A New Future for Hyperloop Technology

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***Abstract-* Existing conventional modes of transportation of people consists 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. Feedback is desired from the community that can help advance the Hyperloop design and bring it from concept to reality.**

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. In this report, the initial route, preliminary design, and logistics of the Hyperloop transportation system have been derived. 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.

***Index Terms-* pneumatic capsule transport, friction coefficient, mathematical simulation, accelerators, Tube transportation.**

I. INTRODUCTION

A Hyperloop is a proposed mode of passenger and or freight transportation, first used to describe an open-source vactraindesign released by a joint team from Tesla & SpaceX. Drawing heavily from Robert Goddard's vactrain, a hyperloop is a sealed tube or system of tubes through which a pod may travel free of air resistance or friction conveying people or objects at high speed while being very efficient.

The Hyperloop Alpha concept was first published in August 2013, proposing and examining a route running from the Los Angeles region to the San Francisco Bay Arearoughly following the Interstate 5 corridor. The paper conceived of a hyperloop system that would propel passengers along the 350-mile (560 km) route at a speed of 760 mph (1,200 km/h), allowing for a travel time of 35 minutes, which is considerably faster than current rail or air travel times. Preliminary cost estimates for this LA–SF suggested route were included in the white paper—US$6 billion for a passenger-only version, and US$7.5 billion for a somewhat larger-diameter version transporting passengers and vehicles[1] although transportation analysts had doubts that the system could be constructed on that budget; some analysts claimed that the Hyperloop would be several billion dollars overbudget, taking into consideration construction, development and operation costs.

The Hyperloop concept has been explicitly "open-sourced" by Musk and SpaceX, and others have been encouraged to take the ideas and further develop them. To that end, a few companies have been formed, and several interdisciplinary student-led teams are working to advance the technology. SpaceX built an approximately 1-mile-long (1.6 km) subscale track for its pod design competition at its headquarters in Hawthorne, California. Some experts are skeptical, saying that the proposals ignore the expenses and risks of developing the technology and that the idea is "completely impractical". Claims have also been made that the Hyperloop is too susceptible to disruption from a power outage or terror attacks to be considered safe.

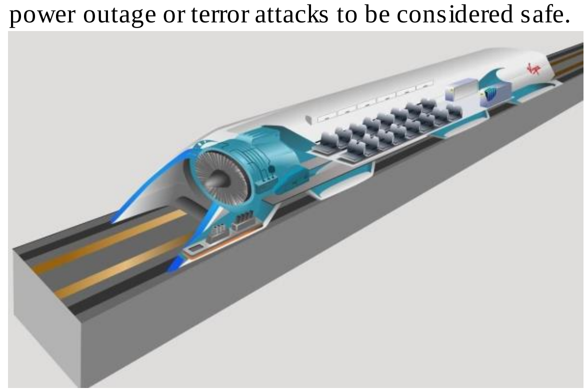

Fig.I Hyperloop

II.CONCEPT OF 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:

A. Capsule
B. Propulsion
C. Route
D. Station Locations
E. Tube

A. Capsule

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). A larger system has also been sized that allows transport of 3 full size automobiles with passengers to travel in the capsule. The capsules are separated within the tube by approximately 37 km on average during operation. The capsules are supported via air bearings that operate using a compressed air reservoir and aerodynamic lift. Two versions of the Hyperloop capsules are being considered: a passenger only version and a passenger plus vehicle version.

Hyperloop Technology 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 Technology capacity by reducing the time between departures.

The current baseline requires up to 40 capsules in activit y during rush hour, 6 of which are at the terminals for loading and unloading of the passengers in approximately 5 minutes.

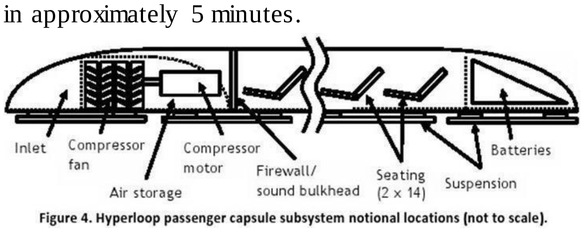

Fig.II Hyperloop passenger capsules

1. Geometry of Hyperloop passenger capsules

In order to optimize the capsule speed and performance, the frontal area has been minimized for size while maintaining passenger comfort.

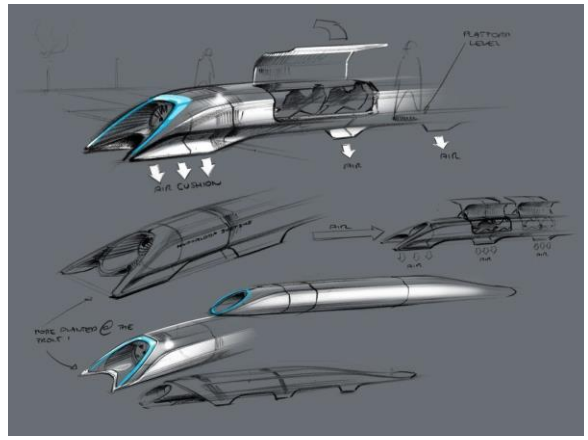

Fig. III Hyperloop passenger transport capsule conceptual design sketch.

