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REVIEW ARTICLE

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HYPERLOOP TECHNOLOGY .THE PASSENGER TRANSPORT SYSTEM

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ABSTRACT
Present orthodox approaches of shipping of folks resides of four unique types: rail, road, water, and air. These modes of transport tend to be either relatively slow (e.g., road and water), expensive (e.g., air), or a combination of relatively slow and expensive (i.e., rail). Hyperloop is a new mode of transport that seeks to change this paradigm by being both fast and inexpensive for people and goods. Hyperloop is also unique in that it is an open design concept, similar to Linux.

Hyperloop consists of a low pressure tube with capsules that are transported at both low and high speeds throughout the length of the tube. The capsules are supported on a cushion of air, featuring pressurized air and aerodynamic lift. The capsules are accelerated via a magnetic linear accelerator affixed at various stations on the low pressure tube with rotors contained in each capsule. Passengers may enter and exit Hyperloop at stations located either at the ends of the tube, or branches along the tube length.

The system consists of capsules that travel between Los Angeles, California and San Francisco, California. The total one-way trip time is 35 minutes from county line to county line. The capsules leave on average every 2 minutes from each terminal carrying 28 people each (as often as every 30 seconds during rush hour and less frequently at night). This gives a total of 7.4 million people per tube that can be transported each year on Hyperloop. The total cost of Hyperloop is under $6 billion USD for two one-way tubes and 40 capsules. Amortizing this capital cost over 20 years and adding daily operational costs gives a total of $20 USD plus operating costs per one-way ticket on the passenger Hyperloop.

INTRODUCTION

1. Hyperloop Transportation System

Hyperloop (Figure 2 and Figure 3) is a proposed transportation system for traveling between Los Angeles, California, and San Francisco, California in 35 minutes. The Hyperloop consists of several distinct components, including:

1. Capsule:

a. Sealed capsules carrying 28 passengers each that travel along the interior of the tube depart on average every 2 minutes from Los Angeles or San

Francisco (up to every 30 seconds during peak usage hours).

b. A larger system has also been sized that allows transport of 3 full size automobiles with passengers to travel in the capsule. c. The capsules are separated within the tube by approximately 23 miles (37 km) on average during operation. d. The capsules are supported via air bearings that operate using a compressed air reservoir and aerodynamic lift.

2. Tube: a. The tube is made of steel. Two tubes will be welded together in a side-by-side configuration to allow the capsules to travel both directions. b. Pylons are placed every 100 ft (30 m) to support the tube. c. Solar arrays will cover the top of the tubes in order to provide power to the system.

3. Propulsion: a. Linear accelerators are constructed along the length of the tube at various locations to accelerate the capsules. b. Rotors are located on the capsules to transfer momentum to the capsules via the linear accelerators.

4. Route: a. There will be a station at Los Angeles and San Francisco. Several stations along the way will be possible with splits in the tube. b. The majority of the route will follow I-5 and the tube will be constructed in the median.

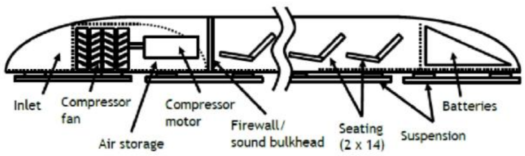

Figure 2. Hyperloop conceptual diagram.
Los Angeles, CA
San Francisco, CA

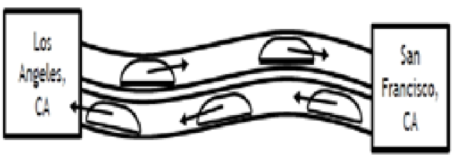

Figure 3. Hyperloop tube stretching from Los Angeles to San Francisco.

In addition to these aspects of the Hyperloop, safety and cost will also be addressed in this study.

The Hyperloop is sized to allow expansion as the network becomes increasingly popular. The capacity would be on average 840 passengers per hour which is more than sufficient to transport all of the 6 million passengers traveling between Los Angeles and San Francisco areas per year. In addition, this accounts for 70% of those travelers to use the Hyperloop during rush hour. The lower cost of traveling on Hyperloop is likely to result in increased demand, in which case the time between capsule departures could be significantly shortene

4.1. Capsule

Two versions of the Hyperloop capsules are being considered: a passenger only version and a passenger plus vehicle version.

