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Pacific Northwest NATIONAL LABORATORY

Grid Impacts of Hyperloop Technology in the United States

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U.S. DEPARTMENT OF ENERGY

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[1] Energetics

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Abstract

This report provides an overview of Hyperloop technologies including the current technology developments and a brief discussion on key components of the Hyperloop system that determine the electric power requirements as a function of time. At-scale Hyperloop systems do not exist yet so a model was used to generate a set of load profiles for conceptual Hyperloop realizations at four locations in the United States—two systems in California and one each in Colorado and Ohio.

In all four cases, the modeled Hyperloop load profiles showed a pulsating characteristic in both active and reactive power. Grid modeling was performed by Pacific Northwest National Laboratory to estimate the grid impacts and to discuss grid integration challenges. This report discusses the outcomes of the grid simulations for four study cases and offers some perspective of how existing large industrial loads with similar load characteristics are treated to accommodate current grid planning guidelines. The report concludes with a discussion on how energy storage systems might be used to eliminate the pulsating load characteristics or significantly reduce it.

Executive Summary

At the request of the U.S. Department of Energy (DOE), Pacific Northwest National Laboratory (PNNL) assessed potential impacts of Hyperloop technology on the U.S. electricity transmission grid. The results of PNNL's assessment are intended to inform DOE's report to the U.S. Congress in response to a mandate in the Energy and Water Development Appropriation Bill, 2019. The bill states that the report should address:

> "… 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. The report should include information about how these systems could be integrated into the electric grid and identify any technological constraints of the grid that must be addressed to allow the broad adoption of Hyperloop technologies." (U.S. Congress 2018)

Hyperloop technology is an innovative transportation concept that transports people or freight through low-pressure tubes at very high speeds of up to 1220 km/h (about 760 mph) (Musk 2013). Current developers are using magnetic levitation to reduce rolling resistance and electro-magnetic induction motors to accelerate and decelerate the vehicles. Aerodynamic friction between the vehicle and the air surrounding it is minimized because of the very low air pressure in the tubes. An individual vehicle is launched and accelerated at a Hyperloop station to its end velocity, and from there, it glides to the next station, with potentially only a few power boosts between stations. Therefore, the electric power (measured in megawatts [MW]) supplied by the electric grid is expected to be required mostly during the initial launch and acceleration phases. If regenerative braking is used, some of this power potentially, could be recovered (i.e., electric energy returned to the grid). In regenerative braking, kinetic energy is converted into electric energy (Oliveira et al. 2014). Because of the relative short pulse-like power demands and the potential power recovery, there could be concerns about potential negative grid impacts that are generally of the nature of large voltage fluctuations or frequency excursions in the bulk power system that could negatively impact grid operation and grid reliability.

Approach

PNNL performed its grid impact assessment over a 7-week period, with a focus on assessing reliability-related impacts rather than determining economic impacts or economic viability of Hyperloop technology. The results of the reliability assessment along with considerations regarding grid integration of Hyperloop technology are documented in this report. PNNL partnered with a mechanical engineering team from Energetics to develop electric power requirements given the many physical and mechanical assumptions of a hypothetical Hyperloop deployment. The PNNL electrical engineering team used these electric power requirements to assess the potential impacts to regional and interconnection-wide grid operations.

PNNL assessed the potential grid impacts of an at-scale Hyperloop system at four U.S. locations (two in California and one each in Colorado and Ohio). The assessment was performed for each location separately. No cumulative grid effects when operating four systems simultaneously were considered. The selection of the locations were based on existing conceptual geographic layouts connecting two or more cities in the United States as published by Hyperloop technology developers. One of the four locations represented a smaller system as an illustrative example for an intra-city transportation application. San Francisco was arbitrarily chosen to represent an intra-city application. Furthermore, considerations were given to represent some diversity of the Hyperloop system size (small versus large) and geographic placements in the U.S. bulk power system. Three systems were located in the Western grid, and the other system was located in the Eastern grid. Given the short study period, the grid assessment focused on the worst-case scenario. Assumptions for the worst-case scenario resulted in a very high pulsating load profile in both active and reactive power. PNNL estimated these worst-case impacts and then provided a discussion on considerations of how grid impacts can be mitigated by a set of compensation technologies to reduce the impacts to an acceptable level for grid integration.

Outcome

The results of this study clearly indicate that the continuous power pulses for Hyperloop transportation applications are sufficiently large in magnitude and ramp rates to likely induce system voltage disturbances that may in some cases violate commonly used planning guides for voltage fluctuations and flicker conditions. Furthermore, system frequency disturbances are of significant magnitude and could be "felt" throughout the entire or major portions of the Western and Eastern Interconnections, respectively. Although the modeling results did not indicate frequency trips, the margins to under-frequency load-shedding thresholds became very small. This may present vulnerabilities to grid operations during large contingency conditions when a large generator or transmission asset trips unexpectedly. It should be noted that the analysis did NOT consider contingency conditions. PNNL simulated normal grid conditions only.

The persistence of these pulsating load profiles during regular Hyperloop operating periods (with high power pulses every 2 minutes when a pod starts up at a station) imposes constant voltage and frequency deviations that are not acceptable for grid interconnections from the perspective of planning guidelines for voltage variations and undue wear and tear on generator assets primarily due to frequency variations.

The simulation results clearly indicate that Hyperloop technologies will require compensation devices to address or preempt the pulsating characteristics of the expected load profile both for active and reactive power. There are examples of how industrial loads with similar load characteristics (e.g., arc-furnace installations) have been successfully connected to the transmission grid in the United States and worldwide, using dynamic compensation equipment, such as static var compensators and static compensators. These examples, however, are not quite of the size (MW and MVar) and persistence that would be needed for a large Hyperloop implementation. Other technologies such as energy storage systems may offer unique capabilities to preempt the pulsating characteristics that the grid would need to absorb by compensating and dampening the sharp power requirements encountered during pod acceleration and by absorbing electric energy during regenerative braking.

While a full compensation strategy for a Hyperloop technology was beyond the scope of this study, PNNL outlined concepts of potential storage solutions to fully eliminate or partially reduce the pulsating load characteristics. For the California case, a high-power, low-energy storage system (capable of moving large quantities of power in and out, but with limited electric energy storage capability) could eliminate the variable component of the electrical demand. The results would be a constant load of 13 MW. The storage size would be a 178-MW and 50-MWh system. The cost was estimated to be roughly $88 million assuming a lithium-ion based battery system. A smaller storage solution that reduces the amplitude of the load pulses was estimate at a cost of roughly $47 million (assuming lithium-ion battery system).

Acknowledgments

The authors would like to thank Dr. Robert Marlay and Dr. Rachel Nealer of the U.S. Department of Energy for their guidance in defining the scope for this analysis and their support throughout the execution of the analysis.

Acronyms and Abbreviations

AC	alternating current
AGC	Automatic Governor Control
DOE	U.S. Department of Energy
EHV	extra high voltage (230kV < V)
EIA	Energy Information Administration
HV	high voltage (35kV < V ≤ 230 kV)
Hz	Hertz expressed in cycles per second
IEC	International Electrotechnical Commission
kg	kilogram
km	kilometer
km/h	kilometer per hour
lb	pounds
m	meter
Mach	Mach number is a dimensionless number that expresses the ratio of local flow velocity to local speed of sound.
mph	mile per hour
MV	medium voltage (1kV < V ≤ 35 kV)
MW	megawatt
NASA	National Aeronautics and Space Administration
NERC	North American Reliability Corporation
PCC	point of common coupling
PNNL	Pacific Northwest National Laboratory
psi	pound per square inch
s	second
SPLC	smart predictive line capacitor
STATCOM	static compensator
SVC	static var compensators
t	metric ton
WECC	Western Electricity Coordinating Council

Contents

Figures

Tables

Introduction

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Because no specificity for any real-world Hyperloop system exists, PNNL chose four study cases that covered some diversity of potential future Hyperloop systems with respect to sizes and locations. Many assumptions needed to be made to overcome the lack of specificity and system details. Therefore, the results of the grid impact assessment are discussed as illustrative examples and considerations for integration of Hyperloop technologies are made in more general terms.

Background of Hyperloop Technology

Although the Hyperloop concept has a rich history reaching back to Robert Goddard in 1904, a 2013 SpaceX publication raised again public attention of this transportation technology as an innovative means for intermediate-range or inter-city travel (Goddard 1991, Musk 2013). Currently there are several Hyperloop companies pursuing commercialization of the technology. Some are making progress in exploring via experiments and short-distance demonstrations the feasibility of the technology for both passenger and freight transport. Others are contributing to underlying advances in the technology. DOE's analysis is independent of this private-sector work but is informed by its progress.

Hyperloop is broadly defined as a surface transportation system that uses capsules or "pods" that travel at high speeds along a fixed track in a tube at partial or near-complete vacuum. Most conceptual designs envision the use of magnetic levitation for lifting and guidance and linear induction electrical devices for acceleration and braking. Such concepts eliminate the need for rails and wheels and minimize energy losses resulting from rolling friction. The low pressure in the tube minimizes aerodynamic resistance.

In terms of convenience, quality of service, time savings and, in some cases, energy efficiency, Hyperloop systems offer potential benefits for both passenger travel and freight shipping. It is being envisioned as a faster means of travel than existing air, rail, or road transport modes, with a particular focus on connecting pairs of cities.

A key benefit of the technology is the high speeds enabled by the system design; speeds of up to 1220 km/h (about 760 mph) in the cruise mode are much faster than existing automotive or rail systems and rival current commercial airplane speeds. Hyperloop systems are designed to reduce travel time relative to air travel by eliminating or greatly reducing the time spent at either end of the journey (e.g., time spent waiting for a plane to leave, taxiing, taking off, landing, disembarking, etc.) The Hyperloop system also will limit the number of intermediate stops between the origin and the destination, which represents another time savings relative to modes such as high-speed rail. The original Hyperloop Alpha concept paper envisioned these time savings as being most pronounced for city pairs that are separated by 900 miles or less (Musk 2013). Beyond 900 miles, it is suggested that supersonic air travel (at speeds higher than currently used in commercial air travel) will be more time efficient. Depending on the logistics of ticketing and passenger/luggage transfer, there may be time savings in those areas as well.

Convenience is another potential benefit for Hyperloop passengers. As currently proposed, Hyperloop systems would dispatch relatively small pods of 20 to 30 people launched relatively frequently from endpoint stations (a pod every 2 minutes or less). This would make Hyperloop travel an attractive option as it would minimize wait times at the station. Such convenience also could reduce the use of passenger cars between cities connected by Hyperloop systems, thus reducing traffic congestion on main routes between the cities. Frequent Hyperloop service also might compete with travel from shorter regional airline flights, thus relieving pressure on hub airports as travel demand will likely increase in the future.

Reduction in energy use also is forecasted as a benefit of deploying Hyperloop technology. As the aerodynamic losses associated with pod travel will be low because of the low air pressure in the tube, each pod will be able to coast for a significant portion of the overall trip length (one estimate is that energy will be consumed over only 10% of the route) (Rail Engineer 2016). Energy input to pod motion will be necessary for initial launch and acceleration and for periodic speed boosts along the route, and if used, regenerative braking will capture a portion of the pod's kinetic energy at the end of each trip. Reductions in energy use (and the shift to the use of electricity for propulsion versus conventional fuels for other transport modes) could result in reductions in criteria pollutants and greenhouse gas emissions.

The tradeoff in emissions reduction between Hyperloop technology and conventional technologies depends on emissions when the electricity is generated.

Current Technology Development Status

Currently, there are several private companies that are making investments to advance the technology and to gain experience using experimental test tracts. They are all at various stages of prototype development and techno-economic feasibility testing with very limited technical information about the technology, energy and power requirements, and potential impacts to the grid.

