U.S. DEPARTMENT OF ENERGY

Effect of Hyperloop Technologies on the Electric Grid and Transportation Energy

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Executive Summary

Hyperloop technology, initially proposed in 2013 as an innovative means for intermediate-range or intercity travel, is now being developed by several companies. Proponents point to potential benefits for both passenger travel and freight transport, including time-savings, convenience, quality of service and, in some cases, increased energy efficiency. Because the system is powered by electricity, its interface with the grid may require strategies that include energy storage. The added infrastructure, in some cases, may present opportunities for grid-wide system benefits from integrating hyperloop systems with variable energy resources.

DOE's analysis of potential grid and energy efficiency impacts is based on conceptual data, as drawn from open sources or made available by developers, and on transportation energy use data. DOE relied, additionally, on studies of hyperloop systems by the National Aeronautics and Space Administration, Volpe Transportation Center, and U.S. Department of Transportation. Modeling of grid impacts was carried out by DOE's Pacific Northwest National Laboratory, utilizing electrical grid representations in three areas of the United States.

Consistent with information found in concept papers, DOE's analysis assumed that a typical travel distance for a hyperloop system would lie within an "intercity" range, that is, between 100 to 1,000 miles. Data indicate that energy use in the intercity market represents about 30 percent of total transportation energy use in the United States.

<u>Potential Effects on the Electric Grid</u>

DOE's modeling found that the energy and power demands of an operational hyperloop system would be significant. The electrical energy required to support one moderately sized hyperloop system over a 24-hour period might be in the range of 500 to 600 MWh/day for passenger travel; and up to 1,900 MWh/day for heavier freight. Peak power demand might be in the range of 100 to 600 MW for passenger systems and up to 2,000 MW for heavier freight systems.

While the amount of energy required would be significant, it would likely fall within the operational capacities of most power generating and transmission networks. For hyperloop systems connected directly to the grid, however, the fluctuating power dynamics could present serious challenges for grid integration. DOE modeling found that the power factor, magnitude, short duration, frequency, and number of power pulses per day, both *from* the grid (for pod launch and acceleration) and *back to* the grid (during periods of regenerative braking), would induce unusual stresses throughout the grid. These stresses, if sustained over time, would adversely impact electrical generating and transmission equipment, power quality, and long-term system maintenance and reliability, with implications for regional grid stability. Such impacts would need to be mitigated by buffering technology or by alternative designs. DOE is aware of innovative designs and technologies that address these issues (see Section II).

Potential Effects on Transportation Energy Demand

DOE's analysis found that hyperloop transport of *passengers*, in selected cases, could save energy by up to 20 percent, compared to passenger travel by other modes, such as air or personal travel in light duty vehicles, as measured in terms of energy used per passenger-mile, and when compared to the average fleet efficiency projected to 2030. Such energy savings would be less, if compared to today's "best in class" vehicles, or to a future fleet with higher vehicle utilization (*i.e.*, passengers/vehicle) factors.

DOE considered a hypothetical case of one 300-mile hyperloop passenger system, carrying 15,000 passengers per day, which derived its travel demand by modal shift from a mix of air, rail, and road traffic. The annual energy savings were estimated to be about 2.8 trillion Btu in 2030, or about 0.01 percent of national transportation energy demand.

The extent to which such savings might be scalable from one exemplar system to a national network, however, would depend on hyperloop's ability to deploy widely and capture significant shares of its respective markets. DOE's analysis assumed varying levels of intercity network penetration from 1 system up to 1,000 systems, with hypothetical energy savings estimates. Passenger travel in the intercity range of 100 to 1,000 miles is limited. Some intercity routes exhibit high traffic volumes and others much less. Energy savings on a national scale would be expected to be proportionate to the extent of deployment, which may itself be limited by intercity travel volumes. Alternatively, if such systems were able to create significant added or induced travel demand, overall energy system use might increase, not decrease.

The analysis shows that hyperloop transport of *freight* would be less energy-efficient per ton-mile shipped than all other modes of freight transport, except for air. In the case of heavier freight transport, DOE estimates that hyperloop systems would be at least 8 times less energy-efficient than transport by water and rail, in terms of energy used per ton-mile shipped; and at least 3 times less energy-efficient than transport by truck. In the case of lighter freight, such as by air, energy savings from modal shift would be limited by the total energy used for air freight traveling in the intercity range, which is estimated to be less than 50 trillion BTU per year, or less than 0.5 percent of national transportation energy use. Scenarios that allocate all forms of higher-value freight to hyperloop, however, including non-air modes of shipping, such as by truck, indicate an *increase* in energy use of around 1 percent of total transportation energy demand, due to loss of energy efficiency per-ton-mile compared to shipment by trucks.

Apart from energy, hyperloop literature suggests that an array of potential benefits may be realized from fully operational hyperloop systems for passenger travel and shipping of freight. These may include economic benefits, environmental factors, reduced congestion, time-savings, grid complementarities, or induced demand. This analysis focused on energy and the grid. No overall net benefit calculation was attempted.

Acronyms and Abbreviations

BTU	British Thermal Unit
DOE	Department of Energy
EI	Eastern Interconnect
EIA	U.S. Energy Information Administration
ERCOT	Electric Reliability Council of Texas
G	Gravitational acceleration rate (9.8 meters/second/second)
GW	Gigawatt
HTT	Hyperloop Transportation Technologies
Hz	Hertz
kV	Kilovolt
mph	Miles per Hour
MVA	Mega volt amp
MW	Megawatt
MWh	Megawatt-hour
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Corporation
PJM	Regional transmission organization that coordinates movement of wholesale electricity in all of parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia
pu	per unit (dimensionless)
quad	Quadrillion (10^{15}) Btu
RMRG	Rocky Mountain Reserve Group
TBtu	Trillion (10^{12}) Btu
STATCOM	Static synchronous compensator
UAE	United Arab Emirates
VAR	Volt-ampere reactive
WECC	Western Electricity Coordinating Council

EFFECT OF HYPERLOOP TECHNOLOGIES ON ELECTRIC GRID AND TRANSPORTATION ENERGY

Table of Contents

I. Purpose of Report

In 2018, motivated in part by growing interest in advanced and novel approaches to intercity transportation modes, the U.S. Department of Energy undertook a study of the energy-related aspects of "hyperloop transportation systems". Such systems are seen as having the potential to increase the energy efficiency of the Nation's transportation system.

The study was framed to: (a) model the demands on the electric grid, and the overall energy consumption of the transportation sector, of varying levels of network penetration of an interconnected hyperloop system; (b) include information about how these systems could be integrated into the electric grid; and (c) identify any technological constraints of the grid that must be addressed to allow the broad adoption of hyperloop technologies. This report lays out the assumptions, methodologies and quantitative results of the research, modeling and analysis and summarizes the study's major findings.

II. What is Hyperloop?

The term "hyperloop" is applied broadly to a category of fixed-guideway surface transportation systems that use capsules or "pods" that travel at high speeds (potentially nearing the speed of sound) in a sealed tube at partial or near-complete vacuum.[1] Most conceptual designs envision the use of magnetic levitation for lifting and guiding the pods and linear electric motors for acceleration and braking. Such concepts eliminate the need for rails and wheels, except near stations and stops, and minimize energy losses due to air resistance, heat and friction.

Figure 1. Broad Hyperloop Concept (Energetics)

Such a hyperloop concept is being offered as a convenient, faster and potentially more energy-efficient means of travel or freight transport than existing modes of air, rail, or road transport. It typically focuses on connecting pairs of cities, as shown conceptually in Figure 1, but could apply to intracity movement, such as to and from a downtown location to an airport or be expanded to a regional network of transportation guideways.

[1] "Hyperloop Commercial Feasibility Analysis: High Level Overview," U.S. Department of Transportation, 2016, https://rosap.ntl.bts.gov/view/dot/12308. Air pressure inside the tube could be as low as 1/100th atmosphere.

Hyperloop History

The basic concept of evacuated tube-based transportation is not new. An initial prototype of such a system was demonstrated at Tomsk Polytechnic University in 1909.[2,3] Robert Goddard, well-known as a pioneer in rocket design and by extension space exploration, proposed and patented a concept with features like those of the hyperloop concept. It involved a tunnel guideway evacuated by vacuum pumps and vehicles levitated by magnets.[4]

Modern researchers continue to work on “evacuated tube transport technologies,” generically noted as “ET3.” Although not studied here, some are targeting international travel systems that might travel over 4,000 miles per hour.[5]

Public interest in such systems was renewed in 2013 with the publication of a concept paper by Elon Musk through SpaceX.[6] Known generally as “Hyperloop Alpha,” the paper presented an overview of the modern incarnation of the Goddard concept. It is a transport system based on modestly-sized pods, each with a carrying capacity of 20-30 passengers, driven by linear electric motors and traveling in a steel tube that has been mostly evacuated of air by vacuum pumps. The paper also introduced some of the major challenges facing widespread implementation of such a system. An initial design sketch of the passenger pod from this 2013 paper is shown in Figure 2.

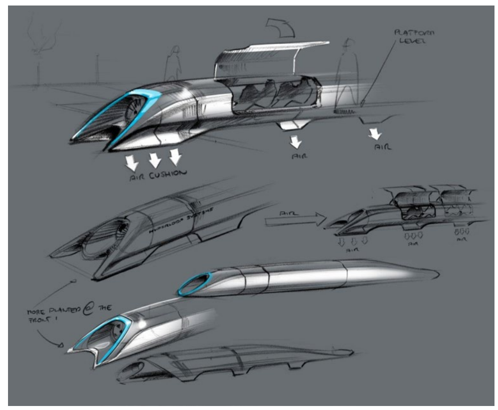

Figure 2. Initial SpaceX Concept for Hyperloop Pod (SpaceX, 2013)

After the 2013 concept paper, SpaceX sponsored a series of competitions to “support the development of functional prototypes and encourage innovation by challenging student teams to design and build the best high-speed Pod.”[7] Several teams competed in these events and demonstrated speeds of up to 290 miles per hour for small-scale pods.[8]

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[2] B. Weinberg, [Motion without friction. pre-α] (in Russian), 1914.

[3] Weinberg, Boris. “Five Hundred Miles an Hour.” Popular Science Monthly, 1917. http://www.et3.com.cn/VTT%20Record/191901-500%20miles%20an%20hour-Boris%20Weinberg-popular%20science%20monthly%201919.pdf.

[4] Goddard, Esther C. Vacuum tube transportation system. United States US2511979A, filed May 21, 1945, and issued June 20, 1950. https://patents.google.com/patent/US2511979A/en.

[5] Oster, Daryl, Masayuki Kumada, and Yaoping Zhang. “Evacuated Tube Transport Technologies (ET3): A Maximum Value Global Transportation Network for Passengers and Cargo.” Journal of Modern Transportation 19, no. 1 (March 2011): 42–50. https://doi.org/10.1007/BF03325739.

[6] Hyperloop Alpha concept paper, SpaceX, 2013, https://www.spacex.com/hyperloopalpha.

[7] SpaceX Hyperloop website, 2018, https://www.spacex.com/hyperloop.

[8] “Students from Germany win third SpaceX Hyperloop Pod Competition,” Washington Post, July 23, 2018, https://www.washingtonpost.com/technology/2018/07/23/students-germany-win-third-spacex-hyperloop-pod-competition/.

Potential Benefits of Hyperloop Technology

As broadly proposed, a main benefit of hyperloop transportation would be to enable faster, safer, more convenient, more energy efficient, and potentially cheaper transit between two points, as compared to existing modes of transport. If such systems were to capture a significant share of the transport market, they might also alleviate congestion on roads, rails and in the air.

Several factors are projected to allow hyperloop technology to increase convenience and reduce travel times between pairs of cities. A key factor is the high speed enabled by the system design – speeds of up to 700 miles per hour during cruise. This is much faster than automotive or rail systems, and rivals or exceeds air travel speeds. Another factor is location and ease of access. An ideal hyperloop system is envisioned to board locally and conveniently, to reduce travel time relative to air travel by eliminating or greatly reducing time spent at either end of the journey. This would include traveling to and from a point of embarkation, such as an airport, waiting for a plane to push back, taxi and takeoff, land, and other delays. Also, a hyperloop system may provide flexible, timely, and demand-based departure scheduling.

Hyperloop proponents also propose to limit the number of intermediate stops between the origin and destination. This offers another opportunity for time savings relative to other surface modes of transport such as high-speed rail. The original Hyperloop Alpha concept paper envisioned time savings as being the greatest for city pairs that are separated by 900 miles or less.[9] The paper suggested that in the future supersonic air travel (at higher speeds than current commercial air travel) might be more time-efficient for distances beyond 900 miles. Depending on the logistics of ticketing and passenger/luggage transfers, there may also be other time savings.[10]

Convenience is another potential benefit for hyperloop passengers. As described, passenger hyperloop systems would dispatch modestly-sized pods of 20-30 people with relatively high frequency, that is, with a pod launched every two minutes or less.[11] Compared to a high-speed train, with its rail cars all connected, hyperloop systems also have flexibility to move pods in cohorts like rail, or independently by routing them along the way to multiple destinations.

As alluded to earlier, an ancillary urban benefit, if there were to be significant use of hyperloop systems for intercity travel, might be reduced traffic congestion by reducing trips made by private vehicles on interconnecting highways, bypass roadways, and circumferential beltways between and around cities. Frequent hyperloop service might also attract travel from shorter

[9] SpaceX, 2013.

[10] SpaceX, 2013.

[11] Average headway for the New York City subway system is between 2.5 and 3 minutes according to 2017 data from the National Transit Database.

regional airline flights, thus relieving pressure on hub airports where it is expected that travel volume will increase in the future.[12]

Hyperloop technology is also envisioned to achieve improved energy efficiency compared to conventional modes of transport. Aerodynamic losses associated with pod travel will be lower compared to other modes because of the evacuated tube (with low air pressure and resulting low air resistance). Each pod may be able to coast with little additional power for a significant portion of the overall length of the trip. Energy input to pod motion will be required for initial acceleration and for periodic speed boosts during cruise. Regenerative braking, however, may capture a significant portion of the pod's kinetic energy at the end of each trip. If captured and stored, such energy could be re-used within the system or transferred to the grid for use elsewhere.

Depending on application and design, there may be other system-wide energy benefits. The power needed to run the vacuum pumps and some portion of the pod transport could be supplied by distributed energy resources, reducing demand for power from the electricity grid. Reductions in energy use from increased efficiency and the substitution of electricity for propulsion for petroleum-based fuels for cars, trucks, buses, rail and air, could result in reduced reliance on oil imports and in reduced emissions of criteria air pollutants and greenhouse gases. The latter would depend on the emissions profile of the electricity generating sources providing the power.

DOE review of concepts did not include economic analysis of various hyperloop system proposals. For added context, some potential economic benefits for hyperloop riders are noted here, as proffered by proponents. Some estimate that ticket prices for hyperloop transport would be relatively low. The Hyperloop Alpha concept paper estimated ticket prices of $20 for a one-way ticket between Los Angeles and San Francisco.[13] Such a ticket price would depend on several factors, many of which are uncertain. These include, among other things, the cost of financing, the costs of rights-of-way and construction per mile, the extent of tunneling versus surface or elevated guideways, the anticipated passenger volume, size of the pod fleet and frequency of pod departures, the continued development of advanced technology, including that required to sustain high vacuum along the long route and the potential for, if any, offsetting public financial support.

Hyperloop developers have also suggested the system could serve as a competitive alternative to traditional freight transportation modes of air, truck, or rail. Reduced travel time, lower cost, and increased schedule flexibility could attract shippers of high-value or time-sensitive freight.

[12] Schafer, Andreas, and David G Victor. "The Future Mobility of the World Population." Transportation Research Part A: Policy and Practice 34, no. 3 (April 1, 2000): 171–205. https://doi.org/10.1016/S0965-8564(98)00071-8.

[13] SpaceX, 2013.

Challenges with Hyperloop Technology

Although there are several potential benefits of hyperloop systems, there are challenges as well. In addition to those noted above, these include pod manufacturing and purchasing of supporting equipment at scale; costs are largely unknown and could be potentially high. The Hyperloop Alpha authors estimated costs of around $16 million per mile for a passenger system. Others have estimated costs of $25-27 million per mile.[14] By comparison, the cost of a rural, undivided, 2-lane paved road typically costs around $2-4 million per mile.[15] The estimated cost of the California high-speed rail plan was recently revised to nearly $150 million per mile.[16] Hyperloop costs would be dependent on whether the transport tubes are built above or below ground, as tunneling would increase the costs for construction, and where the system is located, due to wide variability in surface land and right-of-way costs and subsurface geology. The high speeds also place constraints on turning radii of the guideway curvatures, which may dictate more expensive access to right of ways.

Time savings for a complete trip between two cities will depend to some extent on the location of the hyperloop station within the cities. If the hyperloop station is far from the ultimate destinations of passengers, the first-mile/last-mile transit times may offset the time-saving advantages of hyperloop.

Safety is a critical aspect of any hyperloop system, particularly given the high speeds and near-vacuum conditions of the tubes. Hazard situations, such as a stopped transport pod in the tube, could be alerted by network connectivity among pods and signal approaching pods to begin emergency braking. Headways between pods, or between platoons of pods traveling together, would be designed to provide enough braking distance.[17] Rapid depressurization of capsules or a significant vacuum leak in the transport tubes could be potentially addressed in manners like commercial aircraft. Traveling in an evacuated tube, at 1/1000th atmospheric pressure (*i.e.*, equivalent to flying at 200,000 feet above sea level) would require safety measures to counter leaks or ruptures.

