G force comfort level implies a curvature radius of 39.3 km at 1000 km/h cruising speed). In 2018, Virgin Hyperloop (VH) switched its strategy from the Inductrack to the EMS to integrate its suspension with LSM propulsion.

Option 2): Large-scale Tube Electrification with a Lightweight Capsule

The concept of the rail as a propulsor was popularized by the German Transrapid maglev system. However, it has been concluded that the reason the system failed was that the guideways were too expensive, even though the ride itself was perfect. Virgin Hyperloop (VH) and Hardt are now pursuing this option for the Hyperloop, even though it is well-known that it has massive infrastructure needs. A basic sketch of the system is presented in Figure 7.

The track propulsor can indeed be tailored to the propulsion needs along the track, and therefore, needs less powerful components in the cruise zone of the tube. The linear synchronous motor (LSM) can achieve very good efficiency and power factor, given that the system only energizes the portion of the track where the capsule is situated every time instant.

Due to no slip between the primary and the secondary, it can reach the highest cruising speeds for a given power supply, contrary to LIMs. However, the need for synchronism implies higher complexity in how the system is operated.

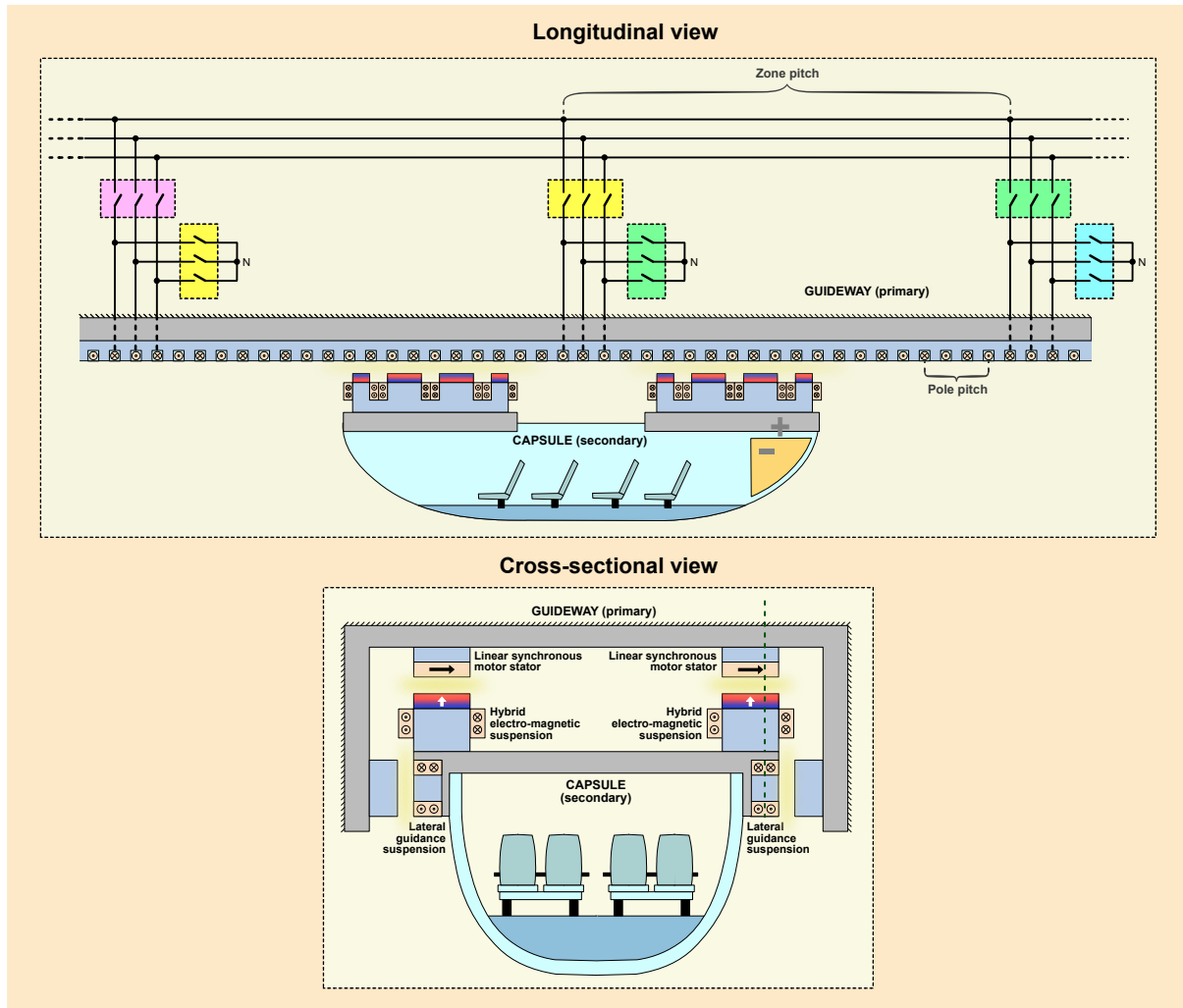


Figure 7 Sketch illustrating of the large-scale tube electrification solution with a lightweight capsule. The concept is depicted in both a longitudinal and a cross-sectional view, respectively. The propulsion system is distributed along the track as a long primary linear synchronous motor (LP-LSM). The levitation is an electro-magnetic suspension (EMS) system with hybrid excitation. The concept refers to the solution proposed by Hardt Global Mobility (URL: <https://hardt.global/technology-development/>).

Option 3): Electromagnetic Launch System with Self-Propelled Cruising

As illustrated earlier, a long track-length is needed for acceleration if the propulsion power level is not sufficiently high enough. This is where the concept of the tube as a propulsor (i.e., option 2) finds its benefit with excellent acceleration performance. For this reason, the Spanish Hyperloop company Zeleros has proposed a similar system as an electromagnetic launch