Virgin Hyperloop One (Los Angeles)

Since 2017, Virgin Hyperloop One has been testing 600 mph Hyperloop systems at a full-scale (500 m [1640 ft] long) test track in Nevada (Taub 2019). Pods have been tested for hundreds of runs that have reached velocities up to 385 km/h (240 mph). The commercialized system is expected to reach a continuous velocity of 820 km/h (510 mph), with over 1070 km/h (670 mph) possible.

In early 2018, the company unveiled its pod prototype that will carry passengers at speeds of up to 760 mph (Collins 2018). In August 2018, it reached an agreement with Spanish state-owned rail infrastructure company Adif to build a $500 million research center in Spain, its first in Europe. The 19,000 m^2 (204,000 ft^2) center, which is planned to open in the small village of Bobadilla in the southern province of Malaga, Spain, by 2020, will develop and test components for Hyperloop systems to improve their safety (Physics.com 2018).

On September 13, 2018, Josh Raycroft, Chief Engineer at Virgin Hyperloop One, testified about the company and its technology before the U. S. Senate Committee on Commerce, Science, and Transportation. More information can be found at the U.S. Senate website.[1]

Hyperloop Transportation Technologies, (Los Angeles)

In February 2019, Hyperloop Transportation Technologies revealed to the public the new full-scale (320 m) test track it is constructing in Toulouse France. The first full-scale series of tests of the Hyperloop passenger pod on this track is planned for April 2019 (Chopade 2019).

TransPod (Toronto)

In January 2019, TransPod announced a new phase of testing and construction that will expand its operations in France. This expansion includes building a new 3-km long test track, opening a subsidiary named TransPod France, and working with new industrial partners (Transpod 2019).

[1] See https://www.commerce.senate.gov/public/index.cfm/hearings?ID=E3D94CC4-AA66-4886-9F16-230B3D254FCF

Hyperloop Technology in China

Reuters reported that Chinese automaker Geely has signed an agreement with the China Aerospace Science and Industry Corporation to build a network of ultra-fast trains with speeds of up to 965 km/h (600 mph) (Railway Technology 2018). The proposals included enabling passenger and freight transportation using pods or specially-developed vehicles operating in low-pressure tubes.

Challenges with Hyperloop Technology

Although there are several potential benefits to Hyperloop technology, there are challenges as well. The cost of constructing such systems at-scale is still unknown and could potentially be high. The Hyperloop Alpha authors estimated costs of around $16 million per mile, but others are estimating costs of $25 million to $27 million per mile (Walker 2018). These costs would be strongly dependent on whether the transport tubes are built above ground or below ground, as tunneling costs would greatly increase the total price for construction, and on where the system is located due to wide variability in land costs.

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 too far from the ultimate destinations of passengers, the first-mile/last-mile transit times will eliminate some of the time advantage of Hyperloop.

Safety, security, and cost are additional critical concerns with Hyperloop technology.

Safety

Safety is a critical aspect of Hyperloop systems, especially given the very high travel speeds and near-vacuum conditions of the tubes. If a transport pod is stopped in the tube, the communication connectivity among pods would alert following pods to engage emergency brakes. Headways between pods would be designed to provide sufficient braking distance (Musk 2013). Depressurization of capsules or significant vacuum leaks in the transport tubes would be addressed in a manner similar approaches used in commercial aircraft. These situations do highlight the issue of a single point of failure for the Hyperloop system, as any problem requiring a pod to stop would require the entire system upstream of the stopped pod to be shut down (Walker 2018). The kinetic energy of the pods traveling at more than 1100 km/h (700 mph) may also be a concern, especially when operating near population centers.

Security

Closely associated with safety is security of the system. At this early conceptual and hardware proof-of-concept stage of development, it is unclear whether Hyperloop systems will require the same high level of transportation security as commercial air travel or the lower level of security similar to passenger rail travel. High levels of security may decrease the time savings advantage relative to other transport modes. Also, the costs of providing security may increase ticket prices if the system operator is made responsible for security services.

Cost

As previously mentioned, Hyperloop technology is expensive so cost can be a major hurdle to successful deployment of a system. In the recent past, several high-speed train projects based on magnetic levitation (referred to as Maglev in the project names) technology have been shelved, with the main reason being the high project costs (Maglev.net 2013). Some of the shelved projects, and the reasons for shelving, are identified below:

- Munich Maglev: Cost over €79 million/km or €127 million/mile (Maglev.net 2013)
- Hamburg-Berlin Maglev: Project was shelved as the cost of upgrading existing lines ($2.097 million/km or $3.37 million/mile) was much lower than the cost of new Maglev train ($20.17 million/km or $32.41 million/mile) (Maglev.net 2013)
- Metrorapid Maglev: Cost of over $45 million/km or $72.43 million/mile , and inefficiency due to operational limitations[1]
- Shanghai-Hangzhou Maglev: Expensive compared to the high-speed rail alternative[1]
- Swissmetro Project: Cost of ₣80 million/km or ₣128.75 million/mile (Maglev.net 2013)
- UK Ultraspeed Maglev connecting London and Glasgow: cost of £75 million/km or £120 million/mile.[2]

The main reason for high costs associated with magnetic levitation trains is that the existing rail infrastructure is not compatible with the technology; therefore, implementation of magnetic levitation technology would require building the required infrastructure from scratch. The Shanghai train would have cost $1.2 billion dollars ($60 million per mile). This level of expense must be justifiable when compared to upgrading an existing railway system, which might be a more economically viable option.[3]

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[1] Railway Technology. Undated. Available at https://www.railway-technology.com/projects/shanghai-maglev/.
[2] Wikipedia. Undated. Available at https://en.wikipedia.org/wiki/UK_Ultraspeed
[3] Wilson C. Undated. "Maglev: Magnetic Levitating Trains." *Electrical and Computer Engineering Design Handbook: An Introduction to Electrical and Computer Engineering and Product Design by Tufts ECE Students.* Tufts University. Available at https://sites.tufts.edu/eeseniordesignhandbook/2015/maglev-magnetic-levitating-trains/.

Modeling the Electric Power Requirements for Hyperloop Technology

Estimating the impacts of an operating Hyperloop systems on the grid requires a model of both the Hyperloop system and the grid. In this section, development of an array of Hyperloop system configurations, operating scenarios, and load profiles are described. They are developed for four different locations; three for *inter*-city transportation and one for an *intra*-city deployment. This provides some diversity with respect to size of the electricity load (inter-city systems are much larger than intra-city systems) and locational diversity impacting the U.S. grid at different locations.

Selection of Multiple Proposed Routes for Hyperloop Transportation Systems

Currently only small-scale prototype Hyperloop technologies exist (Upbin 2017). None of these are at a scale that would meet real transportation functions, although several conceptual designs have been published in the United States, Canada, and Asia. Therefore, to estimate the electric load profiles requires some simulations of at-scale Hyperloop systems. Many assumptions are applied for simulations. They are based on some of the earlier and later conceptual designs, expert consultations, and research undertaken by the National Aeronautics and Space Administration (NASA).

In this study, we selected route representations at four different locations. The three inter-city Hyperloop implementations are in California, Ohio, and Colorado (see Figure 1). The intra-city deployment is in the City of San Francisco, connecting a station near the San Francisco Airport with a location southeast of the Golden Gate Bridge. The intra-city location was chosen arbitrarily. Selection for the inter-city deployments was based on existing conceptual routine suggestions with some locational diversity that would explore impacts in different regional grids.[1] Figures 2 through 6 provide more insights into the assumed geographic layouts. For access to electricity, the assumed Hyperloop station locations are assumed to be in close proximity (less than 10 km [6.2 mi]) of an electric transmission substation with a rated voltage of 138 kV or higher. No further considerations regarding space availability for assumed stations were made.

[1] These three routes represent potential routes, for which hyperloop systems have been suggested or formally studied, for implementation by various developers and technology companies.

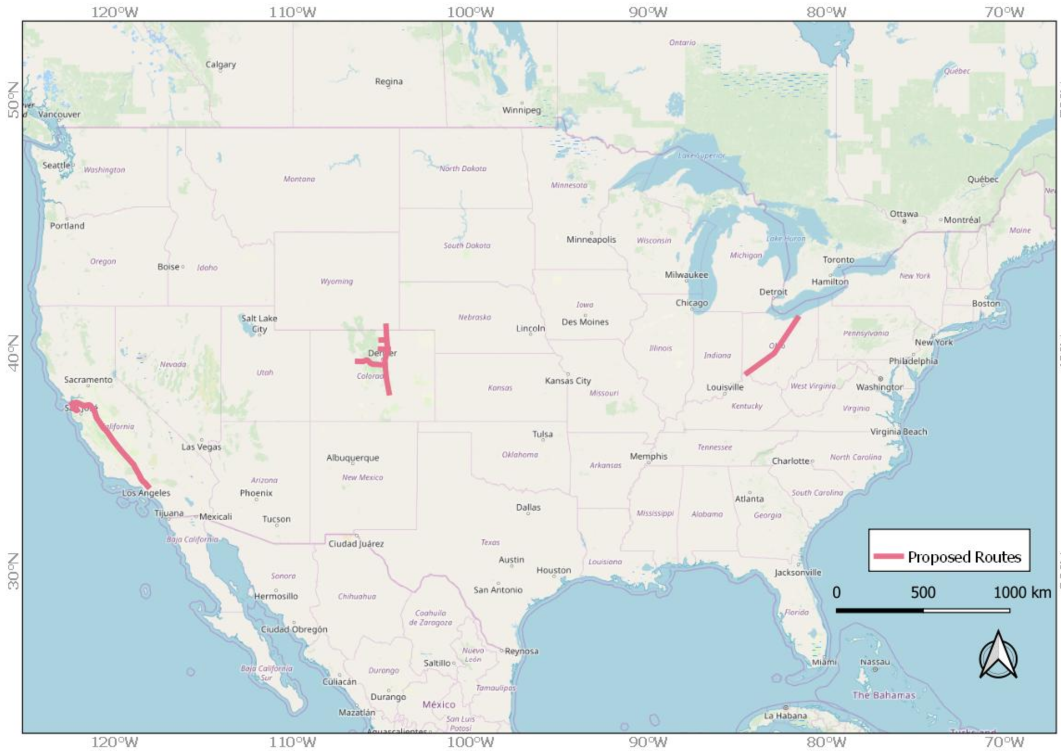

Figure 1. Assumed Hyperloop Routes in California, Colorado, and Ohio

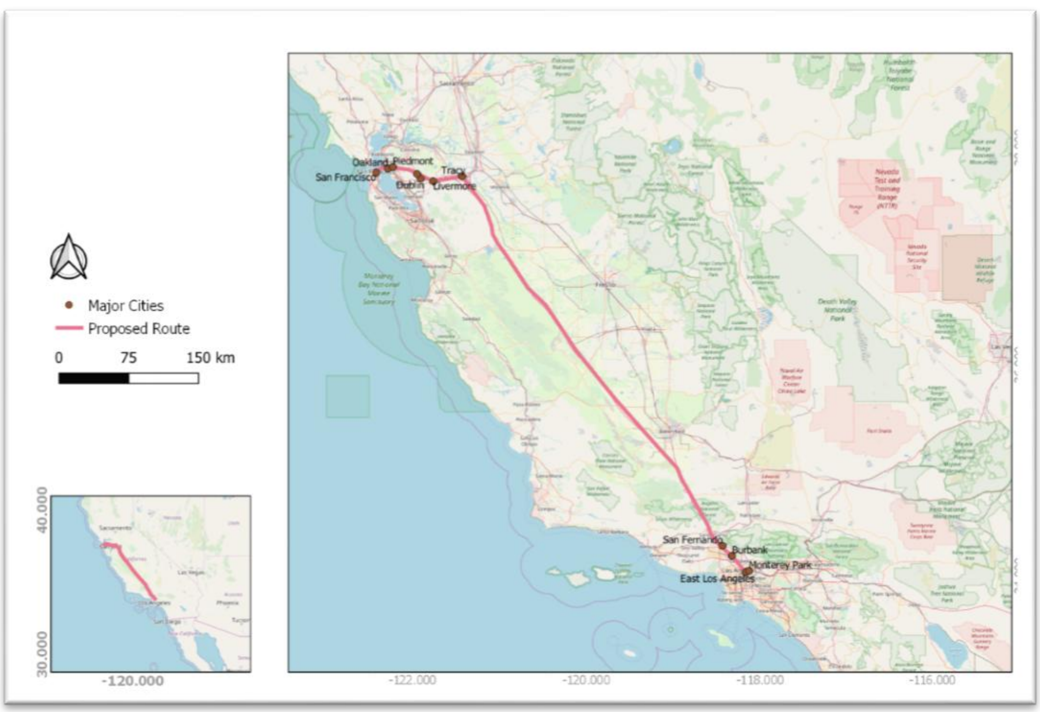

Figure 2. Assumed California Route from Los Angeles to San Francisco. Based on the Hyperloop Alpha Design (Musk 2013)