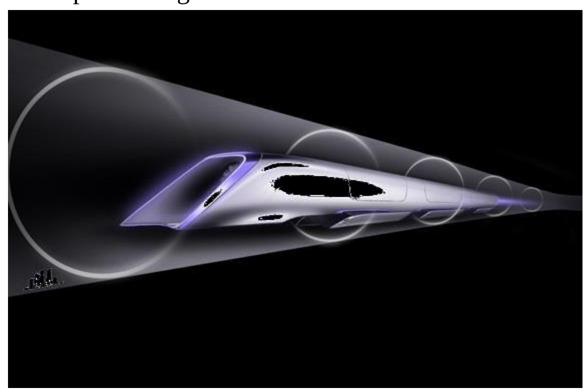

Fig. Hyperloop passenger transport capsule conceptual design rendering.

The vehicle is streamlined to reduce drag and features a compressor at the leading face to ingest oncoming air for levitation and to a lesser extent propulsion. Aerodynamic simulations have demonstrated the validity of this.

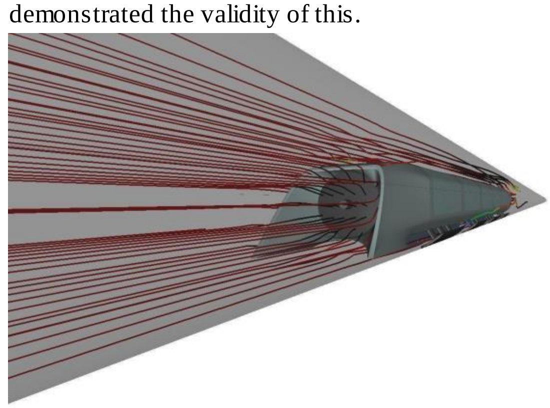

Fig. IV. Streamlines for capsule traveling at high subsonic velocities inside Hyperloop.

2. Hyperloop Passenger Capsule

The maximum width is 1.35 m and maximum height is 1.10 m. With rounded corners, this is equivalent to a 1.4 m2 frontal area, not including any propulsion or suspension components. The aerodynamic power requirements at 700 mph (1,130 mph) is around only 100 k with a drag force of only 320 N, or about the same force as the weight of one oversized checked bag at the airport. The doors on each side will open in a gullwing (or possibly sliding) manner to allow easy access during loading and unloading. The luggage compartment will be at the front or rear of the capsule. The overall structure weight is expected to be near 3,100 kg including the luggage compartments and door mechanism. The overall cost of the structure including manufacturing is targeted to be no more than $245,000.

B. Propulsion

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

The propulsion system has the following basic requirements:

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

The Hyperloop as a whole is projected to consume an average of 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 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. These arrays provide storage of excess power during non-peak periods that can be used during periods of peak usage. Power from the grid is needed only when solar power is not available. This section details a large linear accelerator, capable of the 480 to 1,220 mph 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:

a. Lower material cost – the rotor can be a simple aluminium shape, and does not require rare-earth elements.
b. Lighter capsule.
c. Smaller capsule dimensions.

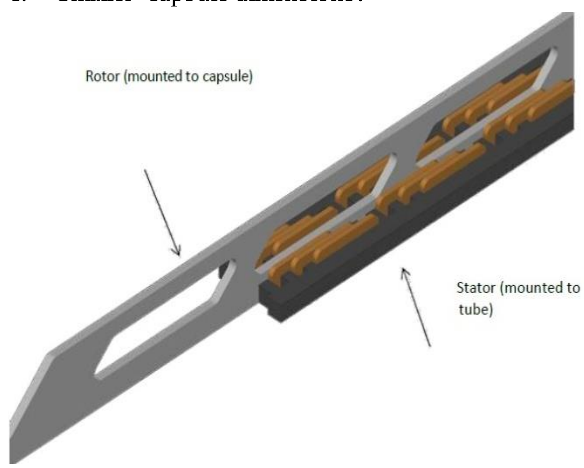

Fig. V. Rotor and Stator 3D Diagram

The lateral forces exerted by the stator on the rotor though low at 13 N/m are inherent ly stabilizing. This simplifies the problem of keeping the rotor aligned in the air gap. Each accelerator has two 70 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. Relatively 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.

C. Route

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

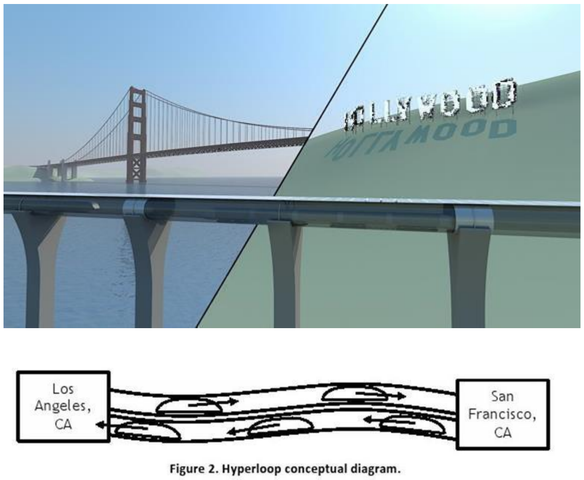

Fig.VI Route

D. Station Locations

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 shortened.