Such situations highlight the importance of safety, as well as the potential vulnerabilities of a hyperloop system, where a single point of failure or the stoppage of any one pod might require the entire system upstream of the stopped pod to be shut down.[18] Given the mass and velocity of the pods, which are traveling over 500 mph, attention may also be drawn to a pod's high level of kinetic energy. This may raise safety concerns, due to the proximity of parts of the system to population centers.

[14] "Hyperloop: Cutting through the hype," Roseline Walker, TRL, June 2018.

[15] Plan Hillsborough. "Cost Estimating Methodology: Transportation Capacity Projects," November 2014.

[16] "California to Scale Back $77 Billion High-Speed Rail Project: Governor." Reuters, February 13, 2019. https://www.reuters.com/article/us-california-governor-rail-idUSKCN1Q12II.

[17] SpaceX, 2013.

[18] TRL, 2018.

Closely associated with safety is the security of the system and its associated risks. At the early conceptual and hardware proof-of-concept stage of development, it is unclear what level of transportation security would be required. It could be comparable to that of commercial air travel or perhaps lower, like that associated with passenger rail. High levels of safety and security assurances and associated compliance costs may weigh as competitive factors.

Finally, the dynamic effects of an operating hyperloop system on a local, regional, or national electricity grid are unknown. No system presently exists. The effects may be estimated or inferred by making assumptions about technologies and loads, specifying hypothetical hyperloop system configurations and operational scenarios, and carrying out simulations of these scenarios on computer representations of actual grids of various sizes in various locations. This is the topic of inquiry and methodological approach illuminated in Section II.

Key Companies Developing Hyperloop Technology

Several start-up companies in North America have begun to explore the commercial potential for hyperloop technology. Selected examples are noted here. DOE's analysis is independent of this private sector work but is informed by its progress.

Figure 3. VHO Test Pod

- Virgin Hyperloop One (VHO), based in the Los Angeles area, has raised more than $300 million in venture capital to begin developing the technology and is exploring the feasibility of building hyperloop systems in diverse locations, such as India, Colorado, Ohio, Missouri, and Texas.[19] It has a test track (DevLoop) in Apex, Nevada.[20] More than 400 tests of the VHO system have been conducted here. A concept for the test pod is shown in Figure 4. VHO is also examining a potential freight concept for palletized freight using the hyperloop concept.[21]
- Hyperloop Transportation Technologies (HTT), based in the Los Angeles area, has begun development of hyperloop technology. The company has raised more than $100 million,

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[19] Testimony by Josh Raycroft (Virgin Hyperloop One) to the Senate Committee on Commerce, Science, and Transportation, 2018, https://www.commerce.senate.gov/public/index.cfm/hearings?ID=E3D94CC4-AA66-4886-9F16-230B3D254FCF

[20] "First Look at DevLoop, World's Only Full-Scale Hyperloop Test Track," Virgin Hyperloop One, 2017, https://hyperloop-one.com/blog/first-look-devloop-worlds-only-full-scale-hyperloop-test-track.

[21] "A New Cargo Brand Built for an On-Demand World," Virgin Hyperloop One, 2018, https://hyperloop-one.com/blog/new-cargo-brand-built-demand-world.

indicating investor interest[22] and is exploring the feasibility of routes in Austria, Slovakia, India, and the United States (Cleveland to Chicago). It has shown a concept for a full-scale passenger capsule (Figure 3) that makes use of a new "smart" lightweight composite skin material with embedded sensors known as Vibranium.[23] It is developing its first test track in Toulouse, France, and plans to begin testing in 2019.[24] HTT is also considering use of the hyperloop system for cargo transport.

Figure 4. HTT Passenger Pod Concept

- TransPod, located in Toronto, Ontario, Canada, is developing its hyperloop system with the aid of partners Liebherr Aerospace and the railway engineering firm IKOS Group.[25] TransPod has proposed a system that will carry both passengers and freight on the same route at the same time. Its pod design strongly resembles a wingless airline jet fuselage, as shown in Figure 5, and is driven by magnetic propulsion. TransPod is exploring a variety of routes in Canada, the U.S., Europe, and Asia, including New York-Boston, DC-Philadelphia-New York, and Chicago-Detroit-Toronto.[26] It plans to build a 1.86-mile test track in France and begin testing in 2020.[27]

Figure 5. TransPod M2A Pod

Technology Approaches

All three of these hyperloop companies are adopting technology approaches that are broadly similar in the utilization of underlying technology. All are propelling pods using linear electric motors[28] and employing passive magnetic levitation[29] to guide and levitate the pods along the guideway at high speeds. Pod sizes appear to be similar, as well, carrying in the range of 20-30

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[22] "Hyperloop Transportation Technologies Surpasses $100 Million in Total Investment," PR Newswire, December 2016, https://www.prnewswire.com/news-releases/hyperloop-transportation-technologies-surpasses-100-million-in-total-investment-300371373.html.

[23] Hyperloop Transportation Technologies website, 2018, http://www.hyperloop.global.

[24] "Toulouse Welcomes Hyperloop Transportation Technologies to Europe's Aerospace Valley with New Facilities," PR Newswire, January 2017, https://www.prnewswire.com/news-releases/toulouse-welcomes-hyperloop-transportation-technologies-to-europes-aerospace-valley-with-new-facilities-300395767.html.

[25] TransPod website, 2018, https://transpod.com/en/.

[26] TransPod website, 2018, https://transpod.com/en/transpod-system/routes/.

[27] Brown, Mike. "This Hyperloop Firm Is Gearing Up to Build the World's Longest Test Track." Inverse. Accessed March 6, 2019. https://www.inverse.com/article/52675-hyperloop-this-firm-plans-to-build-the-world-s-longest-test-track.

[28] "How do linear induction motors work?", Linear Motion Tips, February 22, 2017, https://www.linearmotiontips.com/faq-linear-induction-motors-work/

[29] "Hyperloop Transportation Technologies, Inc. Reveals Hyperloop Levitation System," PR Newswire, May 2016, https://www.prnewswire.com/news-releases/hyperloop-transportation-technologies-inc-reveals-hyperloop-levitation-system-300264946.html.

passengers per pod. Virgin Hyperloop One quotes travel speeds of between 500 and 670 mph, TransPod is aiming for “more than 1000 km/h” or 620 mph,[30] and Hyperloop Transportation Technologies is targeting closer to the speed of sound (760 mph).[31] As may be inferred from the pod images above, pod shapes differ among the companies. All are working toward the common goal of high-speed transport, with limited waiting time for departures, and potential reductions in energy use through high efficiency and use of renewables.

Technology Maturity

As noted above, no hyperloop system is yet operational. Each of the companies described above has test track, with test activities either underway or planned. Concepts for the pods have been displayed. Feasibility studies for potential routes have been initiated and, in some cases, completed.

In general, a hyperloop system is a complex system of many component parts. Some parts are at higher technology readiness levels (TRLs), *e.g.* prototype testing and demonstration, while others, such as control systems, are in early stage development at lower TRLs. Hyperloop manufacturers have not characterized their systems at any specific TRL in the literature available. Any assignment of a single overall TRL would be a judgment based on incomplete information. It is not necessary for the purpose of this report.

LINEAR ELECTRIC MOTORS

Linear motors are, in principle, rotary motors that have been “unrolled” to provide motion along a line instead of rotating shaft. These motors are separated into primary and secondary parts that interact via induced electromagnetic fields when three-phase power is applied to the primary. Either part may be fixed, while the other part moves.

As with conventional rotary motors, linear motors can be used in “reverse” mode as generators to convert the kinetic energy of the moving part into electrical energy to be returned to the grid or to an energy storage device.

The SpaceX competitions demonstrate the feasibility of some of the basic building blocks of a system. As one example, a Massachusetts Institute of Technology team demonstrated stable magnetic levitation, using an electrodynamic suspension system, and an innovative braking system. The MIT system can decelerate a pod with a continuous force equal to 2.4 times that of gravity, or 2.4 G.[32]

Descriptions of key building blocks of hyperloop systems are provided below and in the accompanying side-bars.

[30] TransPod website, 2018, http://www.hyperloop.global/how-it-works.

[31] Hyperloop Transportation Technologies website, 2018, http://www.hyperloop.global/how-it-works.

[32] *MIT Hyperloop Final Report*, Massachusetts Institute of Technology, 2017.

- **Propulsion and Braking**: Long-stator linear motor designs use the track as the primary (powered) winding and the pod as the secondary. This lowers the weight and complexity of the pods, since they do not require a constant connection to a power source. Linear motors can also be used in reverse as power generators, converting kinetic energy into electricity through regenerative braking. Alternatively, the primary winding could be placed on the pods, or replaced altogether with on-board rotary motors, accompanied by on-board energy storage. This would increase pod weight but might simplify other parts of overall system design.

MAGNETIC LEVITATION

At rest and at start-up at low speeds, hyperloop systems rely on conventional wheels and steel rails for support. At slightly higher speeds and beyond, the pod will begin to levitate due to magnetic fields induced in the track. Passive magnetic levitation, or electro-dynamic suspension (EDS), provides minimal friction as the pods are lifted slightly from the track by either electromagnets or a series of permanent magnets arranged on the bottom or top of the pod in what is known as a Halbach array. This special arrangement of magnets focuses the magnetic field on one side, while significantly reducing it on the other.

Passive magnetic levitation requires no external power source for the pod levitation, reducing the overall power requirement for the hyperloop system and ensuring that if any power failure occurs the pod will continue to levitate until it slows nearly to a stop.

- **Levitation**: Lift may be provided by modified electrodynamic levitation systems, some of which are based in part on DOE's Lawrence Livermore National Laboratory *Inductrack*[33] design. *Inductrack* is a type of magnetic levitation, or *maglev,* that uses a special arrangement of permanent magnets, called a Halbach array. Other electrodynamic levitation systems use electromagnets in conjunction with the permanent magnets, or superconductors. For all of these levitation systems, when the pod travels over the track, the motion itself induces a field that produces lift and very little power is required once the pod is in motion.

Existing maglev trains utilize similar technologies, such as magnetic levitation, but differ from hyperloop in other conceptual, technological, and operational aspects. Hyperloop developers are targeting a service across an array of destinations, utilizing on- and off-ramps to create a flexible ultra-high-speed rail system, whereas maglev operates point-to-point. Maglev trains do not operate in an evacuated tube and are therefore limited to lower speeds. The only high-speed maglev system in operation was developed by Transrapid in Germany and implemented on a 19-mile route from Shanghai Pudong International Airport to the outskirts of central Pudong, Shanghai.[34] It is the fastest commercial train currently in operation, achieving 270 mph in daily use. This is about half the speed suggested by hyperloop developers.

Japan's *Chuo Shinkansen* maglev reached 375 mph in testing but is not expected to be operational until 2027.[35] Additionally, both of these trains use active magnetic levitation, in

[33] Post, Richard. "Maglev: A New Approach." Scientific American, January 2000.

[34] "Transrapid Maglev Shanghai - Maglev." Accessed February 13, 2019. https://www.maglevboard.net/en/facts/systems-overview/transrapid-maglev/transrapid-maglev-shanghai.

[35] "Chuo Shinkansen Maglev Line." Railway Technology (blog). Accessed February 13, 2019. https://www.railway-technology.com/projects/chuo-shinkansen-maglev-line/.

contrast to hyperloop developers, which appear to prefer passive maglev, discussed above. Non-maglev high speed rail (HSR) is a competing technology already in use, primarily in parts of Asia and Europe. The current HSR systems operate at speeds that typically achieve a maximum of about 220 mph.[36]

Summary

Hyperloop technology research and development appears to be well underway in terms of conceptual design and testing of various component elements. The idea is attracting several developers, partners, and investors. The state of development, however, is still preliminary. There are competing approaches to addressing its array of implementation challenges. Operational parameters are speculative, and costs are uncertain. No operating system exists today. An analysis of a hypothetical hyperloop system, its impacts on the electrical grid, and its potential effects on national transportation energy demand, requires an array of hypothetical assumptions and modeling scenarios. Conclusions presented in the Sections that follow should be regarded, accordingly, as speculative and should be used with caution.

[36] "Fact Sheet: High Speed Rail Development Worldwide | White Papers | EESI." Accessed February 13, 2019. https://www.eesi.org/papers/view/fact-sheet-high-speed-rail-development-worldwide.

III. Hyperloop Impact on the Electricity Grid

Estimating the impacts of an operating hyperloop system on the electricity grid requires a model of both the system and the grid. In this section, the salient features of the electric grid are called out, with attention given to the need to balance electricity supply with demand, maintain the reliability and quality of power, and manage the effects of intermittent flows of power in and out of the hyperloop system. This is followed by the development of an array of hyperloop system configurations, operating scenarios, and electrical load profiles. Using these load profiles, electric grid simulations are carried out that represent U.S. power grids of various sizes in various locations. Conclusions are drawn from the results about the impacts on the grid, technological constraints, and suggestions for mitigating strategies.

III.A. Key Facts about the U.S. Electricity Grid

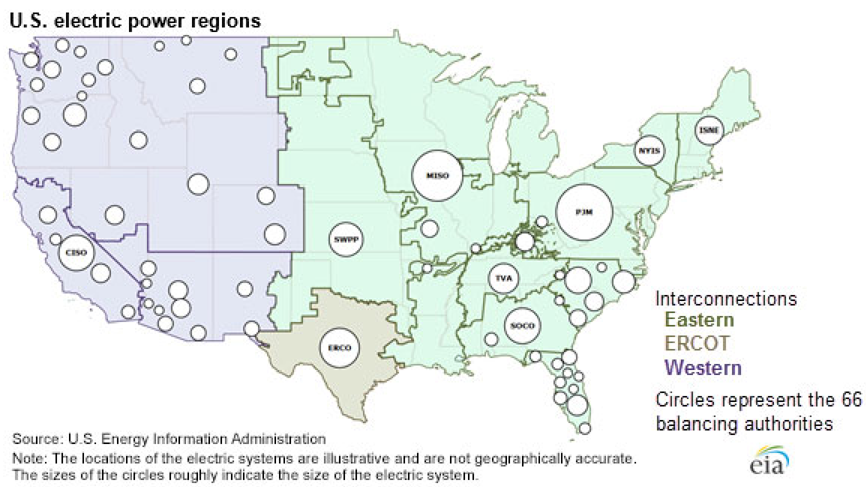


Figure 6. U.S. Electric Power Regions and Interconnects

Electricity is delivered to consumers from sources of generation through the network of power lines, substations, and transformers commonly known as the electricity grid. The grid is divided into the bulk power system, a network of high-voltage transmission lines, and the distribution system that delivers the power from the bulk power system to the individual customers via lower-voltage lines. The U.S. grid consists of 3 interconnections, in which the alternate current (AC) frequency is synchronized, and 66 balancing authorities, whose responsibility is to balance demand with supply on a second by second basis to maintain reliability of the grid (see Figure 6). There are about 3,000 utilities in the United States with about 480,000 miles of transmission lines and 6.3 million miles of distribution lines.[37] This network of utilities serves almost 150 million customers.[38]

Nearly every distribution system is part of a larger regional interconnection. These larger interconnected grids facilitate coordination and planning of electricity supply to consumers.[39] This network structure helps to maintain reliability by providing multiple avenues for power transmission and allowing generation capacity to be shared across load centers. This redundant

[37] "Electricity Distribution System Baseline Report," Pacific Northwest National Laboratory, 2016, https://www.energy.gov/sites/prod/files/2017/01/f34/Electricity%20Distribution%20System%20Baseline%20Report.pdf.

[38] Pacific Northwest National Laboratory, 2016.

[39] "Electricity Explained: How Electricity Is Delivered to Consumers," U.S. Energy Information Administration, 2018, https://www.eia.gov/energyexplained/index.php?page=electricity_delivery.

network helps to prevent any single transmission line or power plant failure from causing service interruptions.

Balancing electricity supply and demand is critical for ensuring the safe and reliable operation of the power grid. Mismatches of supply and demand can result in localized or regional "brownouts" (sustained voltage drops) or "blackouts" (disrupted service). The 66 balancing authorities, also shown in Figure 6, perform this function for their respective parts of the electricity grid. Through functions known as ancillary services,[40] balancing authorities maintain the system frequency of 60 Hertz (cycles per second) and voltage against small mismatches in load and generation. They also maintain a generation reserve to ensure that the grid can recover from a loss of generation capacity. System frequency, voltage, and generation reserve can become issues of concern for grid operators when considering the addition of large and dynamic electrical loads, such as might be presented by hyperloop system deployment. It is typical before large loads are connected to the grid that the grid operator performs grid interconnection studies to assess the impact of new loads to grid operations.[41]

For the purposes of this analysis, hyperloop system grid impacts at three different U.S. locations and with different load characteristics were modelled to represent diversity of the U.S. grid and impacts. The three locations are California, Ohio, and Colorado. In this way, the analysis could identify a range of impacts across a range of grids, each with differing real-life response.

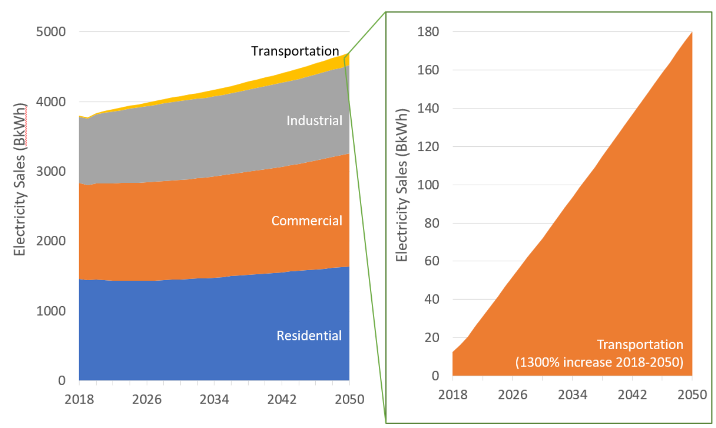


Figure 7: Electricity Sales by Sector, Projected for all Sectors (left) and for Transportation (right), 2018 – 2050, U.S. Energy Information Administration.