Hyperloop Passenger Capsule

Assuming an average departure time of 2 minutes between capsules, a minimum of 28 passengers per capsule are required to meet 840 passengers per hour. It is possible to further increase the Hyperloop capacity by reducing the time between departures. The current baseline requires up to 40 capsules in activity during rush hour, 6 of which are at the terminals for loading and unloading of the passengers in approximately 5 minutes.

Hyperloop Passenger Plus Vehicle Capsule

The passenger plus vehicle version of the Hyperloop will depart as often as the passenger only version, but will accommodate 3 vehicles in addition to the passengers. All subsystems discussed in the following sections are featured on both capsules.

For travel at high speeds, the greatest power requirement is normally to overcome air resistance. Aerodynamic drag increases with the square of speed, and thus the power requirement increases with the cube of speed. For example, to travel twice as fast a vehicle must overcome four times the aerodynamic resistance, and input eight times the power.

Just as aircraft climb to high altitudes to travel through less dense air, Hyperloop encloses the capsules in a reduce pressure tube. The pressure of air in Hyperloop is about 1/6 the pressure of the atmosphere on Mars. This is anfunctioning pressure of 100 Pascals, which reduces the drag force of the air by 1,000 times relative to sea level conditions and would be equivalent to flying above 150,000 feet altitude. A hard vacuum is avoided as vacuums

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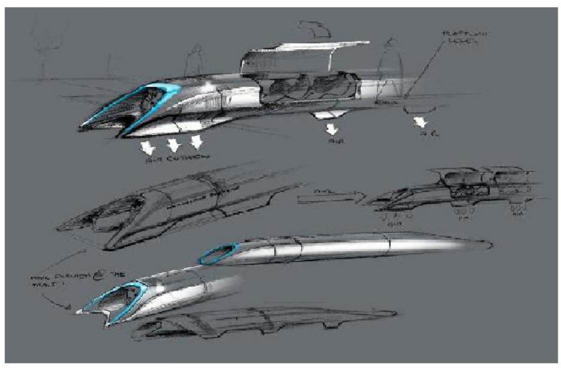
are expensive and difficult to maintain compared with low pressure solutions. Despite the low pressure, aerodynamic challenges must still be addressed. These include managing the formation of shock waves when the speed of the capsule approaches the speed of sound, and the air resistance increases sharply. Close to the cities where more turns must be navigated, capsules travel at a lower speed. This reduces the accelerations felt by the passengers, and also reduces power requirements for the capsule. The capsules travel at 760 mph (1,220 kph, Mach 0.91 at 68 ºF or 20 ºC).

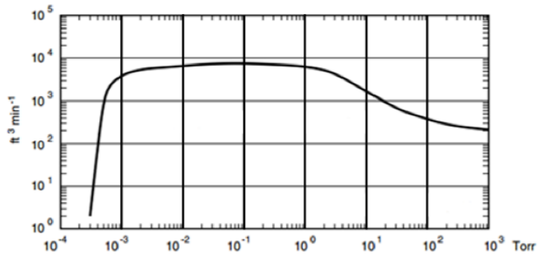
Hyperloop passenger capsule subsystem notional locations (not to scale).



Hyperloop passenger transport capsule conceptual design sketch

4.2. Tube

The main Hyperloop route consists of a partially evacuated cylindrical tube that connects the Los Angeles and San Francisco stations in a closed loop system (Figure 2). The tube is specifically sized for optimal air flow around the capsule improving performance and energy consumption at the expected travel speed. The expected pressure inside the tube will be maintained around 0.015 psi (100 Pa, 0.75 torr), which is about 1/6 the pressure on Mars. This low pressure minimizes the drag force on the capsule while maintaining the relative ease of pumping out the air from the tube. The efficiency of industrial vacuum pumps decreases exponentially as the pressure is reduced (Figure 13), so further benefits from reducing tube pressure would be offset by increased pumping complexity



Typical vacuum pump speed for functional pressure range.