system during acceleration (LSM as a track propulsor), even though they are pursuing a self-propelled capsule in the cruising zone (<https://zeleros.com/hyperloop-technology/>). In this way, their capsule is saving a massive amount of energy needed for acceleration (e.g., potentially reducing the energy reservoir's mass with up to 50 percent²), which makes their vehicle lighter than a fully energy-autonomous solution. It also reduces the tube length needed for acceleration, but at the expense of higher complexity compared to a fully self-propelled solution. Contrary to all the other commercial companies, Zeleros considers aerodynamic propulsion in the cruising zone, powered by an electric rotary motor rather than a linear one. A rotating propulsor will have a very high efficiency because it has a much smaller air gap than a linear induction motor. However, even though the electrical losses are significantly reduced and will be easier to handle, losses are now manifesting in aerodynamic propulsion, which will require extra power instead. Another problem is that the aerodynamic thrust highly depends on the tube's air density, causing competing interests in the design. By selecting a tube operated at the Concorde subsonic-aircraft's commercial pressure levels (1/10 of sea level), the air resistance will be 100 times higher than in a tube operated at 1/1000 of the atmospheric pressure, but only 40 percent of the drag experienced by today's commercial aircraft.

Option 4): Energy-Autonomous Capsule with a Low-Infrastructure Tube

Even though Zeleros proposes a partially self-propelled and scalable solution, Transpod is currently the only company going for a fully energy-autonomous transportation system (<https://www.transpod.com/technology-demonstrator/>). It implies very low construction costs, which means that if the technology is successful, it can further improve the profitability and affordability of the Hyperloop. Basically, this type of system configuration is also the typical system explored in the SpaceX Hyperloop competition for students. An example of such a conceptual system is shown in Figure 8. It is worth noting that SpaceX uses an I-beam track

and that Transpod does not have passive lift skies. In Transpod's technology, the linear motor is also utilized for levitation, guidance, and braking, proposing a very challenging all-in-one solution. Moreover, in order to cope with the limitations in onboard energy storage, Transpod proposes a contactless high-speed power transmission system. The proposed wireless technology takes into account the low pressure inside the tube to potentially maximize the power transmission efficiency.