For additional context, electricity sales in the United States presently amount to about 3,800 billion kilowatt hours (kWh) annually. Sales are projected to increase by about 24 percent, with growth across all sectors, including transportation, as shown in Figure 7,[42] but sales in the transportation sector are expected to grow dramatically.[43] This may help to illuminate some constraints on the results under varying hyperloop system designs and deployment scenarios.[44] Electricity sales in

[40] "Ancillary Services Market," PJM, 2018. https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-services-market.aspx.

[41] NERC, Facility Interconnection Studies, FAC-002-2. August 2014. Available at: https://www.nerc.com/pa/Stand/Reliability%20Standards/FAC-002-2.pdf

[42] *Annual Energy Outlook 2019*, Electricity Supply, Disposition, Prices, and Emissions, 2019, U.S. Energy Information Administration, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2019&cases=ref2019&sourcekey=0.

[43] *Annual Energy Outlook 2019*, Electricity Supply, Disposition, Prices, and Emissions, 2019, U.S. Energy Information Administration, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2019&cases=ref2019&sourcekey=0.

[44] These three grids areas also represent areas where hyperloop systems have been suggested, or formally studied, for implementation.

the three modeled grid areas, that is, California, Ohio, and Colorado, were 257, 146, and 55 billion kWh/year, respectively.[45]

In the following discussion, various hyperloop system configurations are envisioned, for both passenger and freight transport. These are used to build load profiles for energy and power. These profiles, in turn, are use as inputs to grid simulations, which result in the identification of a number of potentially serious grid interfacing challenges, should hyperloop systems be connected directly to the grid. This conclusion is then followed by the introduction of a number of possible mitigating technologies and strategies, including innovative alternative designs for hyperloop systems with less direct grid interconnections.

III.B. Hyperloop Configurations

Assessing the energy and power demands of a hyperloop system requires an understanding of its physical and operating characteristics. Since none are in operation, several hypothetical hyperloop system configurations were envisioned for the purposes of modeling using the parameters shown in Table 1. These include three applications for "pod" transport: (a) passengers (maximum of 30 each); (b) lighter-weight palleted freight; and (c) heavier freight using large shipping containers.

The passenger configuration is informed by the 2013 hyperloop concept paper and illuminated further in modeling work done by NASA.[46] The lighter (pallet) freight configuration envisions a standard passenger airline shipping container. This results in a system defined by parameters that are not too dissimilar from that of the passenger pod design. The heavier freight configuration, as outlined by an early hyperloop proponent, envisions a pod and tube that could accommodate a standard 40-foot intermodal shipping container like those used in railroads and overseas ship transport.[47]

[45] "Electricity sales by state and utility 2017," U.S. Energy Information Administration, https://www.eia.gov/electricity/data/state/sales_annual.xlsx.

[46] Decker, Kenneth, Jeffrey Chin, Andi Peng, Colin Summers, Golda Nguyen, Andrew Oberlander, Gazi Sakib, et al. "Conceptual Feasibility Study of the Hyperloop Vehicle for Next-Generation Transport," n.d., 22.

[47] Telephone communication between the U.S. Department of Energy and the Virgin Hyperloop One Chief Technology Officer, Mr. Rob Ferber, August 28, 2018.

III.C. Hyperloop Energy and Power Demands

Understanding the energy and power demands of a hyperloop system also requires: (a) an assessment of a load profile over time; and (b) an assumption about how the system might be connected to the grid. The analysis below develops a baseline load for the launching of a single pod, overlays on that the load profiles of additional pods launched in sequence, imagines that other pods in the system are arriving and braking, and still others are traveling over distances and require periodic power boosts to maintain speed.

Table 1: Hyperloop System Parameters

	Passenger	Lighter Freight	Heavier Freight
LOGISTICS			
Number of tubes	2 Tubes (in all 3 configurations)		
Operating hours/day	12	18	18
Launch interval (minutes)	2	4	6
Pod load/unload time (s)	60	120	240
Pod capacity	30 people	4,000 lb.	58,000 lb.
Load factor / capacity utilization	70%	60%	60%
SYSTEM DESIGN			
Acceleration and Deceleration (g)	Two scenarios: 0.5g and 1g		
Cruise speed (mph)	629		
Tube diameter (ft)	13.1	15.5	20.6
Tube pressure (psi)	0.125 (less than 1/100 atmospheric)		
Regenerative braking efficiency	80%		
Hotel load (passenger comfort)	20% of total cruise power	None	None

Two cases are assessed. In the first case, the dynamics of power demands are assumed to present themselves at a hyperloop station with a direct connection to the grid. In the second case, other options are considered that envision different approaches to grid connection, some using intermediary and interfacing technologies and others exploring alternative hyperloop systems and pod designs. The analysis below develops load profiles for the case of a direct connection to the grid.

Using the hyperloop system parameters of Table 1, an electrical load profile was developed for one hyperloop system station, second-by-second, for a single day of operation. Figure 8 shows a 4-minute segment of such a profile, where the electricity load shown is due to the operation of a hyperloop system, with many traveling pods operating simultaneously, as described above, with pod launches and arrivals each spaced about 2 minutes apart. Since the model assumes that grid interconnections only exist at each station, all of the energy and power flows along a given pod route segment will be aggregated to the nearest station and presented to the grid. Figure 8 displays the resulting load profile for a passenger example. Other load profiles were developed for heavier weight (or container-size) freight. Load profiles were not developed for lighter (pallet) freight due to its strong resemblance to the passenger system, both in energy and power demand as well as design parameters.

The load profiles were then applied to each of three representative hyperloop routes, where real-life grid representations were available in modeling detail. The three routes selected were:

- San Francisco-Los Angeles, California;
- Cleveland-Columbus-Cincinnati, Ohio; and
- Cheyenne (WY)-Denver-Colorado Springs-Comanche, Colorado

These routes were selected because they are currently under consideration for hyperloop system implementation by the major hyperloop developers.

MAINTENANCE OF TUBE VACUUM

A series of vacuum pumps, either in clusters or evenly distributed across the track, will run constantly to maintain system vacuum during hyperloop operation. The extremely low-pressure operation will lead to leaks due to diffusion, desorption, permeation, micro cracks, and mechanical components. In addition to maintaining vacuum, the pumps will be needed to pump-down airlocks after passengers board pods at each station stop and to complete the initial pump-down when system operation starts. This initial pump-down could occur daily, weekly, or less frequently depending on the operations and maintenance regime.

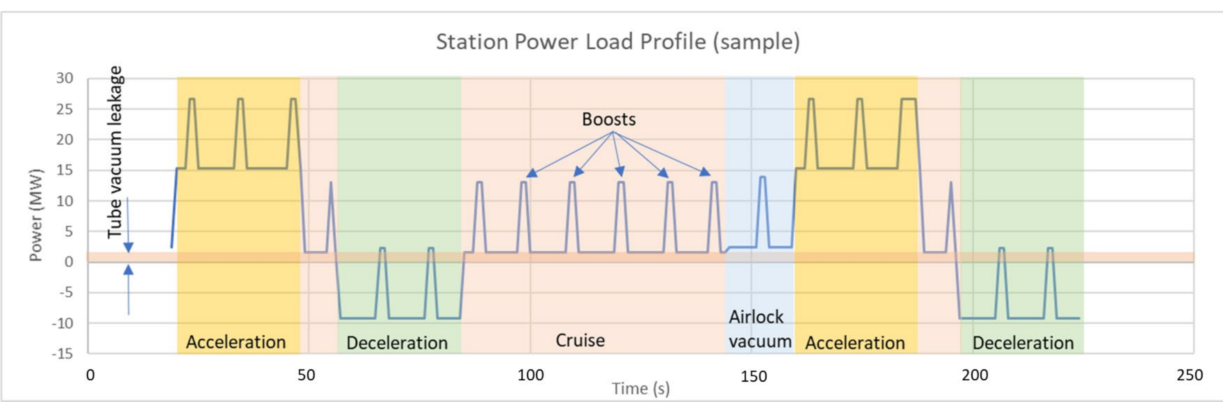


Figure 8: Typical Load Profile for a Single Passenger Hyperloop Station. Note: The station modeled here assumes the boosts to launch the pods and the boosts required to maintain the speed of the pods are distributed from the nearest station with infrastructure provided to the location of the boost along the route. The on-board pod batteries were assumed to be sufficient for smaller loads like passenger comfort, but not for the larger power requirements of pod acceleration and boosting.

Table 3. Three Selected Hyperloop Routes and Grid Characteristics

	California	Ohio	Colorado
Hyperloop Route	San Francisco-Los Angeles	Cleveland-Columbus-Cincinnati	Cheyenne (WY)-Denver-Colorado Springs-Comanche
Route distance (mi)	350	230	200
Interim stops	1	1	4
NERC Region	WECC-CA/MX	PJM	WECC/ RMRG
Installed generation capacity (GW) [1]	53	185	17
Reserve margin (%)[2]	22.5	32.3	36.2

[1] Source: 2018 Summer Reliability Assessment, NERC page 28: Existing-certain capacity

[2] Source: 2018 Summer Reliability Assessment, NERC page 28: Anticipated Reserve Margin for 2018 summer.

Each of the selected hyperloop routes was overlaid on the grid representation for each area and modeled by type of application, that is, passenger and heavier freight. The routes and their respective electrical grid characteristics, including reserve margins, are summarized in Table 2.[48]

Table 2: Hyperloop Energy and Power Demands

	California	Ohio	Colorado
HEAVIER FREIGHT*			
Peak system power [MW]	820	1140	1980
Peak station power [MW]	200	280	200
Total daily energy [MWh]	1680	1300	1850
PASSENGER			
Peak system power [MW]	140	180	560
Peak station power [MW]	40	50	50
Total daily energy [MWh]	640	470	600

Note: All values in the table were calculated based on a 1g acceleration/deceleration; additional 0.5g scenarios were run as well but the results are not shown here.

*See description of *lighter freight* and *heavier freight* in Section IV.C. *Lighter freight* hyperloop grid impacts were not modeled due to its operational similarities to the passenger hyperloop system.

[48] Reserve margin refers to the difference between the maximum available supply of electricity and the maximum peak demand, or (capacity – demand)/demand. See https://www.eia.gov/todayinenergy/detail.php?id=6510.

Modeling the impacts of a full mobilization and nationwide implementation of hyperloop systems, such as on the scale of the interstate highway system or national railroad infrastructure, would be complex and was not attempted. The results pertaining to the three selected routes and their respective grids are believed to be sufficiently insightful to infer the generalized impacts on the electric grid of implementing various hyperloop technology systems at varying levels of network penetration.

The energy and power demands of a hyperloop system vary by location and scenario. The specific power (rate) and energy (quantity) requirements for two hyperloop applications across 3 routes are presented in Table 3. The two applications shown bracket the range of energy and power demands, defined at the lower and higher ends by systems for passengers and heavier weight (container) freight. The demands of the lighter weight freight application were determined to be like that for passengers.
The estimated hyperloop system demands for energy and power may be summarized, as follows:

- Demands for total energy range from 470 to 640 MWh/day for passenger, and from 1,300 to 1,850 MWh/day for heavier freight.
- Demands for total peak power range from 140 to 560 MW for passenger, and 820 to 1,980 MW for heavier freight.

The heavier freight configuration is the more challenging scenario for two reasons. The pod and evacuated tube must be larger to accommodate the dimensions of the 40-foot intermodal freight container. The heavier freight pod-size and its cargo are assumed to have more mass (weight) than the passenger and lighter freight options, requiring more energy and power to move them.

For added perspective, these energy and power demands may be compared to other power elements of an electric grid and are of a similar size and scale. The average natural gas power turbine unit, for example, has a nameplate capacity of about 96 MW. An average conventional coal power unit has a power output of about 350 MW.[49]

Renewable power is often mentioned in conjunction with hyperloop implementation. As a reference to scale, the solar photovoltaic array at the International Airport, Denver, Colorado, which covers 56 acres of land, supplies 10 MW of power. For a hyperloop system traversing 600 miles, if the above-ground right of way for 2 parallel tubes were to be used to install solar arrays of approximately the width of each tube's diameter, the area available might be around 1,900 acres. At peak performance, such a system might produce about 340 MW of power.

[49] Electricity, Capacity of Electric Powerplants by energy source, 2017, U.S. Energy Information Administration, https://www.eia.gov/electricity/annual/html/epa_04_03.html

III.D. Integration of Hyperloop Systems into the Electrical Grid

The steeply pulsed load profiles for the hyperloop systems described in the scenarios and load profiles above, if connected directly, would present serious challenges for the electrical grid. The rapid power flow fluctuations, which could range from 140 to 2,000 MW over periods of time of less than 1 minute, would affect the voltage and alternating current frequency across the power grid.

To maintain reliability and power quality, the voltage and frequency of the grid must be maintained within a specified range. If these ranges are exceeded, protection schemes may be activated to shut down generators and transmission lines to avoid power equipment damage to the grid.

The National Electric Reliability Council (NERC) requires that all new interconnecting facilities, such as a hyperloop system, undergo a study of the potential impacts on the bulk electric system[50]. The developer of a large new industrial load typically works with the utility transmission planner to discuss interconnection specifics, potential impacts, and mitigation strategies. In most cases this requires grid impact modeling.[51]

The envisioned hyperloop system load profiles would also affect both active and reactive power characteristics of the grid. Active power is the electricity that is consumed by a load to perform useful or mechanical work (*e.g.*, moving a train) or to turn electricity into heat (*e.g*., electric arc furnace). Reactive power, in general terms, aligns voltage and current so that real power can do the most work (see side-bar).

[50] NERC, FAC-002-2: Facility Interconnection Studies. Nov. 6, 2014, North American Electric Reliability Corporation, Washington, DC.

[51] This DOE report would not substitute for a NERC-required grid impact modeling study.

Hyperloop-sized electrical loads are relatively large, but not entirely unfamiliar to grid operators. For example, electric arc furnaces, which are used to melt iron and produce steel, draw electrical power from their local grids on the order of 60 MW of power to over 250 MW. They may do so continuously for 30 to 40 minutes at a time. Aluminum production plants may draw as much as 500 MW of power, but do so with a gradual load profile, ramping up and ramping down slowing at the beginning and end of a long-duration production cycle.

Hyperloop systems, by contrast, may draw similar amounts of power, but would do so over a brief time interval of 30 to 40 seconds, stop, and then start again. With pod launches envisioned at intervals under 6 minutes (see Table 1), power draws would pulse the grid at unusually high levels and do so repeatedly throughout the day. Turning on large loads in the range of hundreds of MW often requires coordination with the grid operator, so that generators can be scheduled to supply the large ramping up demands.

REACTIVE POWER

Reactive power is used to provide the voltage levels necessary for active power to do useful work. To maintain the proper voltage levels reactive power may need to be increased or absorbed. Reactive power is critical to maintaining voltage levels on the transmission system. It is measured in volt-ampere reactive (VAR).

Reactive power alone does perform useful work. It is used to create electric and magnetic fields in inductive loads such as a motor. In a motor, a magnetic field must be created between the gaps of the stator and the rotor of the motor to generate torque. The portion of power that contributes to creating the magnetic field is called reactive power. Electric energy cannot be ***directly*** converted into useful energy (rotational energy) as it does in a resistive load such as an incandescent light bulb, that converts electric energy into heat (or visible light). Therefore, inductive loads such as motor demand some amounts of reactive power.

The grid may also be expected, under most hyperloop planning assumptions, to receive power from the deceleration of the pod and its regenerative braking using electric generators. Efficient systems might result in up to 80 percent conversion of the kinetic energy of the high-speed traveling pod back to electrical power. This power would need to be used, or stored, or sent back into the grid, in time-intervals of a comparably brief nature.

Under idealized and theoretical system designs, it might be possible, using automated sensing, dispatching, and controllers, to recycle power simultaneously from a slowing pod and transfer it to a launching pod, which could level out the overall system load. The power could alternatively be dumped to temporary energy storage devices. To be most useful in this setting, such a storage device would need to be capable of withdrawing and supplying that energy at high power and energy transfer rates. Their power rating will need to be in the range of tens of MW.

Section Summary

System load profile dynamics as they are presented at the systems' grid interconnection will likely be a key consideration for hyperloop implementation. Mitigating strategies and technologies are possible, as discussed in Section II.F.

III.E. Grid Impacts

Assuming a direct connection to the grid, the frequency and voltage disturbances over a portion of the load profile of hyperloop systems were modeled in three different locations and on three different regional grids. Illustrative results are shown in Figure 9 and Figure 10. In Figure 9, variations in load demands caused frequency deviations (as represented by changes in the mechanical speed of the rotating generators), as modeled for the Eastern (EI) and Western (WECC) grids. These would be "jolts" to the power generator and cause cycling stresses. Rapid variations in reactive power make it difficult for the generator to manage system voltage, as shown on Figure 10 for the Columbus Station (part of the Ohio case). This can cause flickering both in close vicinity to the load and remotely. In this case small perturbations can be seen as far away as Virginia.