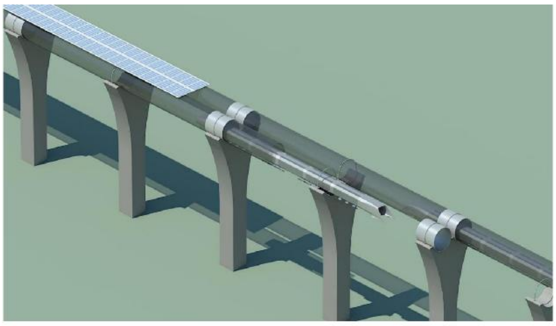
In order to minimize cost of the Hyperloop tube, it will be elevated on pillars which greatly reduce the footprint required on the ground and the size of the construction area required. Thanks to the small pillar footprint and by maintaining the route as close as possible to currently operated highways, the amount of land required for the Hyperloop is minimized. More details are available for the route in section 4.4.

The Hyperloop travel journey will feel very smooth since the capsule will be guided directly on the inner surface of the tube via the use of air bearings and suspension; this also prevents the need for costly tracks. The capsule will bank off the walls and include a control system for smooth returns to nominal capsule location from banking as well. Some specific sections of the tube will incorporate the stationary motor element (stator) which will locally guide and accelerate (or decelerate) the capsule. More details are available for the propulsion system in section 4.3. Between linear motor stations, the capsule will glide with little drag via air bearings

4.2.1. Geometry

The geometry of the tube depends on the choice of either the passenger version of Hyperloop or the passenger plus vehicles version of Hyperloop.

In either case, if the speed of the air passing through the gaps accelerates to supersonic velocities, then shock waves form. These waves limit how much air can actually get out of the way of the capsule, building up a column of air in front of its nose and increasing drag until the air pressure builds up significantly in front of the capsule. With the increased drag and additional mass of air to push, the power requirements for the capsule increase significantly. It is therefore very important to avoid shock wave formation around the capsule by careful selecting of the capsule/tube area ratio. This ensures sufficient mass air flow around and through the capsule at all operating speeds. Any air that cannot pass around the annulus between the capsule and tube is bypassed using the onboard compressor in each capsule.

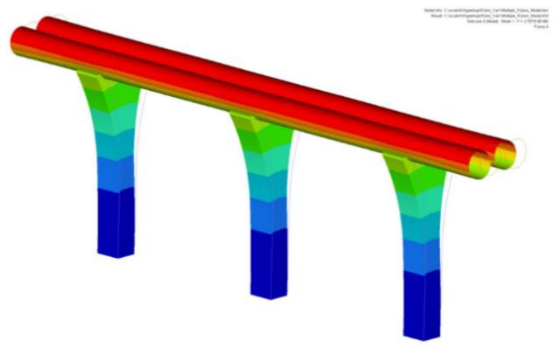


Hyperloop capsule in tube cutaway with attached solar arrays.

Passenger Hyperloop Tube

The inner diameter of the tube is optimized to be 7 ft 4 in. (2.23 m) which is small enough to keep material cost low while large enough to provide some alleviation of choked air flow around the capsule. The tube cross-sectional area is 42.2 ft2 (3.91 m2) giving a capsule/tube area ratio of 36% or a diameter ratio of 60%. It is critical to the aerodynamics of the capsule to keep this ratio as large as possible, even though the pressure in the tube is extremely low. As the capsule moves through the tube, it must displace its own volume of air, in a loosely similar way to a boat in water. The displacement of the air is constricted by the walls of the tube, which makes it accelerate to squeeze through the gaps. Any flow not displaced must be ingested by the onboard compressor of each capsule, which increases power requirements.

The closed loop tube will be mounted side by side on elevated pillars as seen in Figure 5. The surface above the tubes will be lined with solar panels to provide the required system energy. This represents a possible area of 14 ft (4.25 m) wide for more than 350 miles (563 km) of tube length. With an expected solar panel energy production of 0.015 hp/ft2 (120 W/m2), we can expect the system to produce a maximum of 382,000 hp (285 MW) at peak solar activity. This would actually be more energy than needed for the Hyperloop system and the detailed power requirements will be detailed in section 4.3.



