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Hyperloop Design for Transportation

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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 (i.e., road and water), expensive (i.e., air), or a combination of relatively slow and expensive (i.e., rail). Hyperloop is a new mode of transport that seeks to change 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. In this study, 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 trip time is approximately half an hour, with capsules departing as often as every 30 seconds from each terminal and carrying 28 people each. This gives a total of 7.4 million people each way that can be transported each year on Hyperloop. The total cost of Hyperloop in this analysis is under $6 billion USD. Amortizing this capital cost over 20 years and adding daily operational costs gives a total of about $20 USD (in current year dollars) plus operating costs per one-way ticket on the passenger Hyperloop.

Key words: Hyperloop, Design, Transportation etc

I. Introduction

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.

Hyperloop is a proposed transportation system for traveling between Los Angeles, California, and San Francisco, California in 35 minutes.

A new high speed mode of transport is desired between Los Angeles and San Francisco; however, the proposed California High Speed Rail does not reduce current trip times or reduce costs relative to existing modes of transport. This preliminary design study proposes a new mode of high speed transport that reduces both the travel time and travel cost between Los Angeles and San Francisco. Options are also included to increase the transportation system to other major population centers across California. It is also worth noting the energy cost of this system is less than any currently existing mode of transport. The only system that comes close to matching the low energy requirements of Hyperloop is the fully electric Tesla Model S.

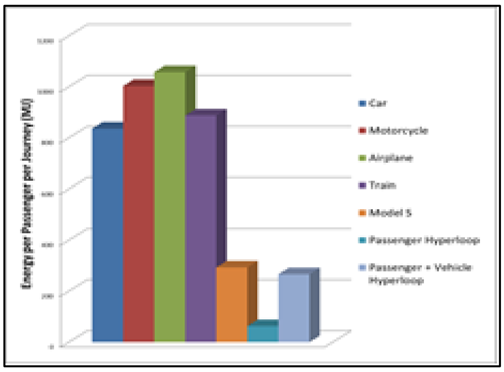

Fig. 1: Energy cost per passenger for a journey between Los Angeles and San Francisco for various modes of transport.

II. The Hyper Loop

The Hyperloop consists of several distinct components, including:

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 23 miles (37 km) on average during operation.
- The capsules are supported via air bearings that operate using a compressed air reservoir and aerodynamic lift.

B. *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 100 ft (30 m) to support the tube.
- Solar arrays will cover the top of the tubes in order to provide power to the system.

C. *Propulsion*

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

D. *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.

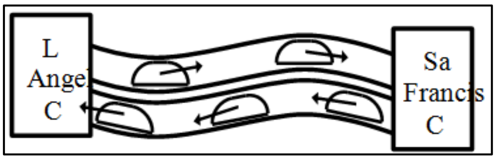

Fig. 2: Hyperloop

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 840 passengers per hour which 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.

III. Capsule

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

A. *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.

B. *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 an operating 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 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).

The proposed capsule geometry houses several distinct systems to reside within the outer mold line .

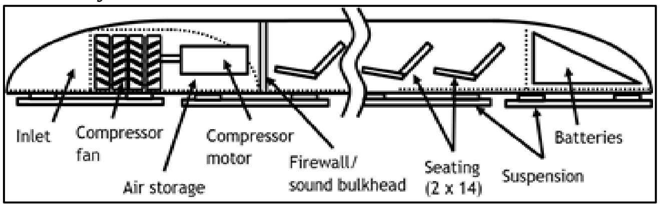

Fig. 3: Hyperloop passenger capsule subsystem national locations (not to scale)

IV. Geometry

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

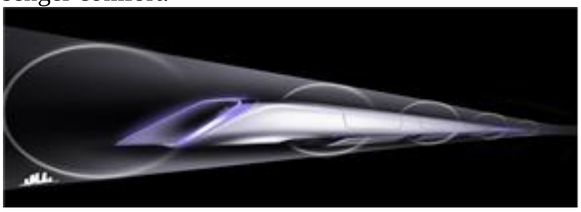
Fig. 4: Hyper loop passenger transport capsule conceptual design rendering.

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 'compressor within a tube' concept.

A. *Hyperloop Passenger Capsule*

The maximum width is 4.43ft (1.35 m) and maximum height is 6.11ft (1.10m). With rounded corners, this is equivalent to a 15 ft2 (1.4 m2) frontal area, not including any propulsion or suspension components.

The aerodynamic power requirements at 700 mph (1,130kph) is around only 134hp (100 kW) with a drag force of only 72lbf (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.

B. *Hyper loop Passenger plus Vehicle Capsule*

The passenger plus vehicle version of the Hyperloop capsule has an increased frontal area of 43 ft2 (4.0 m2), not including any propulsion or suspension components. This accounts for enough width to fit a vehicle as large as the Tesla Model X.

The aerodynamic power requirement at 700 mph (1,130kph) is around only 382hp (285 kW) with a drag force of 205lbf (910 N). The doors on each side will open in a gullwing (or possibly sliding) manner to allow accommodate loading of vehicles, passengers, or freight.