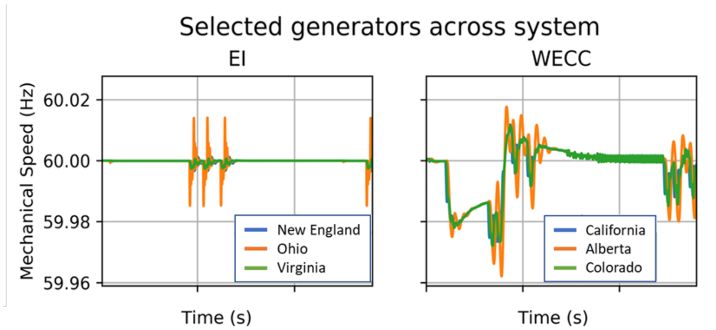
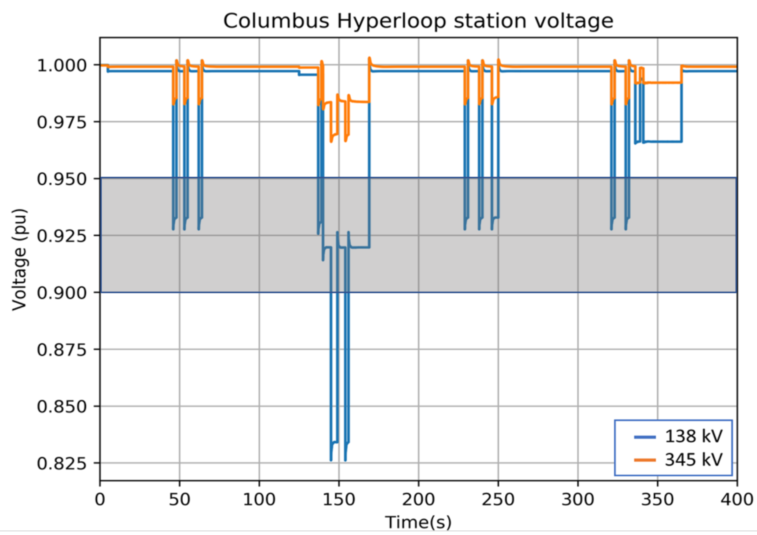


Figure 9: System-Wide Grid Effects of Hyperloop. Shows the rotational speed of selected generators, which corresponds to the grid AC system frequency.



The shaded box represents the range of typical voltage violation thresholds. 0.95pu is typical for normal operation and 0.90pu is typical for contingency situations.

Figure 10. Voltage Drop from Hyperloop Varies by Interconnection Voltage at Columbus (OH) Station. Note the voltage is normalized and indicated with the customary "per unit" (pu) nomination.

In general, the perturbations in electrical grid operation, as modeled here, are not outside the norms of what the electrical grid may experience and should not immediately cause a widespread system failure or outage. If these perturbations were presented repeatedly and sustained over long periods of time, however, they would result in increased wear and tear on generation equipment.

This wear and tear would be the direct result of the grid responses to control frequency and regulate voltage. As the system responds, nearly instantaneously, frequency perturbations would cause variations in torque on generator shafts and bearings and in pressure on turbine blades, with associated material fatigue. Voltage perturbations would induce wear on voltage regulation equipment.

The pulsing nature of a hyperloop system load presents an unusual cycling nature both in amplitude and persistence, imposing significant cycling stresses on grid equipment in the proximity of the load, as well as further out in the larger transmission network. These stresses could contribute to early failure of generators and other grid equipment, with associated costs to the grid operator. Grid operators and rate-payers are likely to find this unacceptable. Moreover, the costs would be difficult to attribute precisely to cause and, accordingly, difficult for utility regulators to allocate properly to the hyperloop system.

Variations Among Grids

Grid modeling demonstrated that hyperloop operation can have a system-wide effect beyond local grid infrastructure. Different grid interconnects exhibit different behavior in this regard. As Figure 9 shows, the Western Electricity Coordinating Council (WECC) grid exhibited more noticeable disturbances from the “spiky” hyperloop load profiles than the Eastern Interconnect (EI) grid, due to WECC’s lower capacity to absorb the dynamic fluctuations. Perturbations from the hyperloop load dynamics reverberate across the entire grid, even for the WECC grid, which covers a larger geographic area.

The specific location of the hyperloop connection relative to a potential point of interconnection to the transmission system is also a consideration. Transmission circuits vary in voltage levels. Lower voltage interconnects have less capacity to absorb load dynamics than higher voltage interconnects. This is shown in Figure 10 for two Columbus, Ohio, substations, one with a voltage capacity of 138 kV and the other with 345 kV.

The lower voltage substation exhibits more voltage drop than the higher voltage substation. Based on this analysis, hyperloop systems would likely benefit from a connection to a substation with voltage of 230 kV or higher. These higher voltage substations are typically spaced further apart and, therefore, may influence a hyperloop system design and its point(s) of interconnection to the grid.

In summary, for a hyperloop system that would connect directly to the grid, without interfacing mitigation strategies or buffering technologies, the simulations of various configurations overlaid on three different grids identified the following impacts:

- The steep ramps of the system’s load profiles are large and unusually stressful on the grid;
- Frequent pulses, and the large demands for both real and reactive power, will seriously impact grid equipment and infrastructure in the form of unacceptable wear on generators and related equipment;
- There will be noticeable degradation of power quality potentially leading to issues such as flicker, which would adversely affect utility customer satisfaction;
- The grid impacts are more pronounced when hyperloop technologies are interconnected at transmission circuits at lower voltage ranges (138 kV) compared to higher voltage levels (*e.g.* 354 kV), so careful station site selection is essential;

- The impacts extend beyond the immediate vicinity of the hyperloop load, and can have system-wide impacts, the magnitude of which depends on the specific regional infrastructure.
- In the modeled cases, the WECC grid experienced more noticeable disturbances than the EI grid; and,
- The modeling results all point toward employing mitigation strategies such that the sharp load spikes can be significantly reduced and spread over longer periods of time.

III.F. Technological Options

The modeling simulations above explored the case of connecting hyperloop systems directly to grid. Under this hypothesis, the grid's infrastructure, it was assumed, could distribute power when and where needed, absorb the stresses of load dynamics, and balance varying energy demands across the network and throughout the system. In sum, the grid would be expected to do everything that is needed to facilitate the technologies' deployment.

In view of the modeling results, however, it seems unlikely that a fully deployed hyperloop system would connect directly to the grid in this manner. It would need to employ strategies and technologies that would either be mostly independent of the grid or self-sustaining apart from the grid, or interface with grid less directly, perhaps using intermediary and buffering strategies with interfacing infrastructure and power electronics on the ground.

Interfacing Strategies

Regarding stationary system infrastructure, electric energy storage systems, such as utility-scale batteries, could address a key hyperloop system challenge. The large *real power* demands present a compelling argument for using energy storage systems, such as batteries or hybrid systems that employ spinning reserves and large-scale capacitor banks, as interfacing technologies. They could supply the dynamic power demands when needed. Power electronics could address the *reactive power* requirements.

Because of the distributed nature of the power demands, located at stations and along the route, installations of energy storage systems could be needed in many places. The two examples of energy storage systems below provide a sense of the options available.

- A simple battery storage system could buffer the variable component of the electrical demand. A high-power low-energy lithium-ion battery system capable of moving large quantities of power in and out, but with limited storage of that electricity, could address the variable component of the electrical demand.
- A more sophisticated dual-mode energy storage system could filter out the high frequency and low frequency variable loads separately, using two batteries specifically designed for these purposes. For example, a *high-power* battery capable of absorbing the high-frequency spikes, combined with a *high-energy* battery addressing the lower-frequency spikes, could

moderate the dynamics of the load demands and reduce overall power requirements by 40 percent.

Several commercially available solutions are available to address the direct grid impacts of a hyperloop system implementation. Such solutions are generally applied on the load-side of interconnection, that is, on the grid-side.

- Series equipment such as reactors, capacitors, SPLC (Smart Predictive Line Controller) and thyristor converters could reduce flickers and voltage fluctuations by smoothing out current variations. These devices boost power during power dips and clip power peaks. SPLCs are already well-proven for use in high power long duration operation.
- Power Factor Compensation Capacitors and harmonic filters consist of passive components, such as capacitors, reactors, and resistors. Examples include Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) to supply the required amount of continuously varying reactive power in addition to power factor correction and harmonic filtering.
    - SVCs have been used for decades to reduce flicker. In addition to providing power factor compensation and harmonic filtering functions, SVCs can supply continuously varying reactive power demand. SVC response times can vary from half of an electrical cycle to 2-3 seconds depending on SVC configuration.
    - STATCOM devices perform power quality parameter correction more quickly and better than SVC devices. STATCOM response times can be on the order of milliseconds.

Alternative Hyperloop Systems and Pod Designs

Alternatively, it may be possible to place the *real power* and *reactive power* compensating equipment on the pods, and accommodating the additional weight, rather than at the stations and grid interconnecting points. This could take the form of fast-charging battery packs, accompanied by the requisite power electronics. Under such a scheme, each pod would supply its own power for levitation, acceleration, and control, as well as other housekeeping needs and amenities, and be capable of receiving and storing internally (on-board) the electricity from regenerative braking upon slowing and stopping.

Hypothetically, the energy and power demands of a hyperloop system in this case would likely be like that estimated earlier or, perhaps, greater, given the added weight of the pods with energy storage on-board. The load profiles presented to the grid, however, would be entirely different from that shown on Figure 8, and more level.

Because there would be energy losses along the route, and because regenerative braking cannot capture and convert all of the kinetic energy to electricity with 100 percent efficiency, these losses would have to be made up by periodic recharging from the grid. The grid interface in this case would be characterized mainly by the need for high-power, but comparatively steady-state, fast-charging units for the on-board pod batteries. The power demands of a fully operating hyperloop system would no longer be a grid challenge due to load profile, but may be a grid challenge for fast recharging at a significant scale.

Section Summary

In summary, the load dynamics of hyperloop systems, if connected directly to the grid, would likely present serious grid interface challenges, which would be unacceptable to most grid operators. However, there appear to be innovative designs, buffering strategies, and technology options that could either isolate or mitigate the direct impacts on the grid. New technologies could be further explored to mitigate any potential issues to the electric grid. Although not proven, it is surmised that, if adequately implemented, and with advance utility planning, a fully operational hyperloop system could be accommodated by, and safely and efficiently integrated with, the existing grid systems in each hyperloop system area.

IV. Hyperloop Impact on Transportation Energy Use

IV.A. Overview of Transportation Energy Use

In the United States, transportation energy use accounted for about 26.5 quadrillion BTU (quads) in 2016. This accounts for one-third of total energy consumption. About 92 percent of that energy consumption is petroleum.[52] Regarding transportation modes, 83 percent (21.9 quads) of total transportation energy use in 2016 may be attributed to on-road applications (light-duty vehicles, medium- and heavy-duty trucks, buses).[53] Air travel represents another 8 percent (2.8 quads); rail a further 2 percent (0.5 quads); with the remainder being divided among marine uses, energy used in pipelines, and other uses.[54]

In 2016 personal passenger vehicles (cars and light trucks) represented 71 percent (15.5 quads) of total on-highway energy use, while freight transport represented 28 percent (6.1 quads) and buses make up the remainder.[55] Freight rail makes up 91 percent (0.5 quads) of the energy use in the rail transport mode.[56]

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[52] *Transportation Energy Data Book 37*, "Quick Facts", Oak Ridge National Laboratory, 2018, https://cta.ornl.gov/data/index.shtml.

[53] *Transportation Energy Data Book 37*, "Table 2.8", Oak Ridge National Laboratory, 2018, https://cta.ornl.gov/data/index.shtml.

[54] Ibid.

[55] Ibid.

[56] Ibid.

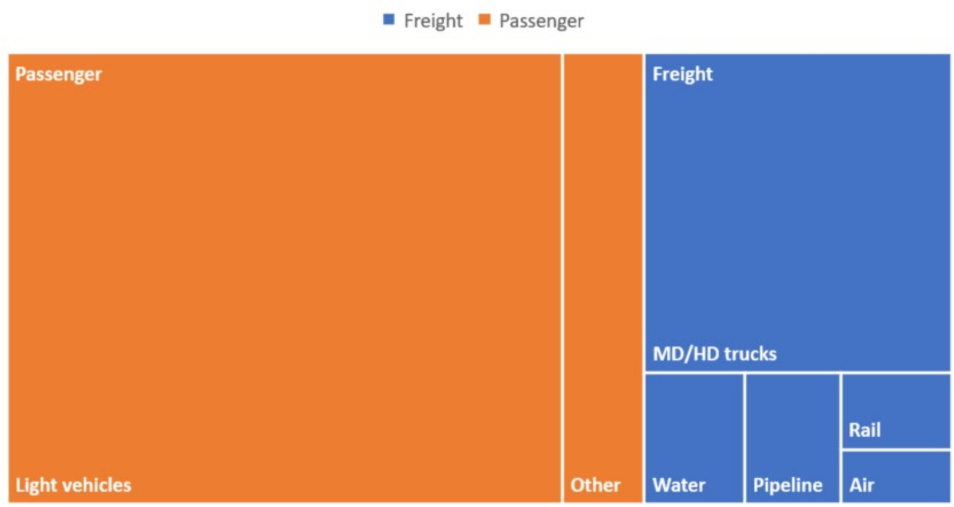

Figure 11. 2016 U.S. Transportation Energy Use by Mode, not including military use or lubricants (U.S. Department of Energy). ***Passenger Other*** **category includes air, water, bus, and rail.**

As illustrated in Figure 11, total transportation energy may be divided into two broad categories, with approximately two-thirds of the energy used for passenger purposes and one-third for freight. The analysis of hyperloop effects on energy demand is likewise split between passenger and freight.

About 87 percent of passenger transportation energy consumption is attributed to light-duty vehicles; air a further 10 percent; and the remainder split between marine uses, buses, and rail. Intercity rail accounts for about a quarter of the passenger rail total, or less than 1 percent of total U.S. transportation energy use.[57]

Freight transportation energy consumption is predominantly due to medium- and heavy-duty trucks (71 percent), followed by marine freight (10 percent), pipelines (9 percent), rail (6 percent), and air (4 percent).

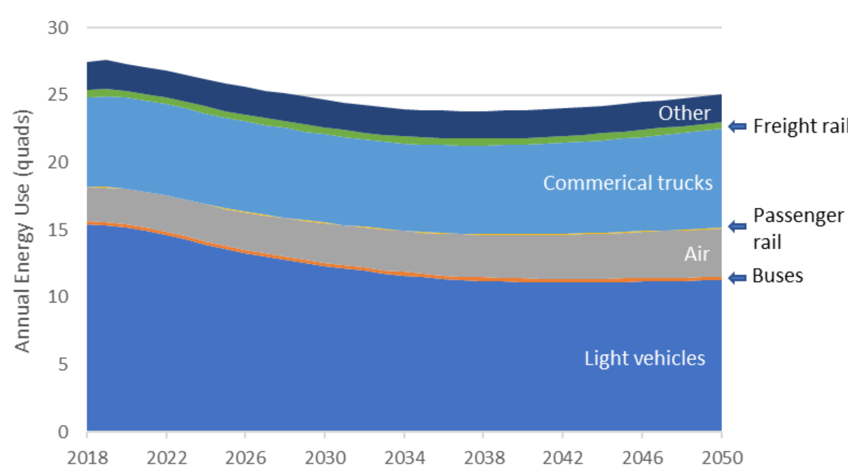

Figure 12: Transportation Energy Use to 2050 (EIA)

For further context regarding the transportation energy outlook, EIA forecasts that overall transportation energy use in the United States will decrease slightly by 2050 due to

[57] *Transportation Energy Data Book 37*, "Table 2.13", Oak Ridge National Laboratory, 2018, https://cta.ornl.gov/data/index.shtml.

increased efficiency and resulting decrease in energy use in the light-duty vehicle sector. Air travel energy use, in contrast, is forecasted to increase by 41 percent and passenger rail energy is estimated to increase by 39 percent by 2050. Energy use in other modes remains relatively unchanged to 2050 as shown in Figure 12.

IV.B. Potential Hyperloop Impacts on Overall Energy Consumption of Transportation Sector

Hyperloop systems have the potential to affect transportation sector energy consumption in two ways: (a) mode switching, where passenger or freight demand may transition to hyperloop from other existing modes, like on-highway vehicles, air, rail, and marine; and (b) induced or generated demand, where additional passenger or freight trips may be created because of the increased capacity, improved quality or timeliness of service, or lower cost of the new systems compared to alternatives.

For reasons cited earlier, no further work is planned to model the effects of induced demand. This analysis focuses on mode-switching and its energy consumption effects, first for passenger travel, and then for freight transport.

Passenger-Related Modal Shifts

Hyperloop systems could potentially capture market share by modal shift of passenger travel from any or all of the existing modes, and under an array of varying circumstances. Systems proposed in the literature mostly focus on passenger travel in a “sweet spot” between city pairs having two salient features: (a) they are sufficiently far apart that travel by automobile or light duty truck would be less convenient; and (b) they are sufficiently close to each other that most travel by air would be less efficient, as measured by time or cost.