4.3. Propulsion

The propulsion system has these basic requirements:

1. Accelerate the capsule from 0 to 300 mph (480 kph) for relatively low speed travel in urban areas. 2. Maintain the capsule at 300 mph (480 kph) as necessary, including during ascents over the mountains surrounding Los Angeles and San Francisco. 3. To accelerate the capsule from 300 to 760 mph (480 to 1,220 kph) at 1g at the beginning of the long coasting section along the I-5 corridor. 4. To decelerate the capsule back to 300 mph (480 kph) at the end of the I- 5 corridor.

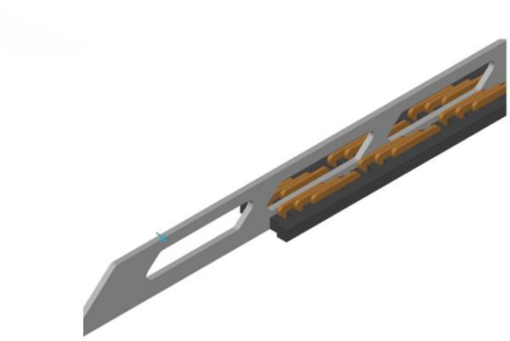
The Hyperloop as a whole is projected to consume an average of 28,000 hp (21 MW). This includes the power needed to make up for propulsion motor efficiency (including elevation changes), aerodynamic drag, charging the batteries to power on-board compressors, and vacuum pumps to keep the tube evacuated. A solar array covering the entire Hyperloop is large enough to provide an annual average of 76,000 hp (57 MW), significantly more than the Hyperloop requires.

Since the peak powers of accelerating and decelerating capsules are up to 3 times the average power, the power architecture includes a battery array at each accelerator, allowing the solar array to provide only the average power needed to run the system. Power from the grid is needed only when solar power is not available.

This section details a large linear accelerator, capable of the 300 to 760 mph (480 to 1,220 kph) acceleration at 1g. Smaller accelerators appropriate for urban areas and ascending mountain ranges can be scaled down from this system.

The Hyperloop uses a linear induction motor to accelerate and decelerate the capsule. This provides several important benefits over a permanent magnet motor:

- Lower material cost – the rotor can be a simple aluminum shape, and does not require rare-earth elements. Lighter capsule. Smaller capsule dimensions. The lateral forces exerted by the stator on the rotor though low at 0.9 lbf/ft (13 N/m) are inherently stabilizing. This simplifies the problem of keeping the rotor aligned in the air gap.



Rotor and stator 3d diagram

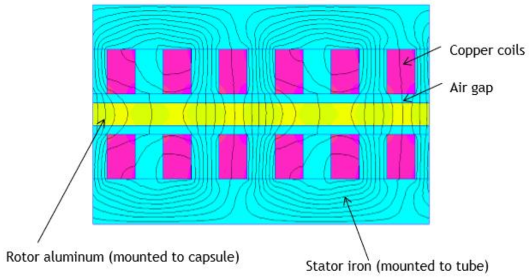
Each accelerator has two 65 MVA inverters, one to accelerate the outgoing capsule, and one to capture the energy from the incoming capsule. Inverters in the 10+ MVA power range are not unusual in mining, drives for large cargo ships, and railway traction. Moreover, 100+ MVA drives are commercially available. Inexpensive semiconductor switches allow the central inverters to energize only the section of track occupied by a capsule, improving the power factor seen by the inverters.

The inverters are physically located at the highest speed end of the track to minimize conductor cost

4.3.1. Capsule Components (Rotor)

The rotor of the linear accelerators is very simple – an aluminum blade 49 ft (15 m) long, 1.5 ft (0.45 m) tall, and 2 in. (50 mm) thick. Current flows mainly in the outer 0.4 in. (10 mm) of this blade, allowing it to be hollow to decrease weight and cost.

The gap between the rotor and the stator is 0.8 in. (20 mm) on each side. A combination of the capsule control system and electromagnetic centering forces allows the capsule to safely enter, stay within, and exit such a precise gap.