The overall structure weight is expected to be near 7,700 lb (3,500 kg) including the luggage compartments and door mechanism. The overall cost of the structure including manufacturing is targeted to be no more than $275,000.

V. INTERIOR

The interior of the capsule is specifically designed with passenger safety and comfort in mind. The seats conform well to the body to maintain comfort during the high speed accelerations experienced during travel. Beautiful landscape will be displayed in the cabin and each passenger will have access their own personal entertainment system.

A. Hyperloop Passenger Capsule

The Hyperloop passenger capsule (Figure 8 and Figure 9) overall interior weight is expected to be near 5,500 lb (2,500 kg) including the seats, restraint systems, Interior and door panels, luggage compartments, and entertainment displays. The overall cost of the interior components is targeted to be no more than $255,000.

Fig. 5: Hyperloop passenger capsule version with doors open at the station.

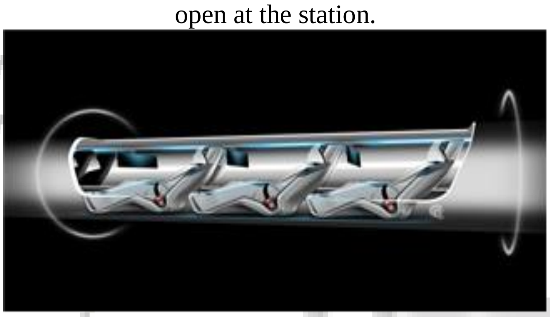

Fig. 6: Hyperloop passenger capsule version cutaway with passengers onboard.

VI. COMPRESSOR

One important feature of the capsule is the onboard compressor, which serves two purposes. This system allows the capsule to traverse the relatively narrow tube without choking flow that travels between the capsule and the tube walls (resulting in a build-up of air mass in front of the capsule and increasing the drag) by compressing air that is bypassed through the capsule. It also supplies air to air bearings that support the weight of the capsule throughout the journey.

A. Hyperloop Passenger Capsule

1) Tube air is compressed with a compression ratio of 20:1 via an axial compressor.
2) Up to 60% of this air is bypassed:
- The air travels via a narrow tube near bottom of the capsule to the tail.
- A nozzle at the tail expands the flow generating thrust to mitigate some of the small amounts of aerodynamic and bearing drag.
3) Up to 0.44 lb/s (0.2 kg/s) of air is cooled and compressed an additional 5.2:1 for the passenger version with additional cooling afterward.
- This air is stored in onboard composite overwrap pressure vessels.
- The stored air is eventually consumed by the air bearings to maintain distance between the capsule and tube walls.
4) An onboard water tank is used for cooling of the air.
- Water is pumped at 0.30 lb/s (0.14 kg/s) through two intercoolers (639 lb or 290 kg total mass of coolant).
- The steam is stored onboard until reaching the station.
- Water and steam tanks are changed automatically at each stop.
5) The compressor is powered by a 436 hp (325 kW) onboard electric motor
- The motor has an estimated mass of 372 lb (169 kg), which includes power electronics.
6) An Up to 85% of this air is bypassed:
- The air travels via a narrow tube near bottom of the capsule to the tail.
- A nozzle at the tail expands the flow generating thrust to mitigate some of the small amounts of aerodynamic and bearing drag.
7) Up to 0.44 lb/s (0.2 kg/s) of air is cooled and compressed an additional 6.2:1 for the passenger plus vehicle version with additional cooling afterward.
- This air is stored in onboard composite overwrap pressure vessels.
- The stored air is eventually consumed by the air bearings to maintain distance between the capsule and tube walls.
8) An onboard water tank is used for cooling of the air.
- Water is pumped at 0.86 lb/s (0.39 kg/s) through two intercoolers (1,800 lb or 818 kg total mass of coolant).
- The steam is stored onboard until reaching the station.
- Water and steam tanks are changed automatically at each stop.
9) The compressor is powered by a 1,160 hp(865 kW) onboard electric motor:
- The motor has an estimated mass of 606 lb (275 kg), which includes power electronics.
- An estimated 8,900 lb (4,000 kg) of batteries provides 45 minutes of onboard compressor power, which is more than sufficient for the travel time with added reserve backup power.
- Onboard batteries are changed at each stop and charged at the stations.

Suspending the capsule within the tube presents a substantial technical challenge due to transonic cruising velocities. Conventional wheel and axle systems become impractical at high speed due frictional losses and dynamic instability. A viable technical solution is magnetic levitation;

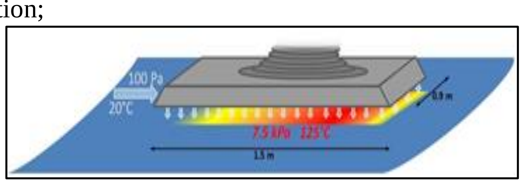

Fig. 7: Schematic of air bearing skis that support the capsule.