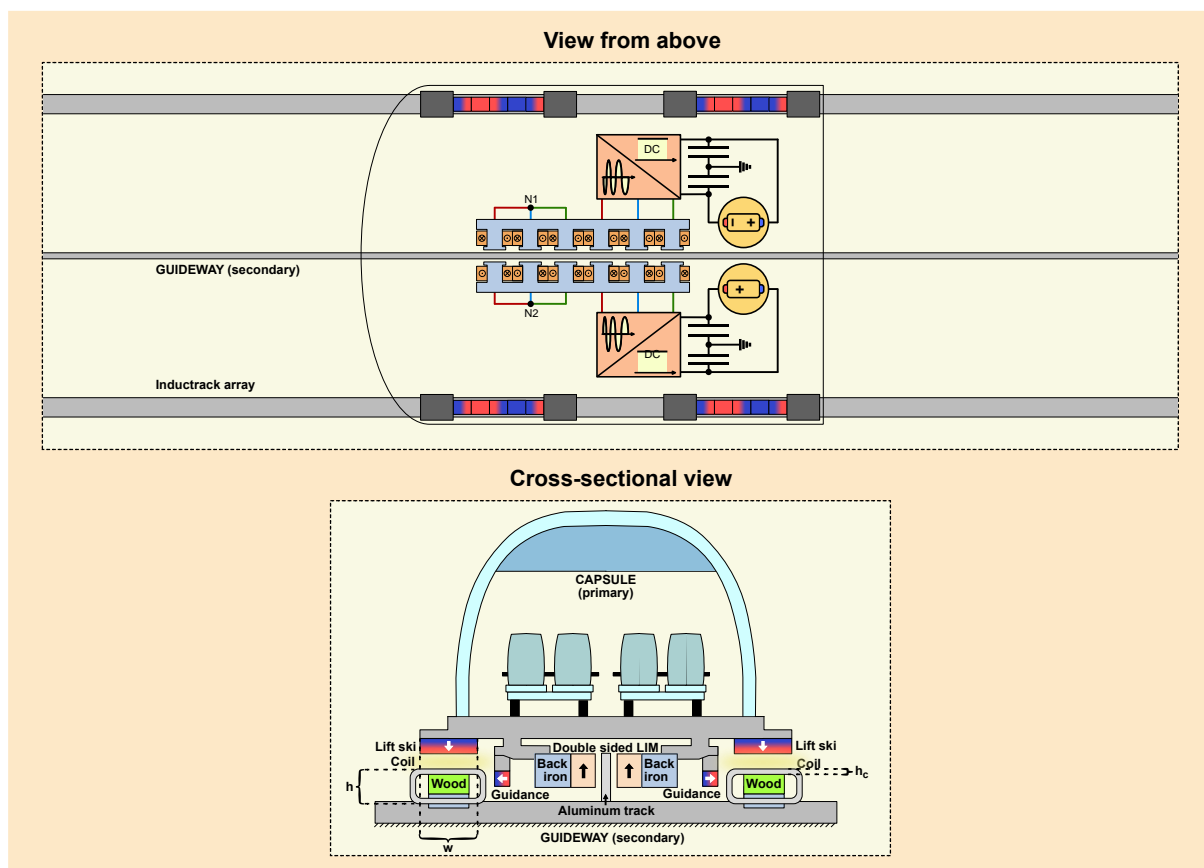


Figure 8 Figure depicts the energy-autonomous capsule solution implying low infrastructure needs and less electrification along the track. The concept is depicted in both view from above and cross-sectionally, respectively. The propulsion system is a short primary double-sided linear induction motor (SP-DS-LIM). It is primarily installed onboard the capsule, while the track is passive with no active components. The levitation is configured as a passive electro-dynamic suspension (EDS) system with auxiliary lift-off wheels and no feedback control needed. The concept refers to a similar solution as proposed by Transpod (URL: <https://www.transpod.com/technology-demonstrator/>), where the passive lift skies were omitted.