Magnetic field strength inside linear induction motor

4.3.2. Tube Components (Stator)

The stator is mounted to the bottom of the tube over the entire 2.5 miles (4.0 km) it takes to accelerate and decelerate between 300 and 760 mph (480 and 1,220 km). It is approximately 1.6 ft (0.5 m) wide (including the air gap) and 4.0 in. (10 cm) tall, and weighs 530 lb/ft (800 kg/m).

Laid out symmetrically on each side of the rotor, its electrical configuration is 3-phase, 1 slot per pole per phase, with a variable linear pitch (1.3 ft or 0.4 m maximum). The number of turns per slot also varies along the length of the stator, allowing the inverter to operate at nearly constant phase voltage, which simplifies the power electronics design. The two halves of the stator require bracing to resist the magnetic forces of 20 lbf/ft (300N/m) that try to bring them together.

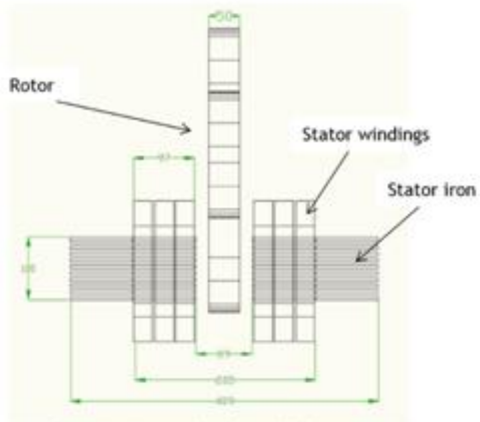


Figure Cross section of rotor inside stator

4.4. Route

The Hyperloop will be capable of traveling between Los Angeles and San Francisco inapproximately 35 minutes. This requirement tends to size other portions of the system. Given the performance specification of the Hyperloop, a route has been devised to satisfy this design requirement. The Hyperloop route should be based on several considerations, including:

1. Maintaining the tube as closely as possible to existing rights of way (e.g., following the I-5). 2. Limiting the maximum capsule speed to 760 mph (1,220 kph) for aerodynamic considerations. 3. Limiting accelerations on the passengers to 0.5g. 4. Optimizing locations of the linear motor tube sections driving the capsules. 5. Local geographical constraints, including location of urban areas, mountain ranges, reservoirs, national parks, roads, railroads, airports, etc. The route must respect existing structures.

For aerodynamic efficiency, the velocity of a capsule in the Hyperloop is typically:

- 300 mph (480 kph) where local geography necessitates a tube bend radii < 1.0 mile (1.6 km)
- 760 mph (1,220 kph) where local geography allows a tube bend > 3.0 miles (4.8 km) or where local geography permits a straight tube.

These bend radii have been calculated so that the passenger does not experience inertial accelerations that exceed 0.5g. This is deemed the maximum inertial acceleration that can be comfortably sustained by humans for short periods. To further reduce the inertial acceleration experienced by passengers, the capsule and/or tube will incorporate a mechanism that will allow a degree of 'banking'. The route has been divided into the following sections:

Los Angeles/Grapevine – South and North I-5 I-580/San Francisco Bay. The Hyperloop route was created by the authors using Google Earth

Conclusions

A high speed transportation system known as Hyperloop has been developed in this document. The work has detailed two version of the Hyperloop: a passenger only version and a passenger plus vehicle version. Hyperloop could transport people, vehicles, and freight between Los Angeles and San Francisco in 35 minutes. Transporting 7.4 million people each way and amortizing the cost of $6 billion over 20 years gives a ticket price of $20 for a one-way trip for the passenger version of Hyperloop. The passenger plus vehicle version of the Hyperloop is less than 9% of the cost of the proposed passenger only high speed rail system between Los Angeles and San Francisco.

An additional passenger plus transport version of the Hyperloop has been created that is only 25% higher in cost than the passenger only version. This version would be capable of transport passengers, vehicles, freight, etc. The passenger plus vehicle version of the Hyperloop is less than 11% of the cost of the proposed passenger only high speed rail system between Los Angeles and San Francisco. Additional technological developments and further optimization could likely reduce this price.

- Faster
- Lower cost.
- Pollution free.
- Immune to weather.
- Safer
- Sustainably self-powering.

- Resistant to Earthquakes.

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