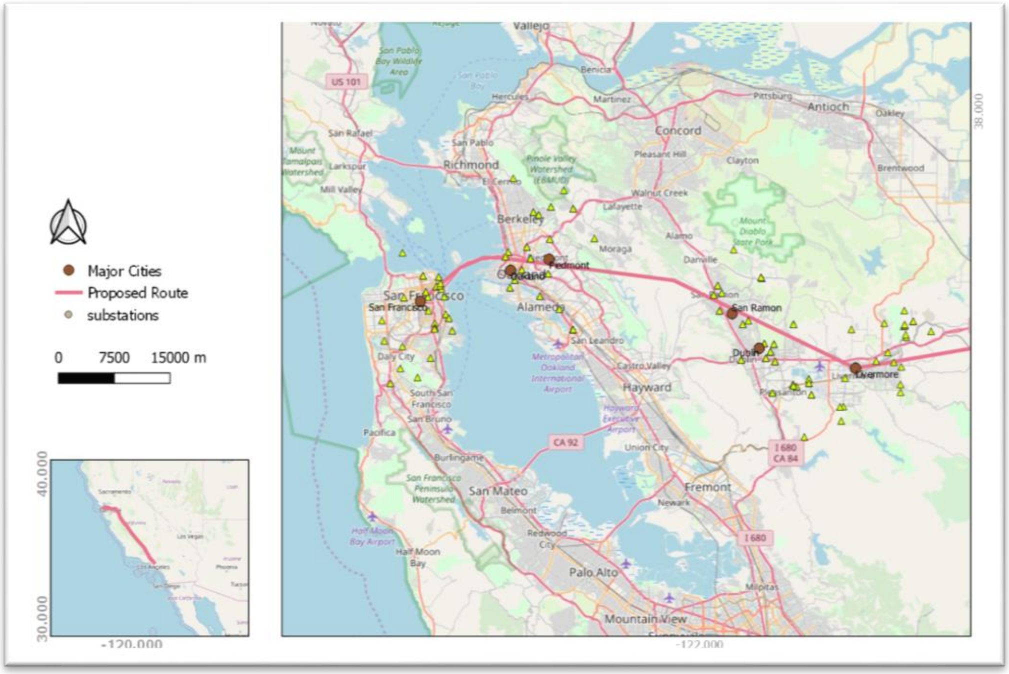

Figure 3. San Francisco Area Zoomed-In, with Electric Grid Substations within 10 km of the Hyperloop Route

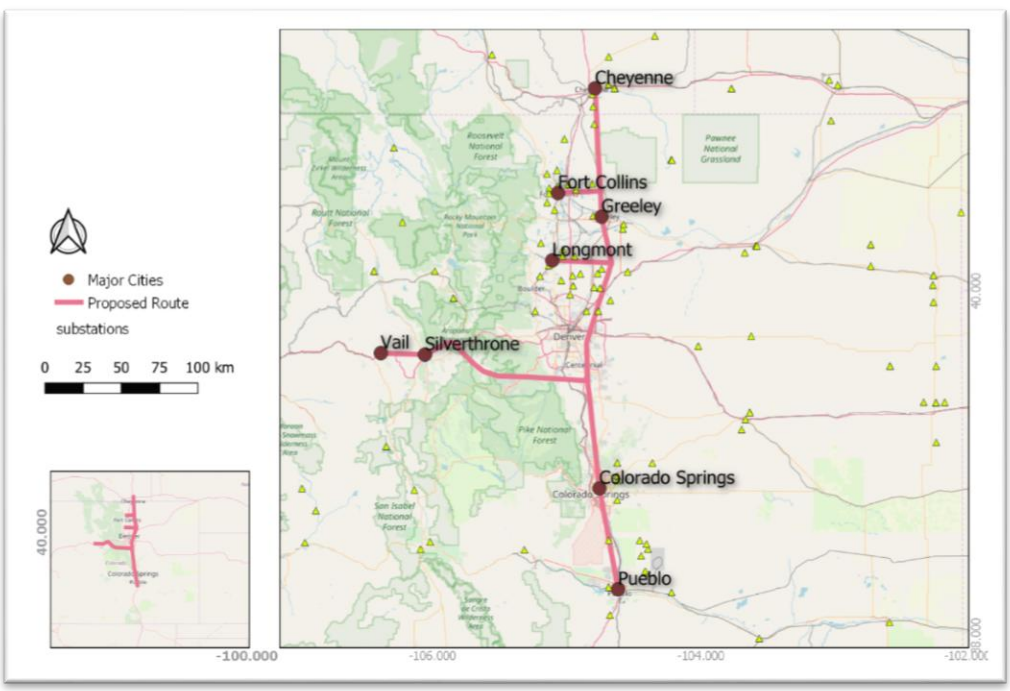

Figure 4. Assumed Colorado Route: Cheyenne-Denver-Pueblo. Based on Hyperloop One Global Challenge Winner[1]

[1] Based on conceptual route from https://hyperloop-one.com/global-challenge-winners/#colorado.

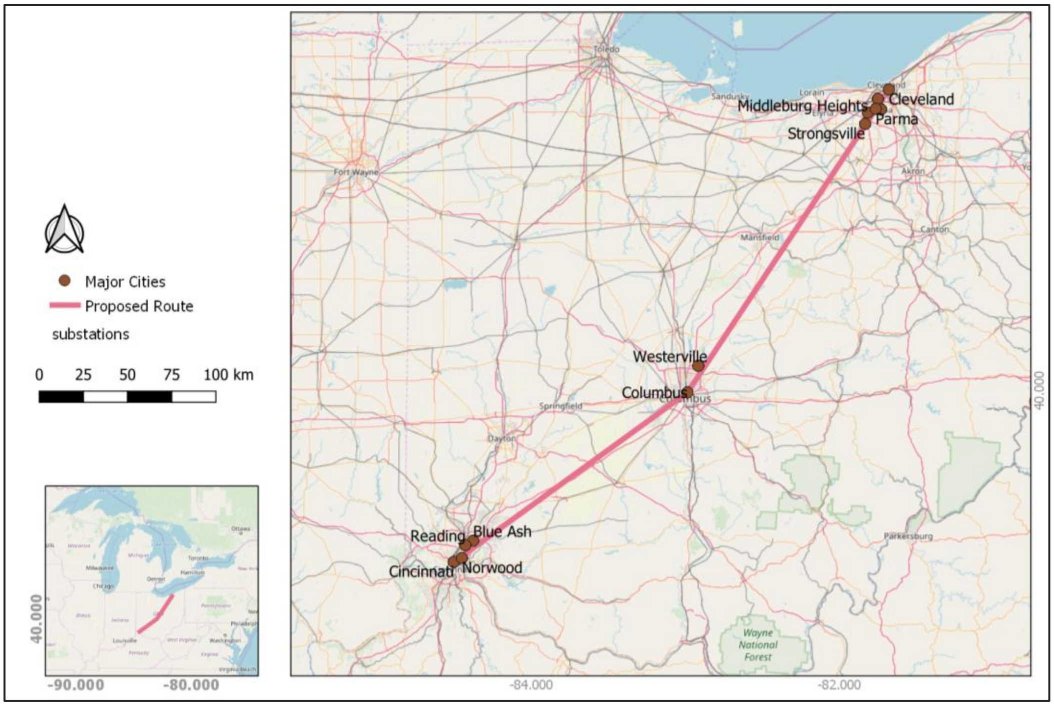

Figure 5. Assumed Ohio Route for the Cleveland-Columbus-Cincinnati Hyperloop System. Based on Hyperloop One Global Challenge Winner. [1])

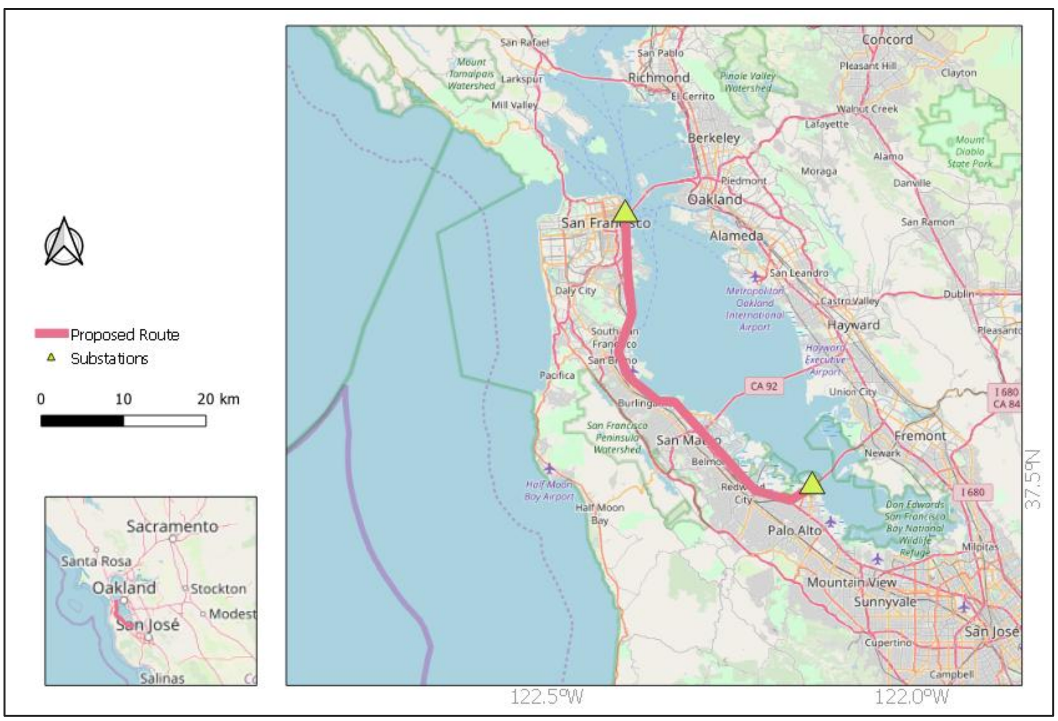

Figure 6. Assumed San Francisco Intra-City Route

[1] Based on the conceptual route from https://hyperloop-one.com/global-challenge-winners/#midwest.

Modeling of Power Requirements and Establishing Load Profiles

Assumed System Design

Analyzing potential grid impacts of an at-scale Hyperloop deployment requires an assessment of the load characteristics that affect grid operations. An Excel-based Hyperloop system model was developed by Energetics to generate the required load profiles for geographically specific systems. It includes a set of default parameters for three modes: 1) passenger, 2) light palletized freight, and 3) heavy (shipping container) freight. Outputs include a full-day second-by-second load profile for a single Hyperloop station, energy intensities (per passenger-distance or per ton-mile), and total passenger or freight capacity per unit time. It is important to note that Hyperloop transportation is a technology that exists in an early stage of development. There are currently no fully operational Hyperloop systems; therefore, all operational parameters and design choices for an at-scale deployment are speculative and highly uncertain.