E. Tube

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. Pylons are placed every 30 m to support the tube. Solar arrays will cover the top of the tubes in order to provide power to the system. 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. 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 100 Pa, which is about 1/6 the pressure on Mars or 1/1000 the pressure on Earth. 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, so further benefits from reducing tube pressure would be offset by increased pumping complexity.

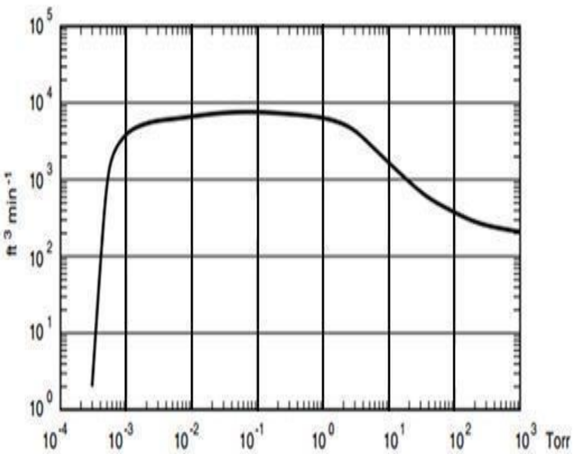

Fig.VII Pressure Graph

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.

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 3.3. Between linear motor stations, the capsule will glide with little drag via air bearings.

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.

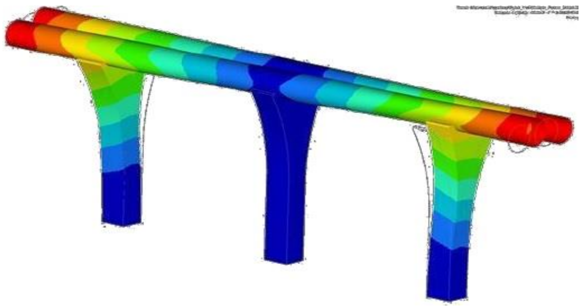

Fig. VIII. First mode shape of Hyperloop at 2.71Hz (magnified x1500)

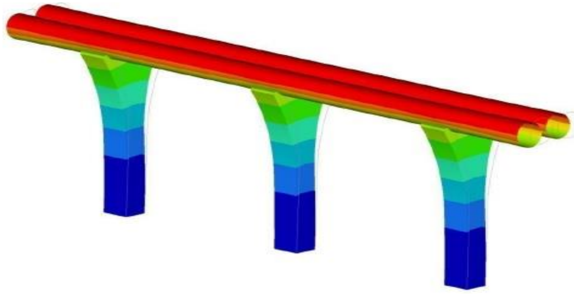

Fig. IX. Second mode shape of Hyperloop at 3.42Hz (magnified x1500)

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 selection 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.

Fig. X. Hyperloop capsule in tube cutaway with attached solar arrays

III. SAFETY AND RELIABILITY

The design of Hyperloop has been considered from the start with safety in mind. Unlike other modes of transport, Hyperloop is a single system that incorporates the vehicle, propulsion system, energy management, timing, and route. Capsules travel in a carefully controlled and maintained tube environment making the system is immune to wind, ice, fog, and rain. The propulsion system is integrated into the tube and can only accelerate the capsule to speeds that are safe in each section. With human control error and unpredictable weather removed from the system, very few safety concerns remain. Some of the safety scenarios used are unique to the proposed system, but all should be considered relative to other forms of transportation. In many cases Hyperloop is intrinsically safer than airplanes, trains, or automobiles.

IV. ADVANTAGES AND DISADVANTAGES

Advantages
1. Faster .
2. Lower cost.
3. Pollution free.
4. Immune to weather.
5. Safer
6. Sustainably self-powering.
7. Resistant to Earthquakes.

Disadvantages
1. Tube pressurization.
2. Turning will be critical (with large radius).
3. Insufficient movable space for passenger.

V. FUTURE WORK

Hyperloop is considered an open source transportation concept. The authors encourage all members of the community to contribute to the Hyperloop design process. Iteration of the design by various individuals and groups can help bring Hyperloop from an idea to a reality.

The inventors recognize the need for additional work, including but not limited to:

1. More expansion on the control mechanism for Hyperloop capsules, including attitude thruster or control moment gyros.
2. Detailed station designs with loading and unloading of both passenger and passenger plus vehicle versions of the Hyperloop capsules.
3. Trades comparing the costs and benefits of Hyperloop with more conventional magnetic levitation systems.
4. Sub-scale testing based on a further optimized design to demonstrate the physics of Hyperloop.

VI. CONCLUSION

A high speed transportation system known as Hyperloop has been developed in this report. The work has detailed two versions 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 every year 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 only 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 transporting 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.

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