Regarding the competitive distance for mode-shifting from conventional travel to hyperloop concepts, the Hyperloop Alpha paper suggests distances “less than 900 miles apart”. Routes proposed by two start-up companies, Virgin Hyperloop One and Hyperloop Transportation Technologies, indicate that most routes under consideration are between 250 and 500 miles in length. Guided by these indications, the analysis that follows adopts a competitive range for mode-shifting for passenger hyperloop systems that is bracketed between 100 miles and 1,000 miles.[58]

[58] While shorter underground tube transport systems have also been labelled “hyperloop”, such as The Boring Company’s system linking O’Hare International Airport to downtown Chicago, these systems do not operate in a partial vacuum and are limited to 150 mph. They are therefore not technically hyperloop technology.

As noted earlier and on Figure 11, passenger transportation accounted for about two-thirds of all U.S. transportation sector energy consumption in 2016. Cars and light trucks consume 87 percent of that, and air another 10 percent, as shown in Figure 13.[59]

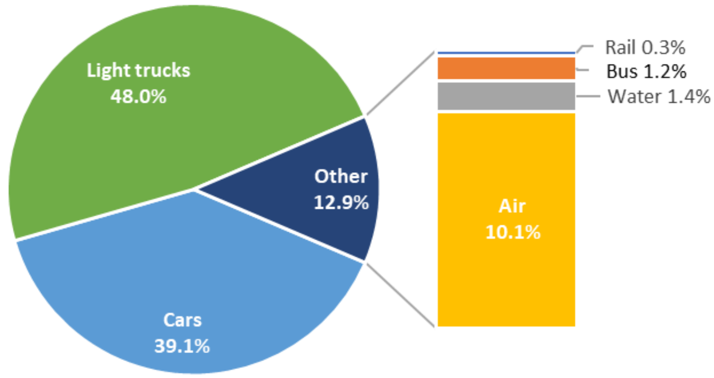

Figure 13: Passenger transportation energy consumption shares by mode (Oak Ridge National Laboratory Transportation Energy Data Book)

Most of the total U.S. demand for passenger-miles traveled (PMT) occurs in the shorter-distances, that is, below 100 miles (66 percent). About 14 percent occurs in the longer-distances of greater than 1,000 miles. This leaves about 20 percent of total PMT in the intermediate or intercity range of 100 to 1,000 miles. Within this range (100 to 1,000 miles), more than three-quarters of PMT falls in the lower portion of the range from 100 to 500 miles. Routes ranging between 250 and 500 miles, as proposed in the hyperloop literature, account for about 5 percent of total PMT. Cars and SUVs hold the largest shares of PMT within each of these sub-divisions of ranges.[60] These data suggest that the targeted market-segment for passenger-based hyperloop systems would likely be about 5 percent of total PMT, but could reach up to 20 percent, and would compete mainly with light-duty vehicles, including automobiles, sport utility vehicles (SUVs), taxis, limos, and like modes of passenger transport, and perhaps from some regional air routes.

Figure 14 compares the energy intensity of a hypothetical hyperloop system to other passenger transportation modes, taking into consideration two examples of load factors. Hyperloop developer estimates suggest that the first system will not be operational until the mid-2020 timeframe. Therefore, rather than assuming hyperloop will replace today's fleet, the analysis uses EIA's projected 2030 fleet average fuel economies for both air and LDVs. These fuel economies were converted to energy intensities based on load factor assumptions and energy content of fuel. Additional assumption and explanation of these estimates is provided in the Appendix, Section V.D.

[59] Oak Ridge National Laboratory, 2018.

[60] U.S. Department of Transportation, Federal Highway Administration, 2017 National Household Travel Survey. URL: https://nhts.ornl.gov.

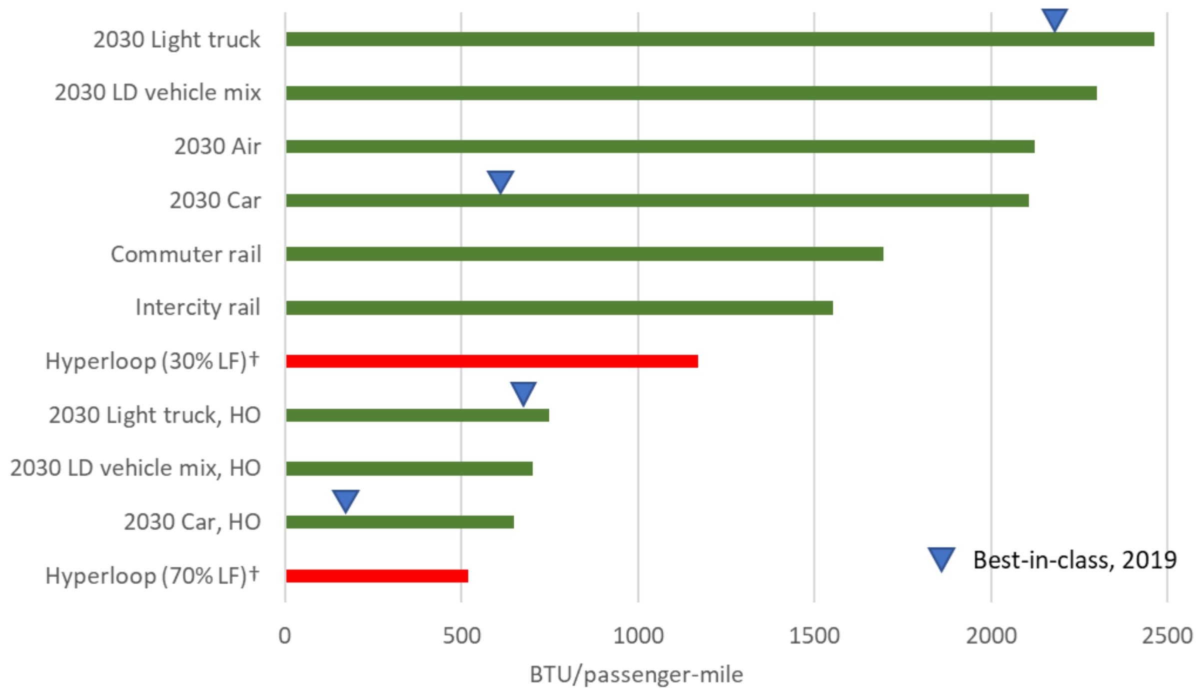

Figure 14: Comparison of energy intensity by transportation mode. BTU = "British Thermal Units", a standard measure of energy. LF stands for Load Factor and HO stands for High Occupancy.[61,62]

These data indicate that hyperloop transport is more efficient, in terms of energy used per passenger-mile traveled, than travel by air and most modes of surface transport, except for high-occupancy light-duty vehicles when operated at a low load factor. It is more efficient than intercity and commuter rail modes.[61,62,63]

From Figure 14 one may infer that hyperloop systems could be significantly more energy efficient than traditional modes of passenger travel when deployed. Travel by automobile, for example, could consume 2 to 5 times more energy per passenger-mile traveled; travel by air could consume 2 to 4 times more; and travel by intercity rail could consume around the same energy or up to 3 times more.[64] These differences, however, decrease significantly, when

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[61] Energy intensity numbers for passenger vehicles were calculated using 2030 fuel economy projections from the U.S. Energy Information Administration's 2019 Annual Energy Outlook. These values represent the average performance of the entire 2030 vehicle fleet, except the best-in-class numbers which represent highly advanced and efficient 2019 vehicles in those classes (a Hyundai Ioniq Electric for car and a Toyota Highlander Hybrid SUV for light truck). LD Vehicle Mix is a VMT-weighted average energy intensity, representing the entire light duty passenger fleet. Energy intensities for each other non-hyperloop mode were calculated using 2016 numbers from Oak Ridge National Laboratory's Transportation Energy Databook (TEDB), Edition 37 (Table 2.14). All numbers are end-use, not well-to-wheels. As a reference, the passengers per vehicle for the figure are: 1.5 for car; 5 for car, high occupancy; 1.8 for personal truck; and 6 for personal truck, high occupancy.

[62] Load factor: The ratio of passengers carried versus the total passenger capacity of a vehicle. Air travel in 2018 has load factors around 80%, while the latest data for public transit estimates a range of 10% (bus) to 30% (commuter rail) load factor. Elon Musk suggested a load factor of 70% for hyperloop systems. Passenger vehicle load factor is typically defined by the number of passengers carried. In this analysis, the baseline load factor was taken to be 1.54 for Car and 1.82 for Light truck, per the TEDB, Appendix A Section 3. TEDB derived these load factors from 2017 National Household Travel Survey data. The high occupancy (HO) load factors were taken from DOE EERE's Alternative Fuel Data Center (AFDC) Mass Transit web page: https://afdc.energy.gov/conserve/mass_transit.html.

[63] Hyperloop system energy intensity is *highly sensitive* to several parameters, including but not limited to: load factor, tube leakage rate, tube pressure, and pod mass.

[64] Each of these multiplier calculations compare *2030 Car* and *2030 Light Truck* to *Hyperloop (70% LF)* and *Hyperloop (70% LF)* from Figure 14.

comparing hyperloop to the most efficient or "best-in-class" 2019 car and truck, as indicated on Figure 14 with tick-marks.

Table 4: Estimates of relevant passenger transportation sector energy consumption by mode and distance band. Source: PMT demand derived from 2017 NHTS data, grouped by the mode(s) and distance band noted. Energy intensities for each mode, as shown in Figure 14, were applied to PMT demand to estimate energy consumption. Total energy consumption was benchmarked to the 2016 value from the Transportation Energy Data Book, Table 2.7 (26,525.9 TBtu).

Mode and distance band	Estimated energy consumption (trillion BTU)	Share of total transportation sector energy consumption (%)
All bus and rail between 100-1000 miles	80	0.3
All air travel under 500 miles*	210	0.8
All on-road light-duty vehicle travel between 250-500 miles	690	2.6
All air travel under 1000 miles*	780	2.9
All on-road light-duty vehicle travel between 100-1000 miles	2700	10.2

* Air travel estimates include trips below the estimated range of feasible hyperloop trip distances (100-1000 miles) because of the high potential for passenger time savings on short flights. Airport check-in, taxi-out, and taxi-in consume a large portion of the total trip time for these shorter flights.

Table 4 provides data on nationwide transportation energy use in the market segments of passenger travel identified as likely applicable to hyperloop competition. The total energy use in these segments is about 3.6 quads, or about 13 percent of total transportation energy demand.

The extent to which hyperloop systems may save energy in these market segments depends on many factors. While hyperloop systems may be relatively energy efficient on a per-passenger-mile basis, they would have to be deployed widely and capture a significant share of each applicable market to have a meaningful effect at the national level.

Consider, for example, the capacity for passenger throughput. In the hypothetical design analyzed in Section II for grid impacts, passenger pods are assumed to launch every 2 minutes on average, with an average load factor of 70 percent, or about 20 passengers per pod. Such a system would be able to transport about 600 passengers per hour in a single lane or tube.[65] This could be up to 1,200 passengers per hour, traveling both ways.

There are more than 3,700 city pairs within the intercity distance ranges assumed for this analysis. A little over 100 of these city-pairs, looking at air traffic alone, experience transport volumes of more than 1 million passengers per year. This equates to average volumes of 2,700 passenger trips per day. Hyperloop deployment at scale might capture 50 percent of regional air travel in the intercity range, or about 100 systems.

Whether 100 or 1,000 hyperloop passenger systems are built and operated, the energy impacts nationwide would depend on the extent to which they could capture or induce market demand

[65] This is highly sensitive to pod launch interval. For example, at a launch interval of 30 seconds, the system could move over 2500 passengers per hour per lane.

and on the extent to which transport volume on any given travel day is capacity or congestion constrained. Because these factors are widely variable and mostly unknown, it is not possible to estimate with confidence the potential energy consumption effects of hyperloop system deployment (network penetration) nationwide.

It is possible, however, to examine a single, hypothetical case. Assume a hyperloop system that connects one city-pair over 300 miles, operating in 2030. Assume it transports on average 7,500 passengers per day, each way, or 15,000 passengers daily, every day of the year, as suggested as operational conditions outlined among hyperloop developers. In this modal shift example, a hyperloop system with a 70 percent load factor might save around 3 trillion BTU (TBtu) per year, or 0.01 percent of projected national energy transportation demand in that year.

If 100 of these systems were operating with the same degree of energy savings, compared to meeting equivalent travel demand with current transportation modes, the energy savings could amount to about 1.1 percent of total projected transportation energy demand in that year. Passenger travel in the intercity range of 100 to 1,000 miles, however, is limited. Some intercity routes exhibit relatively high traffic volumes and others much less. Energy savings on a national scale would not be expected to scale linearly, but would be commensurate with the extent of deployment and the traffic volumes carried. These, in turn, may be limited by the selected routes and intercity travel patterns. Alternatively, if hyperloop systems were to create a significant amount of induced demand, overall transportation system energy use could increase.

Freight

Medium- and heavy-duty trucks are responsible for most of freight transportation's energy consumption (6.1 quads), followed by transport by water (0.6 quads), pipeline (0.8 quads), rail (0.5 quads), and air with smaller shares, as shown in Figure 15.[66] Developers suggest that hyperloop systems could capture a portion of the higher-value short-, medium-, and long-haul freight transport market segments. The U.S. Department of Transportation (DOT) Volpe Center reviewed the hyperloop technology and its potential freight applications[67], and found that:

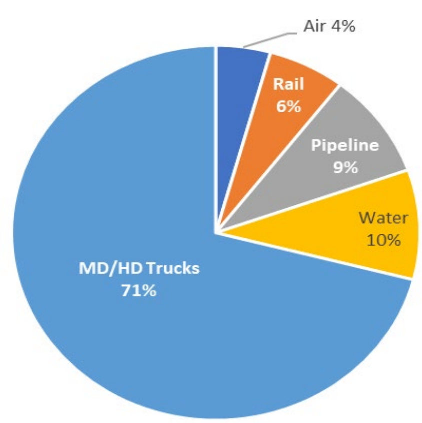


Figure 15. Freight transportation energy consumption shares by mode (Oak Ridge National Laboratory Transportation Energy Data Book)

1. **Truck** freight will likely be more cost effective than hyperloop, while also maintaining quick delivery times (less than a day) for trips less than 500 miles.

[66] Oak Ridge National Laboratory, 2018.

[67] Taylor, Catherine, David Hyde, and Lawrence Barr. "Hyperloop Commercial Feasibility Analysis:" DOT Volpe, July 2016.

2. **Rail** infrastructure is highly efficient for heavy, bulk cargo that is not time-sensitive, and it would likely be difficult for hyperloop systems to penetrate this market.
3. **Air** freight is expensive, energy-inefficient, and is only used for high-value, time-sensitive, or perishable cargo. This market segment, therefore, is open to hyperloop competition, provided that hyperloop developers could successfully build and improve on the highly effective hub-and-spoke networks currently used by air shippers.

The literature typically places the economics of hyperloop shipping, among competing modes, somewhere between air and truck in terms of cost, speed, and reliability, as illustrated in Figure 16.

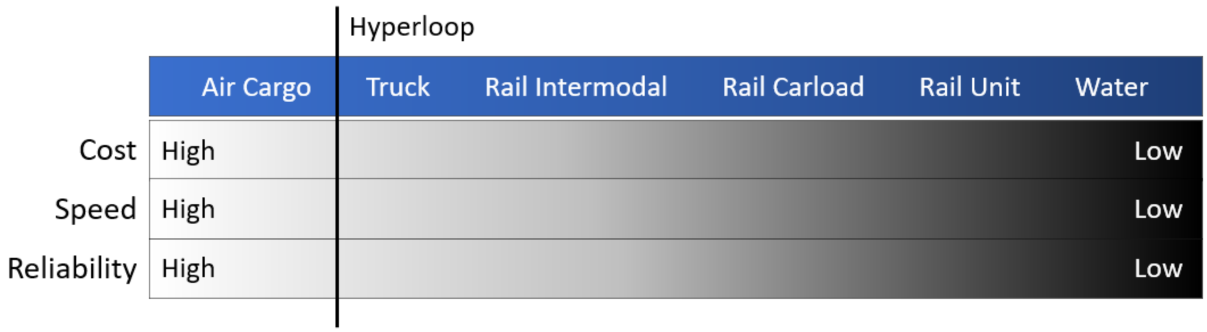
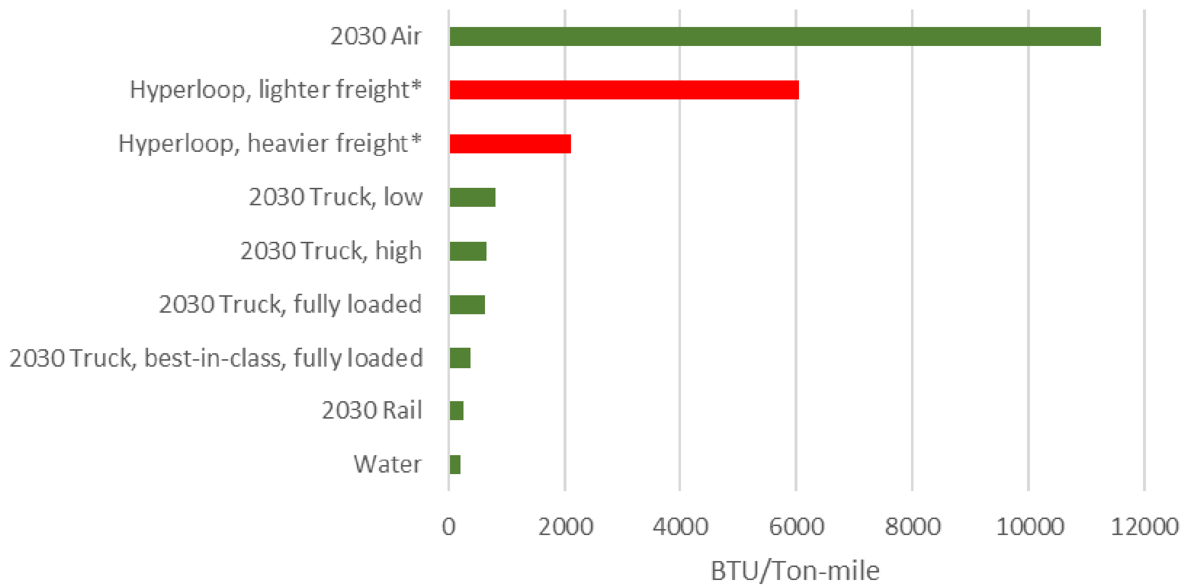


Figure 16. Range of freight transportation mode parameters, estimated. Position of hyperloop is estimated based on literature review.