A conceptual drawing of the SpaceX Hyperloop Pod is shown in Figure 7.

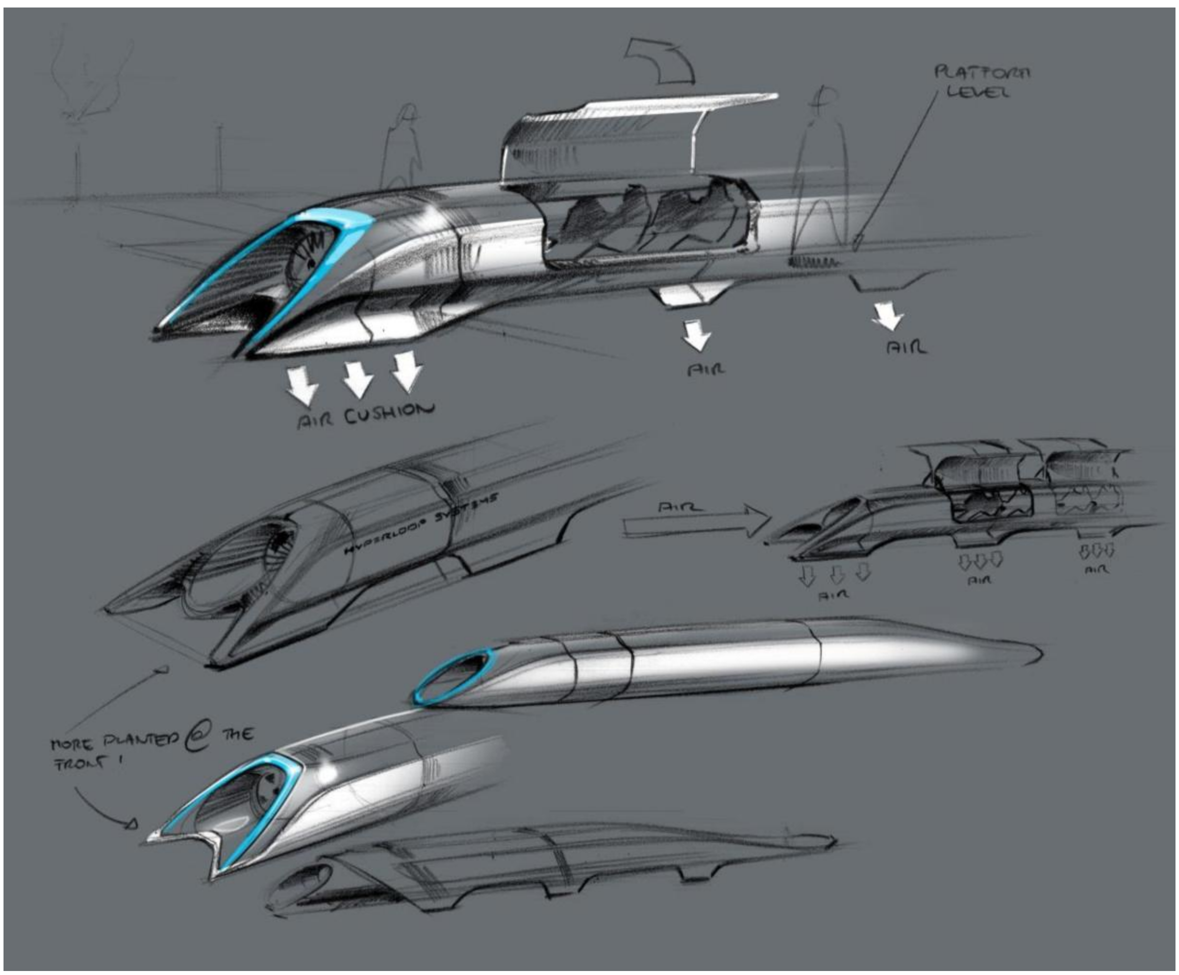

Figure 7. Initial SpaceX Concept for the Hyperloop Pod (Musk 2013)

According to existing literature and developer publications, the energy and power requirements of a fully operational Hyperloop transportation system would be concentrated in the following subsystems: 1) pod propulsion and braking, 2) maintenance of tube vacuum, 3) pod levitation and guidance, and 4) station and pod hotel loads. All three of the major Hyperloop developers[1] are adopting technical approaches that are broadly similar in the use of underlying technology to accomplish these tasks; that is, accelerating magnetically levitated pods using linear motors through a tube held at pressures between 0.001 and 0.01 atmospheric pressure. The assumed system design used in this study is based on the approaches of these developers as well as the modeling work completed by NASA between 2015 and 2017 (Chin and Gray 2015, Decker et al. 2017).

Each of these subsystems are described below and the specific parameters used to characterize each are discussed in the following section. The pod hotel loads[2] were assumed to be a constant 20% of the power required at cruise per discussions with the Electric Power Research Institute.

Propulsion

Proposed Hyperloop systems have almost universally used linear motors for acceleration and deceleration. This lowers the weight and complexity of the pods because they do not require a constant connection to a power source. The assumed system design mimics that suggested by NASA (Chin and Gray 2015, Decker et al. 2017): linear motors are installed on the track directly before, in, and directly after station stops to provide initial acceleration to cruise speed and final deceleration to a stop using regenerative braking. Because the pods operate in a near-vacuum environment, very little power is needed to maintain speed. Linear motors are therefore installed in short segments along the cruise route to provide "boosts" as the pod slows.

Hyperloop proponents are all planning to use regenerative braking to decelerate the pod. This can be accomplished with the linear motors, although not all of the kinetic energy will be recovered due to losses. Eddy current braking will be used at higher speeds if needed, while friction braking will be used at lower speeds (see the Levitation section below).

Tube Vacuum

A key enabler of Hyperloop system efficiency is the reduction of aerodynamic drag due to operation in an evacuated tube. A series of vacuum pumps, either in clusters or evenly distributed across the track, will run constantly to maintain system vacuum during operation. The extreme low-pressure operation will lead to leaks from diffusion, desorption, permeation, micro-cracks, and mechanical components. In addition to maintaining vacuum, the pumps will be needed to pump-down airlocks after passengers have boarded pods at each station stop and to complete the initial pump-down when system operation begins. This initial pump-down could occur daily, weekly, or less frequently depending on the operations and maintenance regime.

Levitation

The original inspiration for Hyperloop technology described in Elon Musk's *Hyperloop Alpha* paper suggested using air bearings to raise the pod (Musk 2013). This approach has been abandoned by all current developers because of the massive volume of air required to maintain enough clearance between the pod and the tube (Opgenoord et al. 2017). Developers have moved to electro-dynamic magnetic levitation and other similar passive magnetic levitation systems. Passive systems use simple metal tracks,

[1] Hyperloop Transportation Technologies, Transpod, and Virgin Hyperloop One
[2] Electric loads for providing light, air conditioning, and other end-use devices such as cell-phone/computer chargers.

or tracks with passive embedded coils, and electromagnets or permanent magnets (in a special arrangement called a Halbach array) onboard the pod for levitation. The pod does not levitate until it reaches a critical speed—usually less than 96 km/h (60 mph)—after which it can achieve very high lift-to-drag ratios. Before the point when lift is achieved, the pod will likely be supported by wheels. The passive system using permanent magnets, developed by Lawrence Livermore National Laboratory and known as *Inductrack*, was selected as the levitation and guidance system for this model (Post, 2000).

Comparison to Current High-Speed Rail and Magnetic Levitation

Existing high-speed trains use magnetic levitation rather than wheels and linear motors for propulsion but differ in other respects. These trains do not operate in evacuated tubes and are, therefore, limited to lower speeds. Transrapid in Germany implemented on 30 km (19 mile) route from Shanghai Pudong International Airport to the outskirts of central Pudong, Shanghai. It is the fastest commercial train currently in operation, achieving 435 km/h (270 mph) in daily use. This is about half the speed suggested by Hyperloop developers.

Japan’s *Chuo Shinkansen* magnetic levitation train reached over 600 km/h (375 mph) in testing but is not expected to be operational until 2027 (Railway Technology 2017). Additionally, both trains use active magnetic levitation, in contrast to Hyperloop developers that appear to prefer passive magnetic levitation. Conventional high-speed rail technology that is not based on magnetic levitation is a competing technology already in use, primarily in parts of Asia and Europe. The current high-speed rail systems operate at speeds that typically achieve a maximum of about 354 km/h (220 mph) (EESI 2018).

Electric Loads Modeled

As discussed above, Hyperloop systems would require electric power for pod acceleration and deceleration, maintenance of tube vacuum, pod levitation, and hotel loads. All the electric loads were aggregated into a single second-by-second load profile to simplify grid modeling. Additionally, we assumed that all the power demands will be met by the grid through dedicated substations in the bulk power system that will act as the point of common coupling (PCC) between the power grid and Hyperloop system. We assume that the PCCs be located only at the stations.

Key Assumptions

An array of Hyperloop system configurations shown in Table 1were developed and modeled to provide load profile inputs for the grid simulation. These include one passenger configuration, largely based on Mr. Musk’s proposal, current developer publications, and work done by NASA (Chin and Gray 2015, Decker et al. 2017), and two freight configurations. The small freight Hyperloop uses an average standard aircraft shipping container or pallet, which results in a system defined by parameters very similar to the passenger design, while the large freight configuration uses a standard 12.2 m (40 ft) intermodal shipping container.

This model provides a great deal of flexibility in operating parameter inputs such as cruise speed, acceleration rate, pod launch interval, pod and tube weight and size, operating pressure, etc.

The parameter space for the exploratory study includes the following key variables:

1. Cruise speed, which influences the duration of the load spikes
2. Pod mass, which influences the amplitude of the load spikes

3. Acceleration and deceleration, including regenerative braking efficiency, which influences the amplitude of the load spikes
4. Pod launch interval, which influences the frequency of the load spikes and the potential for coincident loads
5. Vacuum pump requirements, which influences the base power demand throughout operation and result in the largest total energy demand in the system
6. Route scenario, including number of stations and total length, which influences the base vacuum load, total system peak power and total energy demand, and number of grid interconnections.

The numerical values for the key parameters for the three scenarios are shown in Table 1.

Table 1. Key Hyperloop System Parameters

	Passenger	**Small Freight**	**Large Freight**
Logistics			
Number of tubes	Two (one in each direction)		
Daily operating hours	12	18	18
Launch interval [minutes]	2	4	6
Pod load/unload time [s]	60	120	240
Pod capacity	30 people	1.8 t (4000 lb)	26.3 t (58,000 lb)
Load factor / capacity utilization	70%	60%	60%
System Design			
Acceleration and Deceleration [g]	Two scenarios: 0.5g and 1g		
Cruise speed [km/h (mph)]	629		
Tube diameter [m (ft)]	4.0 (13.1)	4.7 (15.5)	6.38 (20.6)
Tube pressure [Pascal (psi)]	861 (0.125) (i.e., less than 0.01 atmospheric pressure)		
Regenerative braking efficiency	80%		
Hotel load (passenger comfort)	20% of total cruise power	None	None

Cruise Speed

The top cruise speed determines the width of the acceleration and deceleration load spikes. A cruise speed of 1012 km/h (629 mph) or Mach 0.82 was selected based on NASA's analysis of the tradeoff between speed and tube area; Mach 0.82 was the optimal point of operation (Chin and Gray 2015, Decker et al.

2017).[1] This requires the use of a compressor to avoid a "pistoning" effect in the tube.[2] 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 or 833 km/h (518 mph) (Opgenoord et al. 2017). The limited timeframe for this project precluded any computational fluid dynamics analysis, so several parameters and relationships surrounding this phenomenon were based on NASA's results.