Currently, one of the most difficult issues to solve for the self-propelled system is the management of the heat losses onboard. The linear induction motor's efficiency could be as low as 70 percent during cruising, which implies that a significant portion of the inverter rating will feed losses². The white-paper from 2013 proposed an onboard water tank to absorb all the

waste heat and replace the water when it arrives at the station. Unfortunately, this type of solution will add to the total mass of the capsule. It is also difficult to throw heat waste out of the capsule and into the tube because of the lack of air density. As a result of the lack of air, the convective heat transfer is significantly reduced, and the radiation part is dominating.

A summary of the two key concepts of external and self-propulsion is provided in Table 2.

TABLE 2. Assessment of the two main Hyperloop concepts.		
Concepts	Energy-autonomous capsule with a scalable low-infrastructure tube	Large-scale tube electrification with a lightweight & externally driven capsule
Tube Infrastructure	Capsule is self-propelled - it is the best option in terms of affordability, using of few active components	Active rails with significant infrastructure cost, where active components are only utilized during a tiny fraction of the ride
Capsule weight	High – energy storage for onboard propulsion with or without contactless power transmission	Low – lightweight capsule with only onboard auxiliary energy (e.g., for controlling suspension)
Range limitation	Depends on the onboard energy reservoir or the feasibility of a wire-less power supply while moving	Unlimited as the propulsion is external but high investments and the resource intensity favor short range
Acceleration limitation	Power and energy allocated for acceleration affects the range even if regenerative braking under deacceleration is achieved	Acceleration power can be high and the distance needed for acceleration can be low, but creates power spikes for the grid

CONCLUSIONS

This article has introduced some of the most recent technology evolutions of the Hyperloop transportation system, intended to make it feasible, scalable and affordable for implementation. In particular, it can be perceived that the external propulsion enables a lightweight capsule and might have a faster technical development track to realization and commercialization. However, a self-propelled capsule configured like an airplane requires less track infrastructure and utilizes its active components during the whole journey. While its low construction costs would significantly improve the system's profitability and reduce the maintenance of the operated infrastructure, the capsule tends to get heavy when considering the onboard energy storage and thermal management system. Therefore, companies are now considering a hybrid

solution, combining external launching and self-propelled cruising, which balances the benefits and drawbacks of both variants.

In addition to the technical challenges and opportunities, there are also societal changes and policy decisions that might play a role in speeding up Hyperloop implementation. There is currently a push to ban short-haul domestic flights in Europe to accelerate the decarbonization of transport. An alternative to rail is introducing Hyperloop, which has the potential to significantly decrease the energy use per revenue passenger-kilometer when compared to aviation, and at the same time, move with similar or higher travel speed. Still, no full-scale Hyperloop transportation system has yet been demonstrated at subsonic or near-sonic speeds. However, this article tries to give more insight into where the development is going and make predictions on the future realization of this new mode of transport.

FOR FURTHER READING

[1] J. K. Nøland, "*Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review*", vol. 9, pp. 28439-28458, **IEEE Access**, Feb. 2021, URL: <https://ieeexplore.ieee.org/document/9350309>.

[2] D. Tudor & M. Paolone, "*Optimal Design of the Propulsion System of a Hyperloop Capsule*", **IEEE Transactions on Transportation Electrification**, vol. 5, no. 4, Dec. 2019, URL: <https://ieeexplore.ieee.org/document/8892514>.

[3] A. Tbaileh, et. al., "*Modeling and Impact of Hyperloop Technology on the Electricity Grid*", **IEEE Transactions on Power Systems**, vol. 99, no. PP (early access), March 2021, URL: <https://ieeexplore.ieee.org/document/9382792>.

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