Hyperloop freight systems could potentially compete with short-haul air freight and medium- or long-haul trucking freight. According to the latest data from the U.S. Bureau of Transportation Statistics, air freight generates nearly 5 times more revenue per ton-mile than truck freight.[68] While beyond the scope of this analysis, this gap in shipping cost may indicate some level of latent demand for shipping that is faster than truck but cheaper than air.

[68] U.S. Bureau of Transportation Statistics. "Average Freight Revenue per Ton-Mile." Accessed December 21, 2018. https://www.bts.gov/content/average-freight-revenue-ton-mile.

Energy consumption modeling (see Appendix) estimates that hyperloop systems would be more efficient, in terms of energy use per-ton-mile, than air, but would be less energy-efficient than other competing freight modes as shown in Figure 17. The range of system efficiency depends on the size and weight of freight being shipped.[69]



* *Lighter freight* and *heavier freight* hyperloop modes represent aircraft/palletized freight and intermodal shipping contain freight respectively. Additional assumptions are in Section IV.

Figure 17: Energy use of hyperloop systems relative to other freight transportation modes.[69]

The primary factor in favor of mode-switching to hyperloop, it is assumed, would be reduction in the amount of travel time required for shipping high-value, time-sensitive, or perishable goods. Energy efficiency is a factor, but likely to be a secondary consideration, embedded with other cost factors. Freight transport energy efficiency is a positive factor for hyperloop

[69] *Truck, low* and *Truck, high* categories correspond to average heavy-duty truck payloads of 16 and 22.7 tons, respectively. The high payload (22.7 tons) was from Maks Inc. "FAF Freight Traffic Assignment," October 2016, and the low payload (16 tons) from Brown, Austin, and Laura Vimmerstedt. "Transportation Energy Futures Series: Freight Transportation Modal Shares: Scenarios for a Low-Carbon Future," n.d., 94. *Truck, low* also corresponds to the total truck weight used in the DOE SuperTruck research (65,000 lb).

Truck, fully loaded assumes a payload of 47,500 pounds, maxing out the class 8 truck GVWR of 80,000 pounds. This is based on an assumed class 8 tractor weight of 19,000 pounds and 53-foot trailer weight of 13,500 pounds, per EPA's Regulatory Impact Analysis for the Phase II MD/HD GHG Regulation, Table 3.22. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

Truck, best-in-class, fully loaded assumes the same 47,500-pound payload, hauled by a fully-electric truck performing at EIA's 2030 projected new vehicle fuel economy. Medium-duty trucks are not included in this analysis; see note in Section IV.D

Truck and rail energy intensity values are calculated using class 7 and 8 fleet stock and rail stock fuel economy projections from EIA's 2019 AEO. Energy per ton-mile for water is from Oak Ridge National Laboratory's Transportation Energy Databook (TEDB), Edition 37 (Table 2.16). EIA does not publish fuel efficiency projections for water-based freight. The latest data available, from the TEDB, are from 2014.

Air energy intensity is calculated using the distance-based algorithm and fuel-burn rates (by aircraft) from O'Kelly, Morton E. "Air Freight Hubs and Fuel Use," September 2014, 16. EIA does not publish freight-specific air fuel efficiencies; therefore EIA's projected trend in seat-mpg passenger air improvements is applied to the calculated base air freight energy intensity to estimate future air freight efficiency.

See Section V.D for additional discussion of methodology and assumptions.

compared to air transport, because of reduced costs, but a negative factor compared to trucking, which is the major energy consuming freight market segment.

The analysis explored several hypothetical mode-shifting categories to illuminate the areas of freight transport energy use where a hyperloop system might capture market share. One category is air freight traveling under 1,000 miles, as shown in Table 5. This category accounts for about 40 TBtu in total energy consumption. A larger category is freight transport by truck. For all truck freight traveling between 500 and 1000 miles, the energy consumption is 520 TBtu. Narrowing this to the highest-value freight traveling between 100 and 1000 miles, that is, the 25 percent most valuable freight shipped between 100 and 1000 miles, the energy consumption is about 60 TBtu. Additional value tiers are displayed by top 1 percent, 5 percent, and 10 percent.[70]

Table 5: Segmentation of relevant freight transportation sector energy consumption by mode and distance band, 2016. Source: Analysis of FAF data.

	Mode and distance band	Total energy consumption (trillion BTU)
1	Air freight under 1000 miles	40
	Truck Freight Traveling Between 100 and 1000 Miles	
2	Top 1% of value	< 1
3	Top 5% of value	2
4	Top 10% of value	8
5	Top 25% of value	60
	Truck Freight Traveling Between 500 and 1000 Miles	
6	10% of ton-miles	50
7	25% of ton-miles	130
8	100% of ton-miles	520

Trucking energy intensity was estimated using a range of truck payloads. The high payload (22.7 tons) was from *Maks Inc. "FAF Freight Traffic Assignment," October 2016*, and the lower (16 tons) from *Brown, Austin, and Laura Vimmerstedt. "Transportation Energy Futures Series: Freight Transportation Modal Shares: Scenarios for a Low-Carbon Future," n.d., 94*.

Assuming that all air freight is high-value, time-sensitive or perishable, and that similar freight by truck would fall into the top-25 percent tier or higher, the total energy consumption for "high value" freight by these measures, under 1,000 miles of shipping distance for air and 100-1000 miles for trucks, would account for about 100 TBtu. This equates to between one quarter and one half of one percent of total transportation energy demand. The energy associated with high-value shipping by truck for routes between 100 and 1,000 miles is 60 TBtu. This equates to

[70] See Section V.D for methodology and assumptions.

about 0.9 percent of total energy consumed by all medium- and heavy-duty trucks (6.1 quads) in 2016. See Section V for assumptions.

The information from Figure 16 suggests that hyperloop might best compete with high-value air cargo. The data from Figure 17 indicate that diversion of freight demand from air to hyperloop, in this limited but specialized case of "high value", could result in energy savings, due to hyperloop's greater energy efficiency compared to air freight. In the case of a lighter freight hyperloop system, if implemented in the 2030 timeframe, the energy savings might be on the order of 50 percent per ton-mile shipped. In the case of heavier freight hyperloop system, in 2030, the energy savings might be on the order of 80 percent per ton-mile shipped. Recall that the "lighter freight" and "heavier freight" hyperloop systems represent designs that can accommodate, respectively, aircraft/palletized freight and intermodal shipping contain freight.

In the case of mode-shifting to hyperloop systems from high-value truck freight, by contrast, there would be an increase in energy use, due to the loss of higher efficiency truck transport on a per ton-mile basis. Energy use per ton-mile shipped by hyperloop might increase by 3- to 9-fold, compared to the 2030 heavy-duty truck fleet across a range of payloads. See Section V.D for methodology and assumptions.

A two-tube hyperloop freight system between Los Angeles and San Francisco, California may be capable of transporting between 800 million and 1.2 billion ton-miles of freight per year. This assumes 365-day operation, 12 to 18 hours per day, with pod launches every 4 to 6 minutes. It assumes the larger hyperloop tube design, transporting 40-foot standard intermodal shipping containers. The latest freight movement data (2012) estimates that trucks carried 6.7 billion ton-miles between the two cities in 2012.[71] This would imply that a hyperloop system, as hypothesized, could be capable of carrying up to about 20 percent of total truck freight, or 10 percent of combined truck, water, rail, and air freight between the cities.

For freight transport, modal shift to hyperloop systems from high-value air cargo traveling less than 1,000 miles could reduce energy use in the inter-city market segments assumed. While the amount is not estimated, its effect on overall energy demand would be limited by the total amount of energy attributed to this market segment (40 TBtu), the availability of hyperloop transport routes to compete effectively with the well-developed hub-and-spoke air cargo distribution system, and the extent to which hyperloop's offerings would capture market share. The analysis indicates, by contrast, that any modal shift of freight to hyperloop systems from trucking, and not air, would increase overall transportation energy system use in the market segments assumed.

Section Summary

Although costs are unknown, it is possible that hyperloop systems could compete effectively in some high-value passenger, lighter-freight and, to a lesser extent, heavier freight transportation

[71] Oak Ridge National Laboratory. "Freight Analysis Framework Version 4." https://faf.ornl.gov/fafweb/

market segments. If implemented, the energy-related effects on transportation energy consumption of the resulting modal competition would be mixed, with decreases in energy use for passenger and air cargo freight due to relatively higher energy-efficiency of hyperloop systems, compared to competing modes, and increases in energy use for heavier freight due to the opposite.

The magnitude of the effects on a national scale is unknown, in part, because there is no fact-basis for determining or estimating the number of hyperloop systems that might be built or operated and, in part, because it is not known to what extent hyperloop systems would compete for and capture market shares. These variables are sensitive to the comparative economics of competing transport modes and regional circumstances. These, in turn, are linked to consumer choices and modal shifts, which are beyond the scope of this analysis.

Given the uncertainties, the analysis does quantify the relative energy efficiencies of all potentially competing modes, hypothesizes case studies, and points to the direction of changes in energy consumption that might take place under various scenarios. It also sets limits regarding the energy-efficiency effects on national transportation system energy use, based on the amount of energy used or projected to 2030, in each of the relevant market segments.

V. Analysis Methodology (APPENDIX)

V.A. Introduction

Hyperloop technology is a proposed technology and its related transport system designs are still under development. No full-scale operational system has been built or operated. Assumptions about the characteristics of potential full-scale system were required to complete the analysis and are conceptual in nature. These assumptions, when combined with public data on energy use, first-principles of physics and engineering, and modeling tools, as outlined below, resulted in the basis for the report's assessments of the impacts on energy efficiency and the grid. This Appendix describes the modeling tools and assumptions that underlie the assessment.

V.B. Modeling Tools

The grid modeling efforts were completed in two parts: (a) modeling of the load profile of typical hyperloop systems, and (b) modeling of the impacts of this load profile on local and regional grids. Separate models were used for the two parts of the analysis and information was exchanged between the models to develop and converge on a single assessment of hyperloop grid impacts.

For the analysis of transportation energy system impacts, energy demand and load profiles were developed using an Excel-based model generated from the basic operational characteristics and regimes of the a conceptualized hyperloop system (pod acceleration, pod deceleration, pod cruise and speed maintenance, tube vacuum maintenance, pod airlock pump-down for loading and unloading). This model is based on engineering concepts for hyperloop operation and allows users a wide range of flexibility in adjusting basic assumptions about the hyperloop system.

Key inputs include the number of tubes, stops per mile, system length, operating times of day, allowable speeds and acceleration rates, pod sizes and mass (weights), and loading/unloading times. Key model outputs required for this analysis include the energy intensity of hyperloop systems (in BTU/passenger mile or BTU/ton-mile) and the detailed second-by-second electrical load profile for the hyperloop system during a typical day of operation. The energy intensity output was used to assess the potential effect of hyperloop transportation on overall transportation energy, while the load profiles were used as inputs to the electrical grid modeling (described below). Hyperloop systems were assumed to operate 365 days/year.

Impacts of hyperloop electricity demand were analyzed using dynamic, alternating current (AC) power flow models commonly-used by the transmission planning engineering community for interconnection studies. The simulation tool used was Power System Simulator for Engineers (PSSE) software developed by the Siemens PTI and General Electric's Positive Sequence Load Flow (PSLF) model. The data sets representing all grid assets (generators, transmission lines and controls assets) were obtained from 2 power authorities. For the Eastern Interconnection, the

PSSE data sets were developed and validated by the Multiregional Modeling Working Group (MMWG) of the Eastern Interconnection Reliability Assessment Group (ERAG), using a specific data set for studies of the 2018 peak summer condition. For the Western Interconnection, a PLSF data set was used, as developed by the Western Electricity Coordinating Council (WECC), developed by the System Data Work Group (SDWG) with oversight from the Data Subcommittee and other reliability committees. For this study the 2017 dataset representing a summer heavy load scenario was used.

These models assess the steady state as well as dynamic behavior of large transmission systems. System behavior of interest are AC voltage and frequency effects in response to some changes in the system. In this study the changes were induced by the hyperloop load.

V.C. Key Assumptions

Assumptions for Passenger and Freight Systems:

1. A cruise speed of 629 mph (Mach 0.82) was selected due to NASA's analysis of the optimal tradeoff between pod speed and the aerodynamics of the tube area. Mach 0.82 was the optimal point of operation.[72] This requires the use of a compressor to avoid a "pistoning" effect in the tube. The speed limit, or threshold at which losses become too great, for a hyperloop pod without a compressor has been estimated at around Mach 0.675 (518 mph).[73]
2. The passenger system is fully pressurized nightly and evacuated in the morning before restarting operation. This allows for inspections and maintenance on vacuum pumps, pod propulsion and levitation systems, and the tube walls. The freight system, due to the likelihood of higher demand throughout the day as well as lower safety constraints (not transporting passengers), was modeled to fully pressurize once per week for inspections and maintenance.
3. Aerodynamic drag is assumed to be constant (equal to drag at cruise speed) due to negligible magnitude at lower speeds. Friction during low-speed acceleration (before the pod starts to levitate magnetically) was ignored for the same reason.
4. Each tube's starting point is the opposing tube's end point, *i.e.*, there is a single station at the beginning and end of each pair of tubes. All intermediate stations are staggered.
5. Stations share (*i.e.*, evenly split) all electricity loads that are not specific to a single station (*e.g.*, acceleration boosts that occur between stations or vacuum pumps installed between stations).
6. Elevation changes and eddy current losses were ignored.

[72] Decker, Kenneth, Jeffrey Chin, Andi Peng, Colin Summers, Golda Nguyen, Andrew Oberlander, Gazi Sakib, et al. "Conceptual Feasibility Study of the Hyperloop Vehicle for Next-Generation Transport," n.d., 22.

[73] Opgenoord, Max, Chris Merian, John Mayo, Philippe Kirschen, Colm O'Rourke, Greg Izatt, Greg Monahan, et al. "MIT Hyperloop Final Report," August 2017, 134.

7. All system infrastructure routing is assumed, for analytical purposes, to occur in a straight line between origin and destination. It is noted that introducing curvature to the track would require a pod to either rotate axially or slow down, in order to manage lateral acceleration forces.
8. Passenger pod load/unload time estimates were built from the bottom up, *i.e.*, given a pod launch interval along with estimated times for airlock pumpdown and safe minimum headway, how much time is leftover for egress? 60 seconds appeared to be a reasonable estimate and is within the range cited in the literature.[74,75]

Assumptions for Freight-Only:

1. To account for a range of system designs, two different freight hyperloop configurations were modeled. The smaller system (*lighter freight*) is sized similarly to the passenger hyperloop. Pods would carry typical aircraft cargo containers, around the size of an 8’ x 10’ room. These containers would be moveable by forklift, so the pod launch interval was assumed to be 2 minutes shorter than the Hyperloop, larger *heavier freight* case. The *heavier freight* case is sized to transport full-size intermodal freight containers. For reference, a 40-foot shipping container could comfortably fit two Ford F150 pickup trucks end-to-end.
2. Cargo capacity utilization was set at 60 percent, due to freight containers “cubing out” before reaching their weight limit. Data on freight utilization rates is difficult to obtain, but this analysis uses a truck freight estimate from McKinsey. [76]
3. It was assumed that freight would take longer to load than a passenger pod, but there was very little literature on this. Shahooei et al. estimated around 6 minute headways to load shipping containers, therefore an estimate of 6 minutes was used for the large freight pods and 4 minutes for the small freight pods.[77]

V.D. Case Study Analysis Methodology

Passenger and freight case studies using the latest available transportation demand and energy data explored the energy impacts of a range of hyperloop network penetration scenarios. In order to estimate energy consumption of existing modes, passenger- and freight-demand data (passenger-miles-traveled, or PMT, and ton-miles, respectively) were segmented by *mode*, *distance*, and in the case of truck freight, *value*. These transportation demand values were

[74] The following paper estimates 40 seconds for 30 passengers in and 30 out. San, Hor Peay, and Mohd Idrus Mohd Masirin. “Train Dwell Time Models for Rail Passenger Service.” Edited by N. Abd Rahman, Z. Mohd Jaini, R. Yunus, and S.N. Rahmat. MATEC Web of Conferences 47 (2016): 03005. https://doi.org/10.1051/matecconf/20164703005.

[75] Average dwell time of 95s (stdev of 25s) for 324 trains in Zurich. Gysin, K. “An Investigation of the Influences on Train Dwell Time,” n.d., 6.

[76] Chottani, Aisha, Greg Hastings, John Murnane, and Florian Neuhaus. “Autonomous Trucks Disrupt US Logistics | McKinsey.” Accessed January 9, 2019. https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/distraction-or-disruption-autonomous-trucks-gain-ground-in-us-logistics.