Acceleration and Deceleration

Longitudinal acceleration rate is a key determinant of the load spike amplitude, both for power demanded from the grid and power fed back into it. The maximum acceleration depends on what regime the system operators are targeting. An airplane, in which passengers are required to be seated with a seatbelt, reaches maximum acceleration of 0.5g during takeoff (Hoberock 1977). Public transportation systems, which often allow riders to stand and rarely require seatbelts, typically operate at a maximum of acceleration 0.15g (Powell and Palacín 2015). A Tesla Model S driver accelerating from 0 to 60 mph in 2.5 seconds experiences 1.1g.

The *Hyperloop Alpha* paper suggested 0.5g longitudinal acceleration (Musk 2013) and NASA used a value of 1g (Decker et al. 2017). Rather than selecting a single acceleration, scenarios were run at both 0.5g and 1g for this study. The grid impact analysis was performed for the largest acceleration of 1g, which requires the largest power draw from the grid. Per discussions with Dmitri Ryudov at Lawrence Livermore National Laboratory and also based on specifications provided by Hoolboom and Szabados (1994), regenerative braking was included in the model with a deceleration rate equal to the acceleration and at an efficiency of 80%. To explore the most severe scenario, a step function for the acceleration was assumed. These parameter values are upper bounds, as it is unlikely that accelerations and decelerations over 1g will be implemented based on current transportation systems' operations.

As discussed in the *Propulsion* section above, the pods will gradually slow down during the cruise segment due to aerodynamic drag with the remaining air in the low-pressure tube. The model tracks pod speed throughout the cycle and provides "boosts" when a pod slows down to 95% of the top speed, or 960 km/h (597 mph).

Figure 8 shows the speed, acceleration, and power draw for a single passenger pod over the 2 minutes following launch from a station stop.

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[1] This also agrees with speeds announced by Hyperloop developers. Virgin Hyperloop One quotes travel speeds of between 804 and 1078 km/h (500 and 670 mph), TransPod is aiming for "… more than 1000 km/h" or 620 mph, and Hyperloop Transportation Technologies is targeting closer to the speed of sound of 1223 km/h (760 mph).

[2] Traveling near the speed of sound in a tube presents several difficulties because airflow is limited around the pod. This "throttling" of air around the pod, acting like a nozzle, causes air bypassing the pod to accelerate to Mach 1 before the pod does. This point represents the maximum airflow around the pod or the *Kantrowitz Limit*. If the pod continues accelerating, it will start to act like a piston inside of the tube, pushing a column of air several miles long and reducing efficiency.

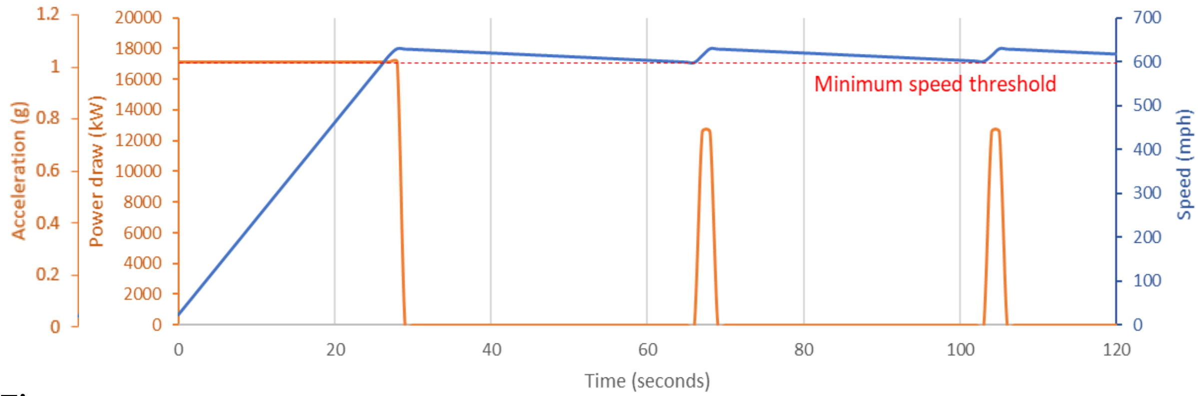

Figure 8. Speed, Power, and Acceleration Traces for a Single Passenger Hyperloop Pod Operating in the 1g Acceleration Scenario along the Inter-City California Route. Note, acceleration and power draw are linearly proportional and can therefore be represented by a single line.

The blue line in Figure 8 illustrates the steady decrease in speed until the lower threshold is reached, at which point a "boost" is provided.[1] The "boost" is defined by a duration (in this case, 2 seconds) and therefore is a lower value (0.7g) than the initial acceleration and deceleration.

Pod Mass

Pod mass is the other key determinant of load spike amplitude. Mass was estimated based on the weight of the pod body, passengers, seats, brake/suspension, magnets, batteries, and other components found in literature published by universities participating in the SpaceX Hyperloop competitions, particularly the scaled-up pod design from the University of Edinburgh (HYPED 2017). The final mass, assuming a passenger capacity of 30 and a load factor of 70%, was 1.4 t (3000 lb) for passenger. On the freight side, assuming a freight capacity utilization of 60%, estimates were 1.2 t (2600 lb) for light freight, and 8.9 t (19,700 lb) for heavy freight.

Pod Scheduling

Varying the number of pods in operation and their launch intervals changes the frequency of the load spikes as well as the coincident load conditions that drive up peak power requirements. This is evident in the load profiles shown in the next section; the peak power demand occurs when a station must supply power for initial acceleration of one pod *in addition to* the boosting accelerations of other pods that previously launched.

The number of pods in operation, their launch interval, and daily system operating hours will ultimately be determined by passenger demand for Hyperloop travel. Based on discussions with Hyperloop developers and information from the literature, we assumed that for a passenger system operating 12 hours per day, each station would launch a pod every 2 minutes on average. The freight systems will likely need more time to load/unload pods and therefore were allotted longer intervals between launches—6 minutes for large freight and 4 minutes for small freight.[2]

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[1] This is an estimate of what will occur. In fact, Hyperloop systems that operate in a manner similar to those modeled here will have linear motors installed at fixed locations on the track, and "boost" will be provided proportionally to what the system operator wants. Pods will not be able to accelerate when they drop to a certain speed, but only when there is a linear motor segment available.

[2] The launch interval was adjusted within a range of ±5 seconds to represent some level of launch flexibility. This avoided unnecessary "triple-stacking" of acceleration and boost loads.

Vacuum Maintenance and Pump-Down

A series of vacuum pumps, either in clusters or evenly distributed across the track, will run nearly constantly to maintain system vacuum during Hyperloop operations. The vacuum system requires a large amount of sustained electric power. There are three main vacuum load types: 1) initial system pump-down, which could occur daily, weekly, or less frequently depending on the operations and maintenance regime; 2) maintaining the vacuum due to leakage; and 3) airlock pump-down when pods prepare to accelerate from a stop at each station. Tube leakage accounts for a substantial portion of the total load; extremely low-pressure operation will lead to leaks due to diffusion, desorption, permeation, micro-cracks, and tolerances in mechanical component manufacturing and assembly. Average power draw to offset leakage was estimated to be 48 kW/mile for large freight, 36 kW/mile for small freight, and 31 kW/mile for passengers.[1]

The passenger system was assumed to be fully pressurized each evening after operations cease and evacuated in each morning before restarting operation. This practice allows for inspections and maintenance on vacuum pumps, pod propulsion and levitation systems, and the tube walls.

Load Profile Output

A sample load profile for a single passenger Hyperloop station is shown in Figure 9. The key operational regimes of the system that either draw electrical power from the grid (i.e., for acceleration, speed boosts during travel, maintenance of vacuum) or push electrical power back to the grid (i.e., regeneration during deceleration) are shown. A 3.6-minute period of two acceleration and two deceleration events are shown. The period in the middle represents the power required during cruising at maximal speed of 1012 km/h (Mach 0.82, 629 mph) with some smaller injections of power to overcome the minimal aerodynamic drag and other losses that slow down the pod.

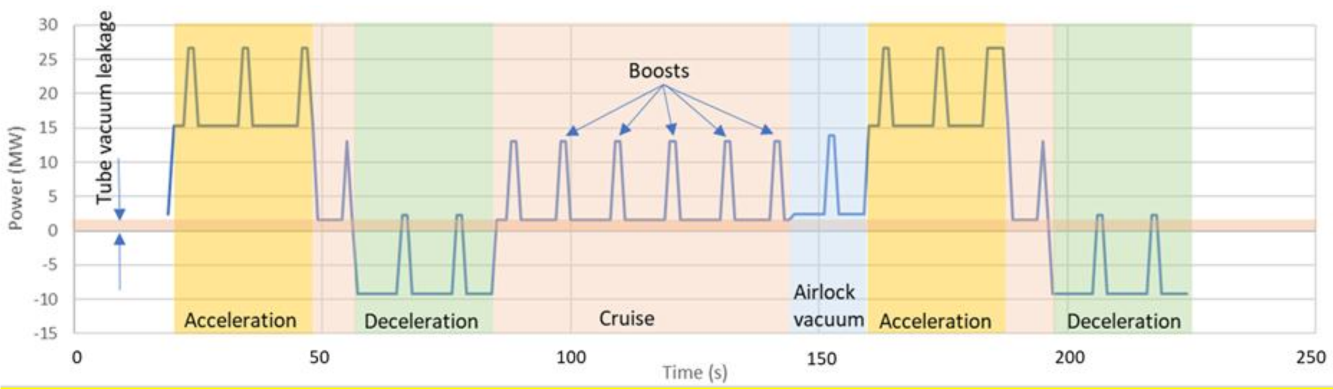

Figure 9. Typical Load Profile for a Single Passenger Hyperloop Station. Note, the station modeled here assumes boosts needed to launch the pods and to maintain the speed of the pods are distributed from the nearest station with infrastructure provided to the location of the boost along the route.

[1] This was based on an upper bound of 15 kg/s informed by the NASA analysis (Decker et al. 2017) as well as input from Hyperloop developers suggesting a higher power draw. The energy intensity results are highly sensitive to this parameter, but the final grid impacts resulting from load spikes are not.

Final Load Profiles by Location

The load profiles were used as forcing function for the grid impact analysis and were superimposed onto the existing load at a transmission substation. Table 2 summarizes the key load indicators for the four hypothetical Hyperloop implementations. Figure 10 and Figure 11 show slices of the load profiles for passenger and freight systems in each of the four scenario regions.

Table 2. Hyperloop Freight and Passenger Scenario Modeled Energy Demand

	California (inter-city)	Colorado	Ohio	California (intra-city)
Number of Stations	4	10	4	2
Freight				
Peak system power [MW]	820	1980	1140	230
Peak station power [MW]	200	200	280	110
Total daily energy [MWh]	1680	1850	1300	120
Passenger				
Peak system power [MW]	140	560	180	60
Peak station power [MW]	35	56	46	30
Total daily energy [MWh]	640	600	241	57

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. **Freight** represents the large freight scenario—transporting intermodal shipping containers. The smaller freight scenario results were very similar to the passenger scenario and was therefore not included in the grid impact analysis.