Externally pressurized and aerodynamic air bearings are well suited for the Hyperloop due to exceptionally high stiffness, which is required to maintain stability at high speeds. When the gap height between a ski and the tube wall is reduced, the flow field in the gap exhibits a highly non-linear reaction resulting in large restoring pressures. The increased pressure pushes the ski away from the wall, allowing it to return to its nominal ride height. While a stiff air bearing suspension is superb for reliability and safety, it could create considerable discomfort for passengers onboard. To account for this, each ski is integrated into an independent mechanical suspension, ensuring a smooth ride for passengers. The capsule may also include traditional deployable wheels similar to aircraft landing gear for ease of movement at speeds under 100 mph (160 kph) and as a component of the overall safety system.

B. Hyperloop Passenger Capsule

Hyperloop capsules will float above the tube's surface on an array of 28 air bearing skis that are geometrically conformed to the tube walls. The skis, each 4.9 ft (1.5 meters) in length and 3.0 ft (0.9 meters) in width, support the weight of the capsule by floating on a pressurized cushion of air 0.020 to 0.050 in. (0.5 to 1.3 mm) off the ground. Peak pressures beneath the skis need only reach 1.4 psi (9.4 kPa) to support the passenger capsule (9% of sea level atmospheric pressure). The skis depend on two mechanisms to pressurize the thin air film: external pressurization and aerodynamics.

The aerodynamic method of generating pressure under the air bearings becomes appreciable at moderate to high capsule speeds. As the capsule accelerates up to cruising speed, the front tip of each ski is elevated relative to the back tip such that the ski rests at a slight angle of 0.05º. Viscous forces trap a thin film of air in the converging gap between the ski and the tube wall. The air beneath the ski becomes pressurized which alters the flow field to satisfy fundamental laws of mass, momentum, and energy conservation. The resultant elevated pressure beneath the ski relative to the ambient atmosphere provides a net lifting force that is sufficient to support a portion of the capsule's weight.

However, the pressure field generated by aerodynamics is not sufficient to support the entire weight of the vehicle. At lower speeds, very little lift can be generated by aerodynamic mechanisms. Temperature and density in the fluid film begin to rise more rapidly than pressure at high speeds, thus lift ceases to increase as the capsule accelerates into the transonic regime.

Lift is supplemented by injecting highly pressurized air into the gap. By applying an externally supplied pressure, a favorable pressure distribution is established beneath the bearing and sufficient lift is generated to support the capsule. This system is known as an external pressure (EP) bearing and it is effective when the capsule is stationary or moving at very high speeds. At nominal weight and g-loading, a capsule on the Hyperloop will require air injection beneath the ski at a rate of 0.44 lb/s (0.2 kg/s) at 1.4 psi (9.4 kPa) for the passenger capsule. The air is introduced via a network of grooves in the bearing's bottom surface and is sourced directly from the high pressure air reservoir onboard the capsule.

The aerodynamically and externally pressurized film beneath the skis will generate a drag force on the capsule. The drag may be computed by recognizing that fluid velocity in the flow field is driven by both the motion of the tube wall relative to the ski and by a pressure gradient, which is typically referred to as a Couette-Poiseuille flow.

VII. COST

The overall cost of the Hyperloop passenger capsule version (Table 1) is expected to be under $1.35 million USD including manufacturing and assembly cost. With 40 capsules required for the expected demand, the total cost of capsules for the Hyperloop system should be no more than $54 million USD or approximately 1% of the total budget.

Although the overall cost of the project would be higher, we have also detailed the expected cost of a larger capsule (Table 2) which could carry not only passengers but cargo and cars/SUVs as well. The frontal area of the capsule would have to be increased to 43 ft2 (4 m2) and the tube diameter would be increased to 10 ft 10 in. (3.3 m).

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 for Hyperloop:	$ 54,000,000	

Table 1: Crew capsule weight and cost breakdown

Vehicle Component	Cost ($)	Weight (kg)
Capsule Structure & Doors:	$ 275,000	3500
Interior & Seats:	$ 185,000	2700
Propulsion System:	$ 80,000	800
Suspension & Air Bearings:	$ 265,000	1300
Batteries, Motor & Coolant:	$ 200,000	5500
Air Compressor:	$ 300,000	2500
Emergency Braking:	$ 70,000	800
General Assembly:	$ 150,000	N/A
Passengers & Luggage:	N/A	1400
Car & Cargo:	N/A	7500

Table 2: Cargo and crew capsule weight and cost breakdown

Total/Capsule:	$ 1,525,000	26000
Total for Hyperloop:	$ 61,000,000	

Table 3: Total Cargo and crew capsule

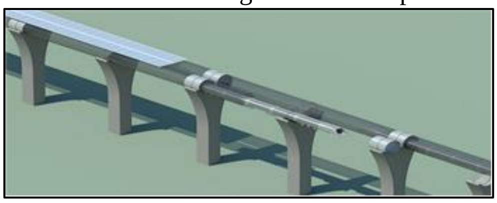

Fig. 8: Hyperloop capsule in tube cutaway with attached solar arrays.

VIII. 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.

The intent of this document has been to create a new open source form of transportation that could revolutionize travel. The authors welcome feedback and will incorporate it into future revisions of the Hyperloop project, following other open source models such as Linux