[77] Shahooei, Sirwan, Ferika Farooghi, Seyed Ehsan Zahedzahedani, Mohsen Shahandashti, and Siamak Ardekani. “Application of Underground Short-Haul Freight Pipelines to Large Airports.” Journal of Air Transport Management 71 (August 2018): 64–72. https://doi.org/10.1016/j.jairtraman.2018.06.008.

multiplied by energy intensity estimations for both existing modes and hyperloop to develop the energy consumption of each transportation mode, at which point an energy impact could be assessed.

Both passenger and freight case studies included several simplifying assumptions:

1. Only modal shift, or diverted demand, was included in the analysis. Induced demand was not explicitly included.
2. Hyperloop operators identified a feasible business case for deployment and operation.
3. Each hyperloop system operated between two cities without any intermediate stops.

Passenger Case Study

The passenger case study outlined the potential hyperloop system impacts on energy efficiency in the passenger transportation sector. The case study development followed a 5-step process:

1. Calculate the hypothetical PMT demand using hyperloop operational parameters as provided by hyperloop technology developers in public sources
2. Develop a hypothetical system length that is representative of potential hyperloop implementation. The hypothetical system will include several city pairs with sufficient existing demand to divert to hyperloop
3. Estimate energy intensities for (a) the current modal distribution (*e.g.* cars, light trucks, air, etc.), using a passenger-miles-traveled (PMT) weighted average and (b) a hyperloop system
4. Determine the energy consumption required to meet the hypothetical PMT demand by applying energy intensities for (a) current modes and (b) hyperloop
5. Compare the two energy consumption results to estimate energy impact of hyperloop system implementation at varying levels of network penetration, including 10, 100, and 1,000 separate systems[78]

Hyperloop PMT Demand and Hypothetical Route Length

Each hyperloop system was assumed to carry approximately 15,000 passengers each day; 7,500 passengers each way. This is based on the current hyperloop model parameters reported by technology developers: average pod launch interval of 2 minutes[79], daily operation of 12 hours, and a 70 percent load factor[80].

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[78] Recent literature suggests that about 10 intercity systems are under consideration in the United States. Credit: Meredith Rutland Bauer (compiled from numerous company and government communications) and Sean Quinn (graphics), as appearing in Smart Cities Dive (https://www.smartcitiesdive.com/news/hyperloop-ultrafast-transportation-environment/544516/)

[79] Telephone communication between the U.S. Department of Energy and the Virgin Hyperloop One Chief Technology Officer, Mr. Rob Ferber, August 28, 2018.

[80] Hyperloop Alpha concept paper, SpaceX, 2013, https://www.spacex.com/hyperloopalpha.

The analysis assumed that the magnitude of demand described, namely, 15,000 passengers per day, exists between each hypothetical city pair. The process outlined below was used to identify the travel distance bands containing city pairs with sufficient PMT demand to meet or exceed the hypothetical 15,000 passenger/day hyperloop capacity.

1. Use 2017 National Household Travel Survey (NHTS) data to determine the modal distribution of PMT demand for a distance band that contains the hyperloop system length under consideration.[81] An example using a length of 300 miles with a distance band between 250 and 350 miles is shown in Figure 18 below. This represents the *average* PMT distribution by mode across *all* destinations spaced between 250 and 350 miles apart.[82]

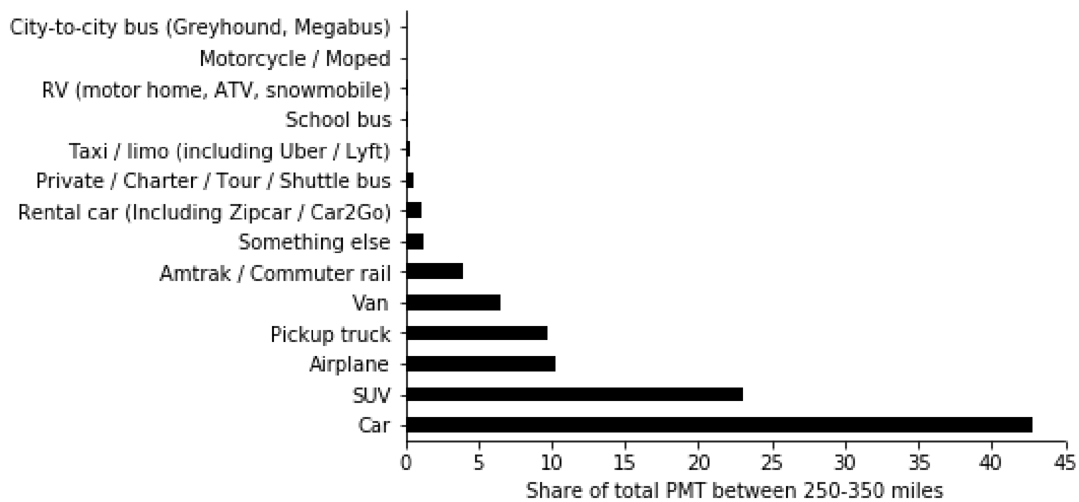

Figure 18: PMT distribution by mode for trips between 250 and 350 miles. Source: Analysis of 2017 NHTS.

2. Calculate the total PMT demand for each hyperloop system, using the specified 15,000 passengers per day and the route length in question. In the case of a 300-mile route, the demand estimate was 1.65 billion PMT per year, calculated as 15,000 passengers per day x 300 miles x 365 days per year. The portion of this attributed to "Airplane" can be calculated using Figure 18 above; in this case, 10 percent x 1.65 = 0.165 billion PMT.
3. Use Bureau of Transportation Statistics' (BTS) T-100 Air Carrier Domestic Market data to estimate the PMT demand between each city pair in the given distance band: continuing the above example, city pairs between 250 and 350 miles apart. [83] Determine if there is

[81] U.S. Department of Transportation, Federal Highway Administration, 2017 National Household Travel Survey. URL: https://nhts.ornl.gov.

[82] The distance band in each route length analysis spanned +/- 50 miles of the specified route length to ensure that a sufficient range of city pairs and PMT demand were included, both in NHTS and the T-100 data. Specifying a single trip distance, *e.g.* 300 miles, produces a significantly smaller dataset (*i.e.*, there are only a couple of cities pairs that are 300 miles apart, not 301 or 299).

[83] U.S. Bureau of Transportation Statistics. "T-100 Domestic Segment Data." Accessed February 19, 2019. https://www.transtats.bts.gov/databaseinfo.asp?DB_ID=111.

sufficient PMT demand between each pair to meet the "Airplane" share of total PMT, which is 0.165 billion PMT in the example 300-mile case. There were an estimated 840 city pairs total in the 300-mile range, 10 of which meet the required air PMT demand.

The air PMT demand was of particular interest because it signals an existing consumer demand for high speed travel. Additionally, PMT demand at the city pair level was not available for LDV transportation modes. It was assumed that, if the air PMT demand between two cities was sufficient to meet the air share of hypothetical PMT demand, that the LDV PMT demand scaled proportionally and was also sufficient.

This process was repeated for several hypothetical hyperloop system lengths. The number of city pairs that met the air PMT demand in (3) above are shown in the last column in Table 6 below.

Table 6: Estimates of the number of city pairs within each distance band that meet the minimum air PMT demand required to sustain mode-switch to hyperloop. Source: Threshold air PMT demand estimate from 2017 NHTS data; city pairs and air PMT demand estimated from U.S. BTS T-100 Air Carrier data,

Distance band (miles)	Total number of city pairs	Number of city pairs meeting air PMT demand requirement
50-150	1,200	80
150-250	1,000	15
250-350	840	10
350-450	740	0
450-550	770	0
550-650	700	0
650-750	670	0
750-850	570	1
850-950	540	1
950-1,050	500	1

The final hyperloop system length used for the passenger case study was 300 miles, encompassing PMT demand between city pairs spaced between 250 and 350 miles apart. This has a reasonable number of city pairs with sufficient air PMT demand, is entirely within the hyperloop system range of 100-1000 miles selected for this report and includes the Los Angeles to San Francisco route originally suggested in the *Hyperloop Alpha* paper.

It should be noted that, if the PMT demand for this 250-350-mile distance band were spread out and *averaged* across all 840 city pairs, there would not be enough total PMT demand for 840 hyperloops, even if 100 percent of PMT across all modes were diverted. That is, the total passenger carrying capacity for a series of 840 hyperloop systems at the 15,000 passenger/day level is more than the total number of passengers currently moving between those city pairs. As a result, hyperloop systems would need to induce a significant amount of additional PMT to continue operating at 15,000 passengers per day. This is shown in Figure 19 in the form of average daily PMT demand, alongside the total U.S. passenger transportation demand across all distances.

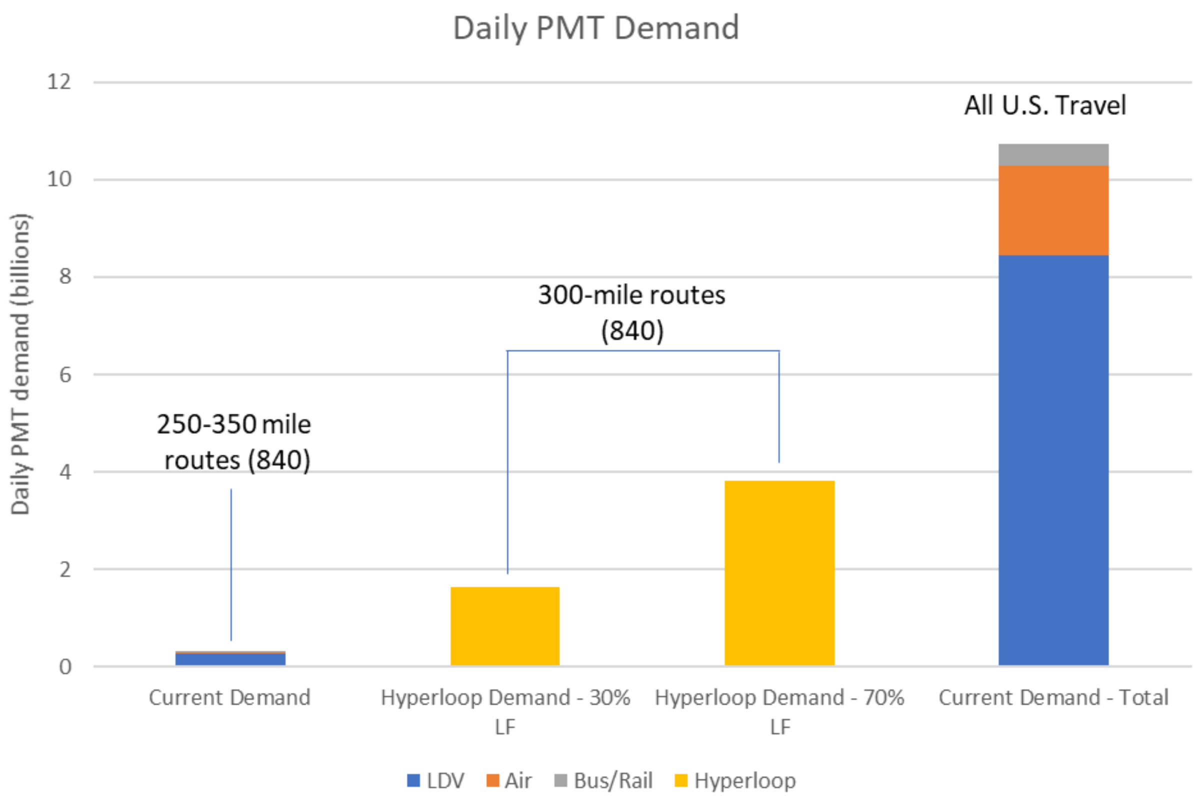

Figure 19: Estimated daily PMT demand from 840 city pairs spaced between 250 and 350 miles apart, compared to 840 hyperloop systems operating 12 hours per day with 30-passenger pods and 2-minute launch intervals. **Source for Current Demand and All U.S. Travel: National Household Travel Survey[81,84] Source for Hyperloop Demand: Current analysis.**

Therefore, the final results shown in Table 8 and discussed in the report were of two categories: (a) no induced demand, including the single and 10 city pair estimates; and (b) assumed induced demand in the hyperloop case and increased demand in the current modal distribution case , including the 100 and 1,000 city pair estimates. Expressed another way, the city pairs analyzed in case (a) have sufficient passenger demand to use the estimated hyperloop passenger capacity, while the additional city pairs in case (b) do not currently use or need that much passenger capacity. Although not modeled explicitly, an induced demand equal to the excess hyperloop capacity could be created by the hyperloop systems. The latter case, covering the 100 and 1,000 city pair scenarios, assumes that the demand would exist regardless of hyperloop implementation, *i.e. the energy consumption impacts of increases in PMT were not included*.

[84] The *LDV* category was assumed to include the following NHTS-defined mode options: *Car, Pickup truck, SUV, Van, Rental car (including Zipcar / Car2Go), Taxi / limo (including Uber / Lyft), and Something else*. *Something else* is a catch-all category in the survey, responsible for around 1.2% of the PMT demand in the distance band assumed.

Energy Intensity Calculations

The analysis assumed that PMT demand along this 300-mile hypothetical route was fully met either by a mix of current modes or by hyperloop (effectively replacing all passenger modes for this route with hyperloop). The energy intensity of hyperloop was estimated from the known system characteristics of hyperloop as part of the Report to Congress analysis. The 2017 national Household Travel Survey (NHTS) provided a distribution of PMT across all current modes, for a range around the selected route length, to determine the composite energy intensity of the current set of transportation modes for comparison to hyperloop.[81] According to the NHTS, air and light-duty vehicle (LDV) modes fulfill most of the demand (around 95 percent) across similar distances.

Hyperloop developer estimates suggest that the first system will not be operational until the mid-2020s. Therefore, rather than assuming hyperloop will replace today's fleet, the analysis uses EIA's projected 2030 fleet average fuel economies for both air and LDVs. These fuel economies were converted to energy intensities based on load factor assumptions and energy content of fuel.[85]

It is possible to calculate a *weighted average* energy intensity using the NHTS-derived PMT distribution discussed earlier in this section and the energy intensities calculated from EIA's projected fuel economies, as shown in Table 7 below. The PMT distribution by mode is from 2016-2017 data and the energy intensities are all based on 2030 EIA projections, except for the bus and rail categories.[86][87] The latter exception has a negligible impact on the final weighted average energy intensity due to its small PMT share, around 0.4 percent, in this distance band. Weighted energy intensities were also calculated for 2025 and 2050, as shown in Table 8.

[85] LDV energy intensity is calculated using the equation below, with load factors of 1.54 for cars and 1.82 for light trucks, based on TEDB Ed. 37, Appendix A Section 3.

$$Energy\ Intensity\ \left(\frac{BTU}{PMT}\right) = \frac{Energy\ Content\ \left(\frac{BTU}{gallon}\right)}{Fuel\ Economy\ \left(\frac{mile}{gallon}\right) * Load\ Factor\ (passengers)}$$

Air energy intensity is calculated using the equation below, with all inputs from EIA's 2019 AEO.

$$Energy\ Intensity_{air} = \frac{energy\ content_{jetfuel}}{seat\ mpg * load\ factor}$$

The energy contents of gasoline and jet fuel were assumed to be 120,429 BTU/gallon and BTU/gallon respectively, per EIA. https://www.eia.gov/outlooks/aeo/pdf/appg.pdf

[86] Bus and rail transportation modes are highly dependent on load factor. EIA does not publish projected load factor estimates through 2030; therefore, the energy intensities for these modes were held constant at 2016 values from the Transportation Energy Data Book, Ed 37, Table 2.14.

[87] It is assumed that the distribution of PMT by mode, from 2016-2017 NHTS data, is *constant* through 2050.

Table 7: Calculation of the PMT-weighted energy intensity for trip distances between 250-350 miles. PMT and PMT shares were estimated from 2017 NHTS. *School bus* was not included due to its negligible PMT, accounting for < 1 percent of the total.

Mode	PMT (billion)	Share of total	Energy intensity (BTU / PMT)	Year for energy intensity estimate
Air	11.6	10%	2,100	2030
Car	50.9	45%	2,100	2030
Light truck	45.3	40%	2,500	2030
Amtrak / Commuter	4.6	4%	1,600	2016
Intercity / Shuttle bus	0.7	1%	1,000	2016
Combined	**49.2**	**100%**	**2,200**	**Mixed**

Operating under the assumption that the excess demand for any more than 10 city pairs will be either induced by hyperloop or applied to the current modal distribution, the three different scenarios represent three levels of network penetration:

1. A single system to understand the impacts of one hyperloop deployment
2. Ten systems to estimate the impact from implementing all currently planned hyperloop proposals in the United States.
3. One hundred systems to explore the impact of hyperloop deployment across all city pairs with air travel demand greater than 1 million passengers per year.[88]

Each of the systems was assumed to be identical, namely, 15,000 passengers per day over a two-way 300-mile route. The final passenger-mile demands for each system were converted to energy using the energy intensities of each mode: composite air, LDV, bus, and rail, compared to hyperloop with a 70 percent load factor. Table 8 details the results from which the final range of impacts were drawn.

[88] Analysis of BTS T-100 data estimates a total of 108 city pairs with demand over 1 million passengers per year.

Table 8: Energy impact calculations for the passenger case studies. The percentages represent the share of projected total transportation energy demand in that year, per EIA's 2019 AEO. The current analysis estimates that the PMT demand for 1 and 10 city pairs is currently available to sustain hyperloop developers' operational conditions.