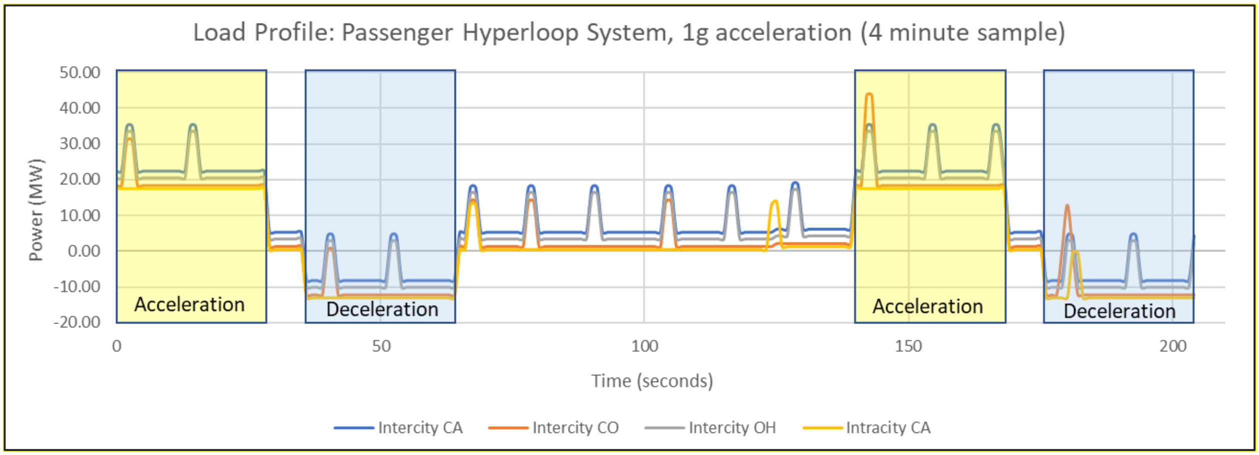

Figure 10. Load Profile Sample for each of the Passenger Hyperloop System Geographic Scenarios. Note, the load profiles each show two 30-second acceleration periods (shaded in yellow) and two 30-second deceleration periods. These are different pods pulling into the station, sequentially, while the load spikes between accelerations and decelerations are due to pods further down the tube that require boosts.

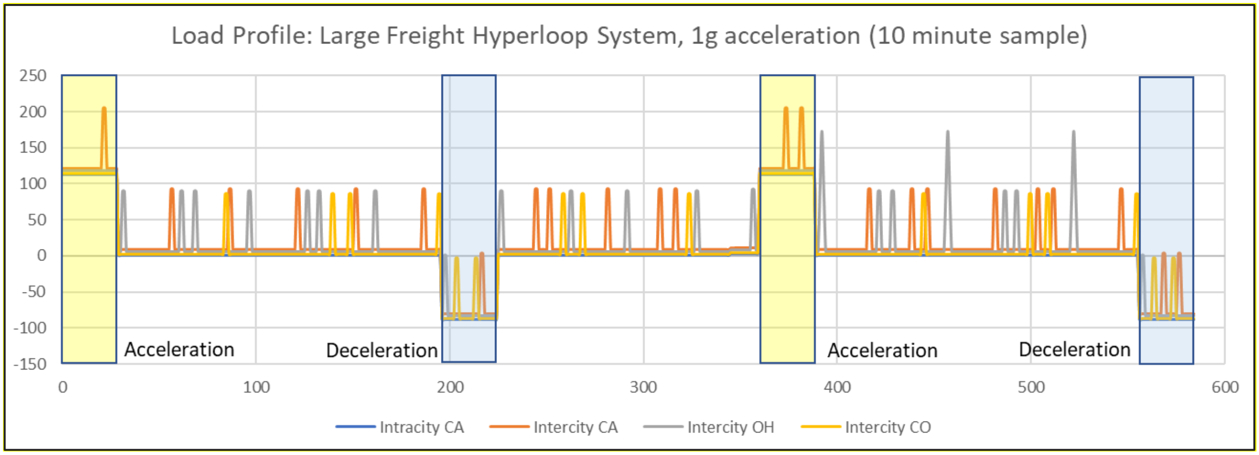

Figure 11. Load Profile Sample for each of the Large Freight Hyperloop System Geographic Scenarios. Note, the load profiles each show two 30-second acceleration periods (shaded in yellow) and two 30-second deceleration periods. These are different pods pulling into the station, sequentially, while the load spikes between accelerations and decelerations are due to pods further down the tube require boosts.

At each station, the electric power demands are imposed on the substation of the transmission system closest to the Hyperloop station for further grid impact analysis. The total load requirements for the entire system are shown in Table 2. It should be noted that the sequencing of starting and stopping pods in the system was such that pods started and arrived at the same time to avoid any congestion in the Hyperloop tubes. This led to a synchronized load driving up the peak demand.

Analyzing Grid Impacts

In this section, we describe the methodology of the grid impact analysis. First, we start with an overview of the U.S. bulk power energy system and then explain the physical mechanism of grid operations being analyzed in this study. We discuss the results of the grid impacts for four study cases. Finally, we conclude with specific concerns that transmission planning engineers may focus on when assessing Hyperloop facilities.

Key Facts about the U.S. Electricity Grid

Electricity is delivered to consumers from sources of generation through the network of substations, transformers, and power lines commonly known as the electricity grid. Power is sent from power plants through high-voltage transmission lines to substations, distribution transformers, and distribution lines to customers throughout the country. There are around 3000 utilities in the United States with approximately 480,000 miles of transmission lines and 6.3 million miles of distribution lines (Warwick et al. 2016). This network of utilities serves almost 150 million customers (Warwick et al. 2016).

Most grids at the local level are interconnected at a regional level to increase overall grid reliability. These interconnection occur at the transmission level.

These larger interconnected grids facilitate coordination and planning of electricity supply to consumers (EIA 2018a). Figure 12 illustrates the three main interconnection regions—the Eastern Interconnection, the Western Interconnection, and the interconnection operated by the Energy Reliability Council of Texas, which is known as ERCOT.

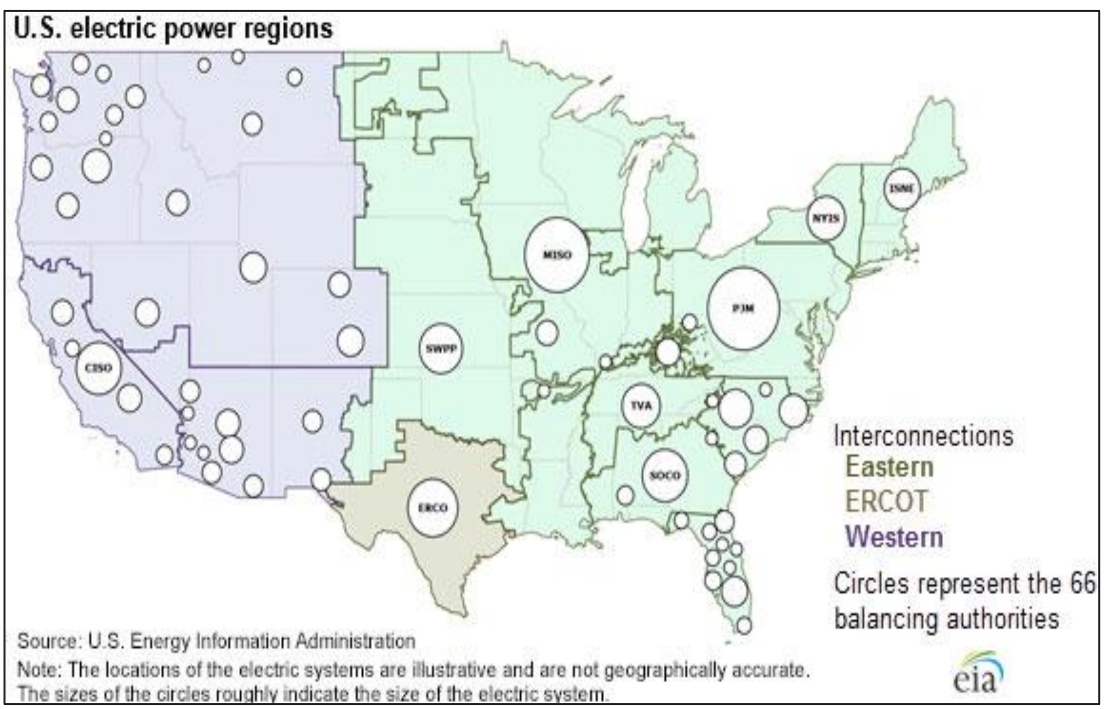

Figure 12. U.S. Electric Power Regions and Interconnects (EIA 2018)

Each circle within an interconnection represents a balancing authority. Balancing authorities are responsible for balancing demand and supply to maintain the nominal alternating current (AC) frequency of 60 Hz. The AC frequency is controlled within each interconnection separately, with little or weak interconnection among them. The aggregation to large transmission networks within an interconnection is done to increase the reliability of any portion of the grid in cases of unplanned outages of any large asset (e.g., a generator or transmission line). A strong transmission system allows power to be re-routed from other areas in case of a generator failure, thus preventing loss of electric service.

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” (voltage drops) or “blackouts” (disrupted service). The 66 balancing authorities, also shown in Figure 12, perform this function for specific parts of the electricity grid. These functions are known as ancillary services,[1] which include maintaining the system frequency of 60 Hz 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 a large electrical load, such as might be presented by Hyperloop system deployment. Because of their large power requirements, large electric loads are generally connected to the transmission system rather than to the distribution system.

Approach used for Grid Impact Analysis

A Hyperloop load qualifies as a large facility as described by NERC’s Facility Interconnection Studies (NERC 2014), and as such, an interconnection study is required before actual interconnection to the grid. Interconnection studies generally address any grid impacts a large facility would have during normal and contingency conditions in the bulk power system.

Because of the tight timeline of this study, only a reliability study under normal conditions was performed. This eliminated contingency analyses that addressed the impacts of a Hyperloop load during stress conditions that might occur during a contingency when a generator or transmission asset may trip unexpectedly. Furthermore, any economic impacts that examined changes to the generation mix due to Hyperloop technologies were out of scope as well.

Grid Phenomena Modeled and Tools Used

This analysis only focuses on potential grid reliability impacts under normal operating conditions. It addresses the potential grid response during a set of worst-case Hyperloop load behaviors that would stress the grid. The specific stress case we analyzed was the heaviest pod (i.e., the freight pod) with the highest acceleration (1g), resulting in the sharpest rise of the Hyperloop load.

The grid’s response of interest is the immediate dynamic response of the entire transmission network as a function of time in seconds, which represents the electro-mechanical behavior of the grid as an integrated system. The electro-mechanical response includes effects such as inertial behavior given by the rotational mass of conventional generators and the responses of voltage and primary frequency controls (i.e., generator speed governors and automatic voltage regulators). These are closed-loop controls at the generators that measure the local frequency and voltage and then respond instantly. In addition, protection schemes on generators and transmission assets were considered as well. These protection schemes would isolate high-value assets from disturbances when a certain threshold values in voltage and frequency were exceeded. There are minimum and maximum thresholds for the protection schemes.

[1] PJM Learning Center. Undated. “Ancillary Services Market,” Available at https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-services-market.aspx.

Industry-grade grid tools, and data sets are used in this study. The models are positive sequence, AC, power flow engines, and electro-mechanical dynamic models, which are grid industry standard. The tools that implements these models are General Electric's Positive-Sequence Load Flow (GE PSLF), and Siemens Power Technologies Inc. Power System Simulator for Engineering (Siemens PTI PSS®E). Most utilities in the North American Western Interconnection (WECC) use the GE PSLF tool, while most utilities in the North American Eastern Interconnection use the Siemens PTI PSS®E tool. Accordingly, in this study, the GE PSLF tool was used to model the WECC system, and the Siemens PTI PSS®E tool was used for the Eastern Interconnection. Data representing the ever-evolving U.S. bulk power system were established by NERC and industry groups with input from each utility and regional transmission operator of the interconnections.

Data used for the WECC were the typical summer, high load, scenario for 2017. For the Eastern Interconnection, the scenario was a typical summer peak load scenario for 2018. The database used for the Eastern Interconnection is developed annually by the Multiregional Modeling Working Group under Eastern Interconnection Reliability Assessment Group, with input from each utility and regional transmission operator. The Multiregional Modeling Working Group is responsible for developing all Eastern Interconnection power flow and dynamic base case data sets, including seasonal updates to summer and winter power flow study scenarios. For the WECC system, the data sets are developed annually by the System Data Working Group of WECC, with contributions from various planning and operating entities within WECC.

What was NOT Considered

What was not studied are longer-time feedback behaviors from control centers and operators that recognize either frequency or voltage disturbances and then provide counter actions to return the system its normal operating point. These behaviors generally require longer duration responses and thus are modeled in more complex contingency analyses, specifically 1) automatic generation control (AGC) which is part of frequency and interchange control was not considered, and 2) voltage and reactive power control, which is usually manual control by operators in the United States. These control actions require a supervisory control and data acquisition system that collects data, processes the data, and then decides on control actions to be sent out through the network to individual control devices. This full turn-around sequence from data acquisition to control response generally requires several tens of seconds to minutes and thus where too long for the initial system response studied in this report.

Furthermore, not analyzed are fast electro-magnetic dynamics that are generally important for the design of power system equipment and installation. These behaviors are generally of higher dynamics than the electro-mechanical effects with very short time constants in the micro-second range (Debnath et al. 2001). Modeling and analysis of electro-magnetic dynamics is likely to be required by utilities as part of an interconnection study at the time of permitting the Hyperloop technology (i.e., to examine the behavior of power electronics implemented with the Hyperloop technology). The authors of this studies considered this physical mechanism of lower priority, particularly, given the enormous data specificity of the power electronics and all of the uncertainties associated with the engineering assumptions of Hyperloop concepts.

In addition, the influence of implementing Hyperloop technology on the generation mix was out of scope for this analysis.

Potential Concerns of Grid Impact Introduced by Large Loads

The electrical load of assumed Hyperloop implementations is large by any comparison even when compared to large industrial loads. The Hyperloop load profile shows very sharp increases in power demands that would raise concerns by grid planning engineers without even having performed any modeling. The structure of the load profile and its magnitude are likely to affect frequency disturbances throughout the interconnection, as well as voltage disturbances in closer proximity to the load. NERC requirements for frequency and voltage deviation are summarized below.

NERC Requirements with Respect to Frequency Deviations across a Grid Interconnection

Power system frequency is a quantity that indicates the balance between electricity production and consumption. Large deviations in frequency can cause automatic generation and load tripping and, in the extreme case, loss of synchronism of many generators leading to a blackout. This balance and synchronism need to be maintained in real time. For this purpose, various types of control actions are used depending on time scales. The fastest control is the generator speed governor control (also called primary frequency control), which provides an almost immediate response (deployment starts in milliseconds and it is fully deployed in tens of seconds); this control is used to immediately arrest power imbalances, and many generators contribute automatically across a synchronous interconnection. The second control is the AGC (also called secondary frequency control), which is used to restore system frequency to the normal condition and to control power interchanges among utilities to scheduled values. This type of control is slower; commands are usually issued every 2 to 4 seconds and the full deployment of this control is usually achieved in minutes. As discussed above, the AGC control is out of scope for this study.

For the fast-changing load profile of a Hyperloop system, the generator speed governor control would react across the whole interconnection, due to the fast changes in Hyperloop load profile. AGC could compensate only for variability in the time scales of minutes. The severity of these effects can be measured by the frequency deviation in a power system model. Frequency deviations should be maintained within acceptable ranges. NERC defines that for the Eastern Interconnection, frequency ranges for continuous operation for generators are between 59.5 and 60.5 Hz, with wider ranges accepted, between 57.8 and 61.8 Hz, if their duration is shorter, up to 2 seconds for 57.8 Hz[1] (see Figure 13). For an excessive frequency deviation of 59.3 Hz in the Western Interconnection[2] or 59.5 Hz in the Eastern Interconnection,[3] automatic under-frequency load shedding will be initiated. If the frequency is not recovered, under-frequency generation tripping will start, and the system could face more extreme consequences.

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[1] NERC Standard PRC-024-2 . Undated. *Generator Frequency and Voltage Protective Relay Settings*. Available at https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-024-2.pdf.
[2] WECC Off-Nominal Frequency Load Shedding Plan, May 2011. Available at: https://www.wecc.org/Reliability/Off-Nominal%20Frequency%20Load%20Shedding%20Plan.pdf
[3] NERC Standard PRC-006-NPCC-1 Automatic Underfrequency Load Shedding. Available at: https://www.nerc.com/files/PRC-006-NPCC-1.pdf

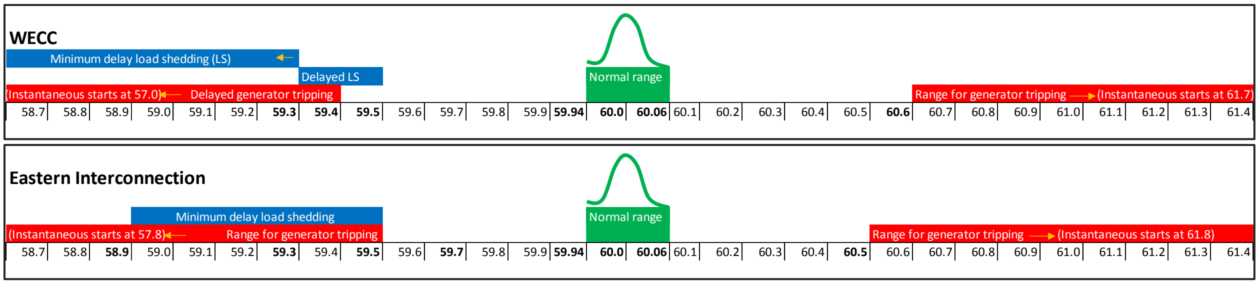

Figure 13. Frequency Range for Normal Operation and Frequency Tripping Thresholds

As it can be seen in Figure 14**Error! Reference source not found.**, the AC system frequency under normal operating conditions is fairly tightly controlled and very rarely exceeds thresholds discussed above. Power system operators maintain frequency very close to 60 Hz, to avoid ranges of concern at which load or generation tripping would occur. In turn, the system frequency only approaches these ranges of concern when large contingencies occur in the system, such as the sudden loss of the largest generation source.

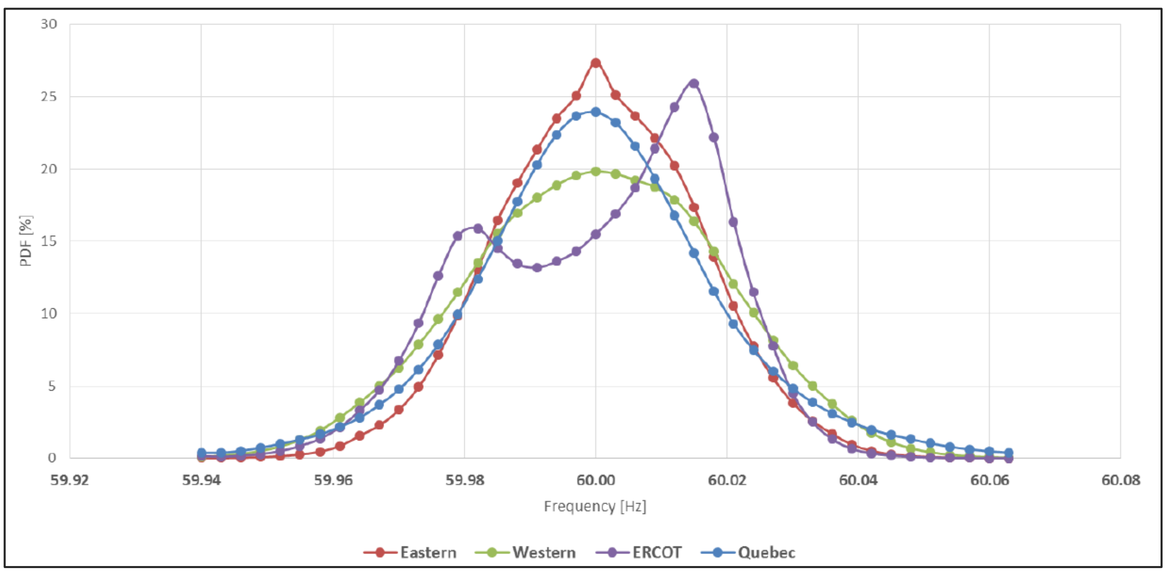

Figure 14. Comparison of 2013-2016 Interconnection Frequency Probability Density Functions (NERC 2017)

NERC Requirements Regarding Voltage Deviations

Voltage levels must be maintained within a tight range. High or low voltages can be detrimental to electrical equipment, and fast variation of voltages could cause power quality concerns, such as flicker.

To maintain voltages within acceptable ranges, the system should have sufficient reactive power compensation. Reactive power is an indication of energy exchanges between electrical and magnetic fields that occur 60 times per second in AC power systems. Currents in power lines and in electrical loads such as motors feed magnetic fields with inductive reactive power. An excess of inductive reactive power (high magnetic fields) could cause voltages to decrease. To compensate for this effect and help maintain voltages, power systems use elements that increase electric fields such as capacitors.

The assumed Hyperloop system exhibits rapid changes in both active and reactive power demands. To compensate for the sharp reactive power pulses, dynamic reactive power compensation equipment as needs to be deployed. Dynamic compensation is expensive compared to capacitors.

The ranges of voltage accepted by transmission operators should be between 0.95 and 1.05 per unit[1] for normal operation (NERC 2016). During faults, a voltage could be as low as 0.85 per unit for 5 minutes (NERC 2016), In addition, power quality effects such as flicker depend on how fast the voltage is changing. The voltage could be within acceptable NERC ranges but if it changes rapidly, flicker problems could arise (Rossman and Johns 2008).

NERC Requirements with Respect to Flicker

Although associated with light sources, flicker is more generally used in the context of voltage fluctuations. Voltage fluctuation is a sudden and noticeable change in voltage level, usually caused by fluctuations in power demands of variable loads. The IEEE 1453-2015 standard provides guidance to system operators, owners, and engineers who are responsible for providing electrical service to installations that causes voltage fluctuations (IEEE 2015). The IEEE standard adapted the flicker computation from the International Electrotechnical Council (IEC) 61000-4-15 standard (IEC 2008).

[1] In power systems analysis, a per-unit system is an expression of system quantities relative to a base or reference unit. For different voltage ratings of transmission lines, the reference unit could be 138 kV or 230 kV, etc.

Discussion of Results

PNNL performed simulations of potential Hyperloop impacts that would occur if the load profiles shown in Figure 10 and Figure 11 were exposed directly and unmitigated to the grid. We focused on the frequency and voltage deviations for four study cases. Because of the short time available to complete the study, grid simulations were limited to the freight pod configuration as it resulted in the most severe load profiles. The simulations of Hyperloop locations and their respective impacts to the U.S. grid are listed in Table 3.

Table 3. Scope of the PNNL Analysis

Locations		No. of Stations	Grid Impacted
California:	Los Angeles to San Francisco	4	WECC
California:	Intra-city (San Francisco airport to Golden Gate Bridge)	2	WECC
Colorado:	Cheyenne (WY)-Denver-Pueblo	10	WECC
Ohio:	Cleveland-Columbus-Cincinnati	4	Eastern Interconnection

Frequency and voltage disturbances over a portion of the load profile of Hyperloop systems are shown for three different locations in Figure 15. Variations in active load demands cause frequency deviations that "jolt" the power generator. Rapid variations in reactive power cause voltage deviations.