Year	BTU/PMT	1 city pair (TBtu)	1 city pair (%)	10 city pairs	100 city pairs *	1,000 city pairs *
2025	2,500	-3.2	-0.01%	-0.1%	-1.3%	-13%
2030	2,200	-2.8	-0.01%	-0.1%	-1.1%	-11%
2050	1,900	-2.3	-0.01%	-0.1%	-0.9%	-9%

* Note: There is currently insufficient intercity passenger travel (PMT) to support hyperloop systems at these higher levels of nation-wide implementation, that is, at 100 and 1,000 city pairs. The energy savings shown are hypothetical estimates should there be induced travel demand, or greatly expanded intercity travel in the future, to make up for the travel demand shortfalls.

Freight Case Study

The calculation of energy impacts of a freight mode shift requires calculating the energy consumption for each mode, given a specific freight demand (ton-miles) requirement. For the freight case study, freight demand was collected from the latest Freight Analysis Framework (FAF).[89] This was done for air freight and the highest 25 percent of truck freight in terms of value, only including freight traveling between 100 and 1,000 miles (the general range being proposed for hyperloop systems).[90] Energy consumption, measured in BTU, was calculated for each using the corresponding energy intensities of the freight mode (air or truck), measured in BTU/ton-mile. Energy intensities, estimated using 2030 EIA projections, were applied to the latest freight demand (2016) to estimate total energy consumption for air and truck freight. This was then compared to the amount of energy that would be required for a hyperloop system to meet the same total freight demand (in ton-miles).

Ton-miles

The total air freight demand under 1,000 miles was calculated using shares from the U.S. BTS' segmentation of FAF data on 2015 ton-mile distribution by distance band, applied to U.S. BTS'

[89] Oak Ridge National Laboratory. "Freight Analysis Framework Version 4." https://faf.ornl.gov/fafweb/.

[90] Air freight under 100 miles was also included but was negligible and did not impact the results.

latest available (2016) total air freight ton-mile demand.[89,91] The relevant portion of this segmentation table is shown in Table 9 below.

Table 9: Mode Share of Air Freight Ton-Miles by Distance Band: 2015. Relevant distance bins are emphasized. (Source: FAF, U.S. BTS)[89,91]

Mileage range	Share of air ton-mile demand (%)	Ton-mile demand estimate, 2016 (millions)
Below 100	< 1%	< 10
100 - 249	**< 1%**	**< 10**
250 - 499	**9.9%**	**1300**
500 - 749	**8.3%**	**1100**
750 - 999	**8.5%**	**1100**
1,000 - 1,499	12.7%	1700
1,500 - 2,000	14.7%	1900
Over 2,000	45.7%	6000
Total	100%	13100

For truck freight, hyperloop was assumed to primarily compete with higher value shipments (*i.e.*, those shipments that are valuable enough that time is more important and potential cost to the shipper can be higher). Due to the limited availability of data segmented *both* by distance *and* value, truck freight demand was segmented using raw FAF data.[89] The results of this analysis are shown in Figure 20. The top 25 percent most-valuable freight is indicated by the red annotations. This segment of truck freight demand, the top 25 percent most-value truck freight traveling between 100 and 1000 miles, represents around 2.5 percent of *total* truck freight demand or 50.2 billion ton-miles.

[91] For shares, also see U.S. Bureau of Transportation Statistics, "Value, Tonnage, and Ton-Miles of Freight by Distance: 2015." https://www.bts.gov/content/value-tonnage-and-ton-miles-freight-distance-2015. For totals to which these shares were applied, see: https://www.bts.gov/content/us-ton-miles-freight

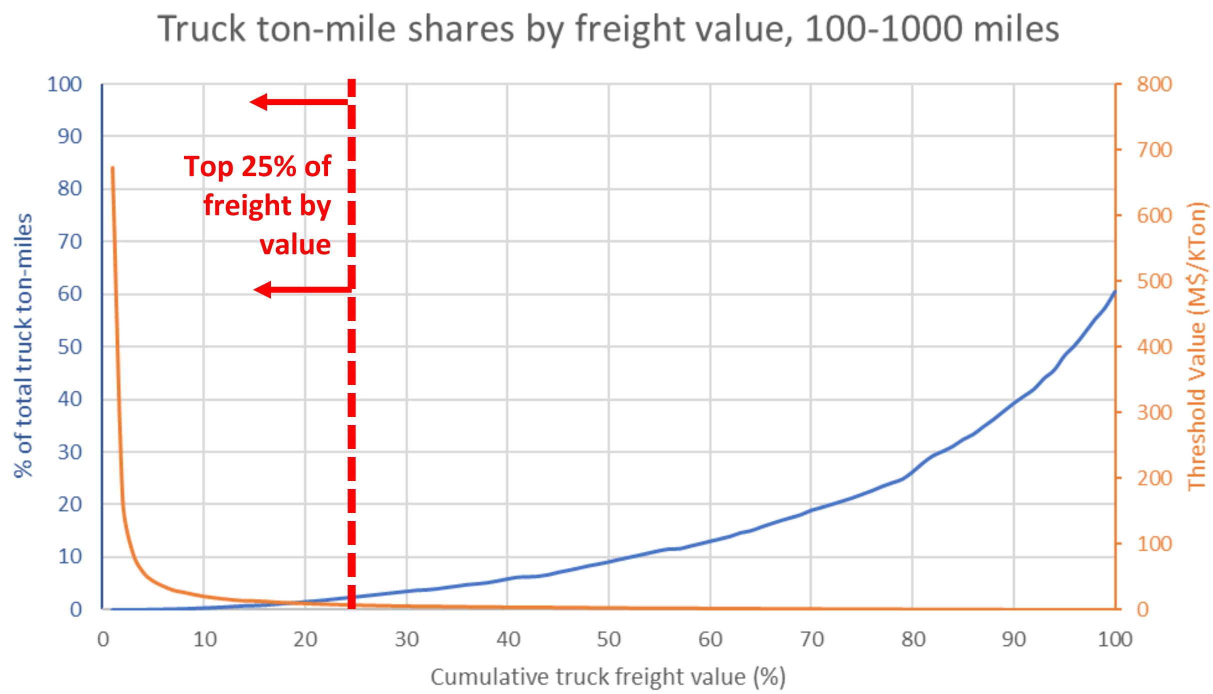

Figure 20: Analysis of truck freight demand by freight value (Source: Analysis of FAF data)[89]

Energy intensity

The baseline air energy intensity was calculated using the distance-based algorithm and fuel-burn rates (by aircraft) from a 2014 paper by Morton O'Kelly.[92] This algorithm is reproduced below.

$$Fuel\ burn\ \left(\frac{kg}{ton}\right) = \frac{(A + B * D)}{P}$$

where

A is the fuel burned per flight regardless of length, *e.g.* taxi, takeoff, and landing (kg/flight)
B is the fuel burned per unit distance (kg/nautical-mile)
D is the distance (nautical miles)
P is the payload (tons)

O'Kelly estimates each of these variables for several common freight planes using data from 2011 and 2012. The calculation results are reproduced in Figure 21.

[92] O'Kelly, Morton E. "Air Freight Hubs and Fuel Use," September 2014, 16

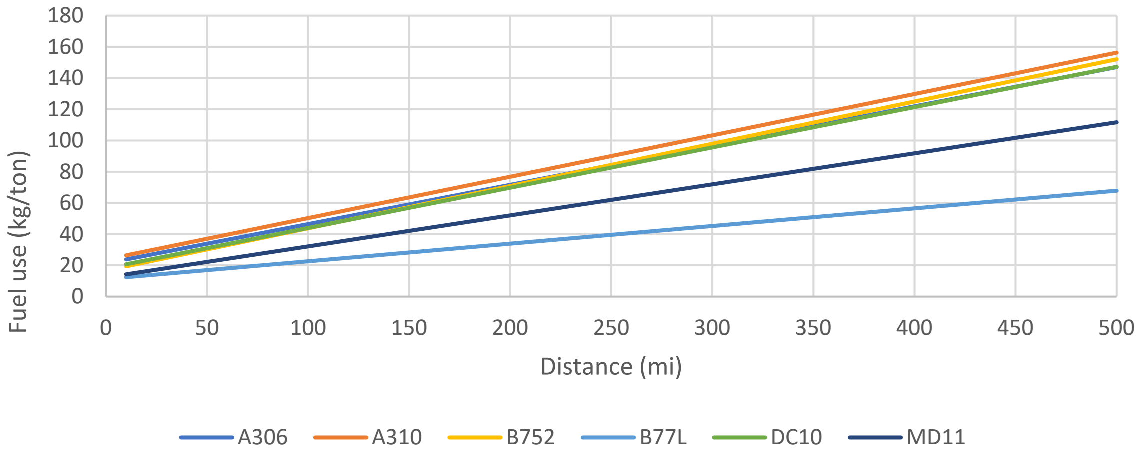

Figure 21: Fuel use by aircraft, estimated using the algorithm and input values from O'Kelly 2014.

These results were then used to derive energy intensity in BTU per ton-mile for each plane. A straight average across all planes was used to estimate a single energy intensity value for each distance as shown in Figure 22.[93] The distance band of interest in this study, 100-1,000 miles, is marked in red.

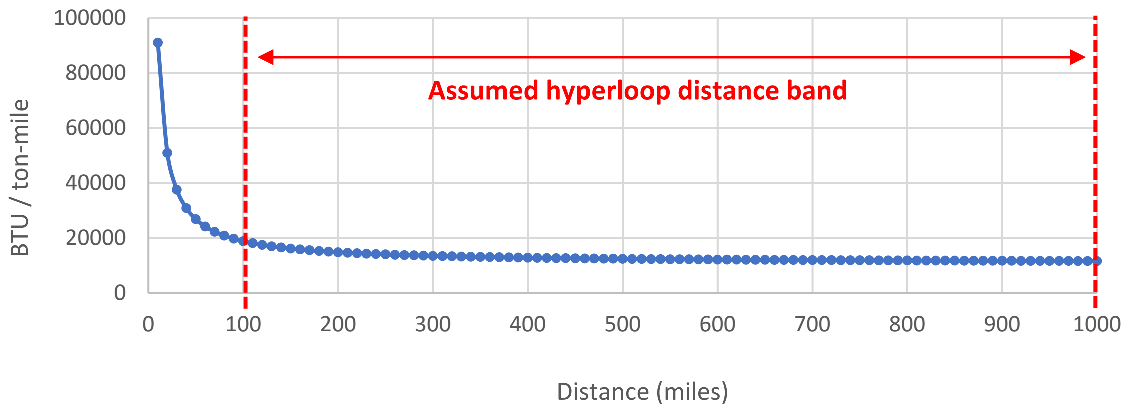

Figure 22: Relationship between air freight energy intensity and distance shipped.

Air freight energy intensity rapidly increases as trip distance decreases due to the fuel use on the ground and during takeoff and landing being a greater portion of the total fuel use. This analysis was only interested in the 100-1,000-mile band, therefore the distribution of air ton-miles and energy intensities within that band were used to calculate a weighted-average energy intensity. This is shown in Table 10.

[93] The distribution of ton-miles by plane type was not available to calculate a weighted average.

Table 10: Distribution of air freight demand by distance band, with final ton-mile-weighted air energy intensity in the last row. Sources: BTS for freight demand shares and totals, O'Kelly for energy intensity algorithm.[89,91,92]

Distance band (miles)	Air freight demand (million ton-miles)	Share of 100-1000-mile air freight demand	Average energy intensity (BTU/ton-mi)
100 - 249	< 10	0.1%	16,000
250 - 499	< 10	37.0%	13,000
500 - 749	1300	31.0%	12,100
750 - 999	1100	31.9%	11,700
100-1000	1100	**100%**	**12,400**

The final energy intensity of 12,400 BTU/ton-mile is used as the baseline to project efficiency increases. EIA does not publish freight-specific air fuel efficiencies; therefore, EIA's projected trend in passenger air is applied to this baseline to estimate future air freight efficiency through 2050.

The truck energy intensity values were calculated using EIA projected fuel economies.[94] EIA assumes a specific payload for these trucks, namely 38,000 pounds.[95] The current hyperloop analysis assesses energy intensities for a range of different payloads, therefore it was necessary to modify EIA's fuel economy projections to account for the range of operating weights.

The National Renewable Energy Laboratory (NREL) published a 2015 paper that estimates a weight elasticity of fuel consumption for heavy duty trucks running on three different drive cycles.[96] The simple average of the results is 0.49 percent, meaning, for every 1 percent change in truck weight, there will be a corresponding 0.49 percent change in fuel consumption. This is applied as shown below to convert EIA's fuel economy to energy intensities for different

[94] Truck freight demand in the 100-1,000-mile distance band was assumed to be primarily met by Class 7 & 8 heavy-duty regional- and long-haul trucks.

Class 4-6 delivery trucks are typically used for shorter regional and last-mile deliveries. This is illustrated in U.S. DOE's Alternative Fuel Data Center's visualization of U.S. Federal Highway Administration Table VM-1 (https://afdc.energy.gov/data/10309), which indicates that delivery trucks (assumed to be primarily Class 4-6 single-unit trucks) travel around 12,000 miles per year, versus Class 8 trucks which travel on average around 67,000 miles per year.

Assuming 250 days of operation per year (no weekends or holidays), this equates to an average of 48 miles per day for delivery trucks and 250 miles per day for Class 8 trucks. Therefore, the energy intensity for "truck freight" in this report, which analyzes freight demand over distances between 100 and 1,000 miles, indicates the energy intensity for freight carried by Class 7 & 8 tractors. It is assumed that the energy intensity for this segment does not vary across the distance band.

[95] This is the same payload required for EPA Phase II MD/HD regulations, per the RIA, Table 3.22. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

[96] Wang, Lijuan, Kenneth Kelly, Kevin Walkowicz, and Adam Duran. "Quantitative Effects of Vehicle Parameters on Fuel Consumption for Heavy-Duty Vehicle," 2015. https://doi.org/10.4271/2015-01-2773.

payloads, where *HHV* is the energy content of a gallon of diesel fuel.[97] The calculation results are shown in Figure 2.

$$Energy\ intensity_a = \frac{HHV_{diesel}}{Payload_a} * \left[\frac{1}{MPG_{EIA}} + \left(\left(\frac{Payload_a - Payload_{EIA}}{Payload_{EIA}}\right) * elasticity * \frac{1}{MPG_{EIA}}\right)\right]$$

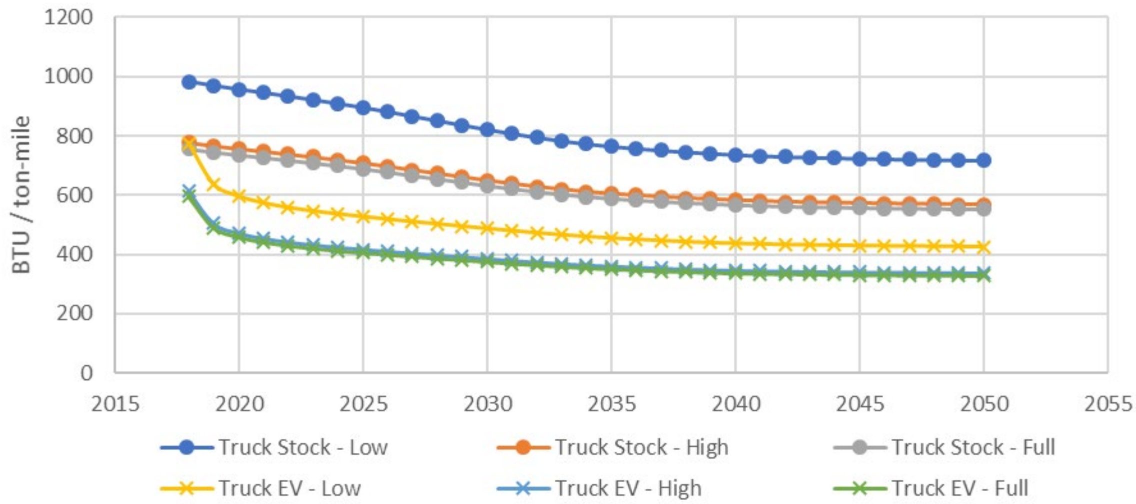

Figure 23: Estimates of energy intensity for freight case study. Sources: Fuel economies from EIA AEO 2019, payloads from sources cited in the Report to Congress, Figure 17.

Total energy impact

To calculate the total energy, the total ton-miles for each mode (air freight and top 25 percent of truck freight by value) from FAF were multiplied by the energy intensities derived above, leading to an estimated 40 TBtu of energy used for air freight and 60 TBtu for truck within the 100-1,000-mile distance band. To develop the equivalent energy use for hyperloop freight systems, the total ton miles for air and highest-value freight were assumed to transfer completely to hyperloop. The summed ton-miles across both modes were multiplied by each of the hyperloop freight energy intensities (light and heavy, as shown in Figure 17 in the report), which were compared to the truck and air energy consumption to identify a range of potential impacts. This process is summarized in Table 11 below.

[97] The energy content of diesel fuel was assumed to be 137,381 BTU/gallon, per EIA: https://www.eia.gov/energyexplained/index.php?page=about_energy_units

Table 11: Summary of mode shift energy impact estimation for 2030, from air and high-value truck to hyperloop.

Mode	Demand (billion ton-miles)	Energy intensity (BTU/ton-mi)	Energy consumption to meet demand (TBtu)	Energy impact as percent of projected 2030 transportation energy
Truck	50.2	700	40	-
Air	3.5	11,200	40	-
Truck and air	53.7	-	80	Baseline
Hyperloop, lighter	53.7	6,000	320	**+ 1.0%**
Hyperloop, heavier		2,100	110	**+ 0.1%**

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