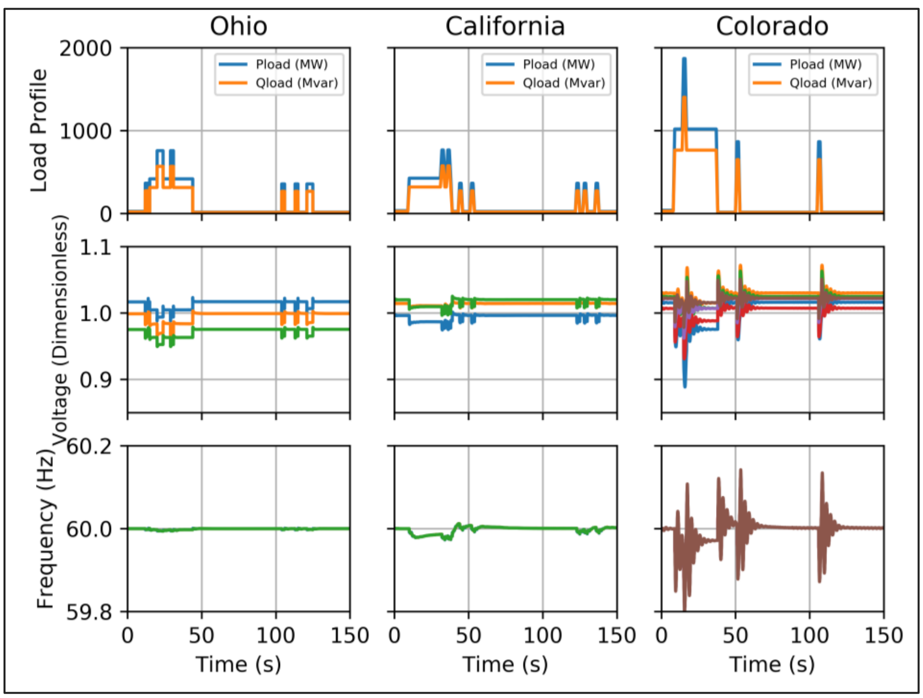

Figure 15. Modeled Impacts of Hyperloop Operation on Grid Frequency and Voltage for Three Inter-City Locations for a Freight Pod. The Load Profile (Pload) represents the active power requirements of the entire Hyperloop system. Qload represents reactive power demands.

Voltage Disturbances Impacts

The Hyperloop impact on voltage is more local to buses at the station and the surrounding area. As shown in Figure 15, the voltage and frequency impacts in Colorado are the largest compared to Ohio and California. This is not surprising as Colorado exhibits the largest load impact and the weakest or less densely meshed transmission network. California and Ohio have similar sized load profiles, but impacts in California are less due to the stronger transmission interconnection in the area, compared to Ohio.

The impact of a Hyperloop system in intra-city San Francisco is small compared to the inter-city routes. This is mainly due to smaller pod sizes, lower acceleration, and fewer stations. The results of the Hyperloop grid integration in San Francisco intra-city system are shown in Figure 16. The figure shows the comparison between passenger and freight station load impacts. The impact of the passenger Hyperloop is barely noticeable. The voltage has small fluctuations, which does NOT raise voltage flicker concerns. For the freight Hyperloop, the voltage response is more noticeable; however, it is still too small to cause voltage issues or flicker concerns.

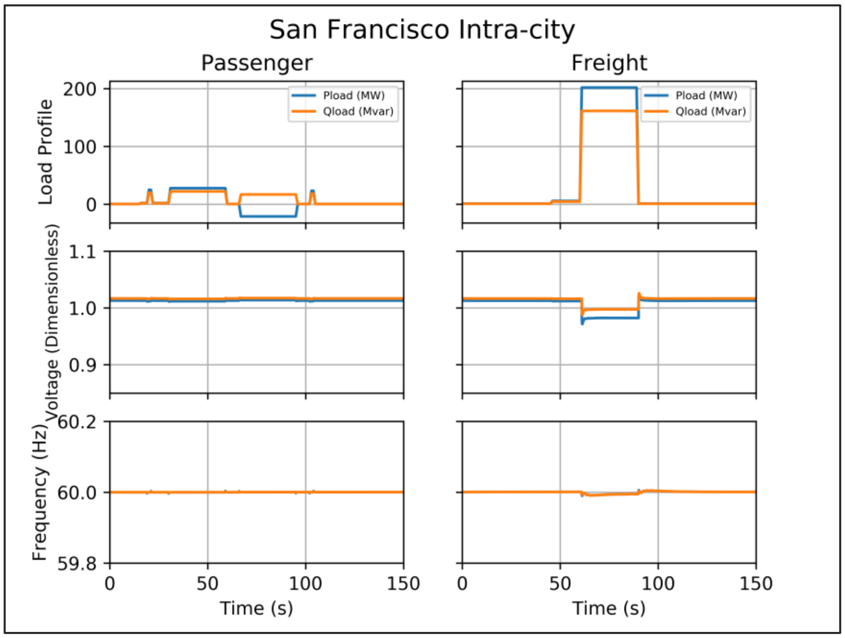

Figure 16. Impact of Hyperloop Voltage and Frequency for San Francisco Intra-City Passenger and Freight Pods

The location of the Hyperloop point of connection with the local grid and the voltage level of the transmission line also matters. Lower voltage interconnects will have less capacity to absorb load increases associated with the Hyperloop than higher voltage interconnects. Voltage impacts are shown in Figure 17 for two substations in the Columbus, Ohio, area. The voltage capacities are 138 kV and 345 kV. The substation with the lower voltage capacity exhibits a more severe voltage drop than the substation with the higher voltage capacity. Based on this modeling analysis, Hyperloop systems will probably require connections to substations with voltage capacities of 230 kV or higher. These higher capacity substations are typically spaced further apart and therefore may increase the expected cost of Hyperloop system grid interconnections.

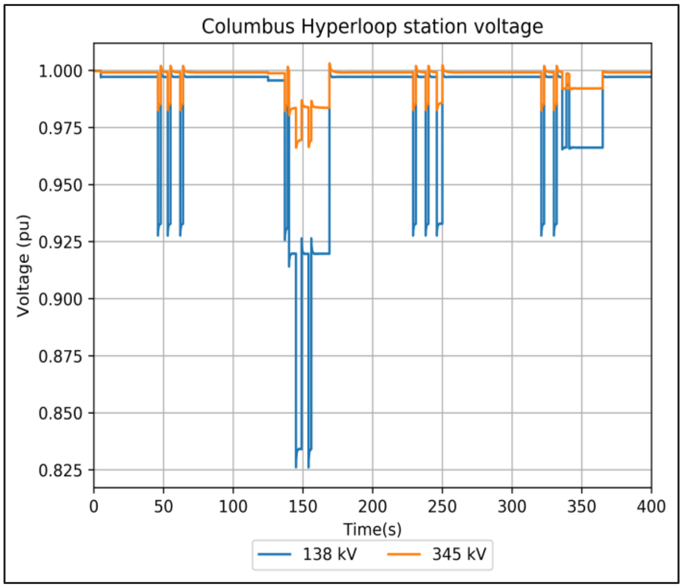

Figure 17. Voltage Drop from Hyperloop Varies by Interconnection Capacity

Rapid Voltage Change Estimation Results and Impact

Sudden load changes are the most common causes of rapid voltage changes in the network. The sudden change in the Hyperloop loading can present undesirable impacts on system voltages and could cause rapid voltage changes. The impact of Hyperloop rapid load change in Colorado area was investigated using the IEC planning guides against flicker (IEC 2008). In this study, only the freight scenarios were considered as they represent highest energy demands. Figure 18 shows significant voltage disturbances during the start-up of Hyperloop pods at substations in the vicinity of a station.

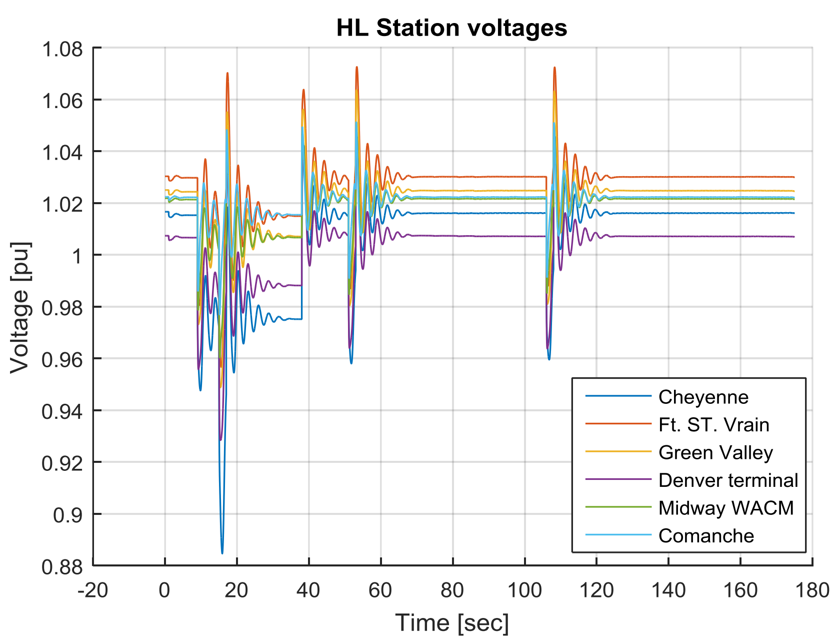

Figure 18. Impacts of Hyperloop Operation in Colorado on Grid Voltage at Various Bus Locations

The grid simulation results indicate that three substation locations exceed the IEC planning guides for preventing flicker. This requires mitigation equipment to be integrated into the grid. The other Hyperloop locations (California and Ohio) met the IEC planning guidelines.

System Frequency Disturbance Impacts

Results comparing the Hyperloop grid impact on frequency are shown above in Figure 15. Similar to voltage response, the frequency impact is most severe in Colorado because of the larger load, compared to California and Ohio cases, and the weaker grid interconnection. The California and Ohio cases show similar the impacts with slightly more response in the frequency in California compared than Ohio.

As Figure 15 shows, the WECC grid exhibits more noticeable disturbances from the rapid Hyperloop load changes than does the Eastern Interconnection grid. This indicates that the WECC has less inertial and governor response capacity to absorb the shocks of Hyperloop load spikes. Unlike a voltage disturbances, which is more a local phenomenon that diminishes at distances far away from the root cause, an AC system frequency disturbance spreads throughout the entire interconnection. Different grid interconnects exhibit different behavior in this regard. Perturbations from the Hyperloop load spread across the entire grid, as can be seen in Figure 19.

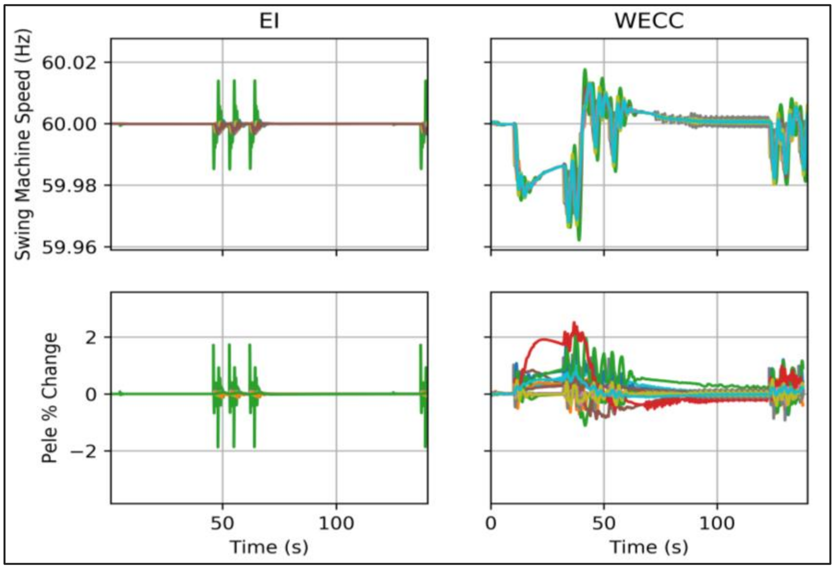

Figure 19. System-Wide Grid Effects of the Hyperloop Technology

Overall, none of the simulations (California, Colorado, or Ohio) triggered an under- or over-frequency tripping event, meaning that generators or loads are likely to be disconnected from the grid. In cases of a contingency (e.g., generator or transmission trips), the additional load impacts of a Hyperloop may add to existing stress conditions such that the relatively small frequency reserve of 0.3 Hz (59.8 to 59.5 Hz) may vanish (see Figure 20). While no load or generator tripping under normal grid conditions was observed during the simulations, there could be significant wear and tear on the generators as they would endure these conditions for every pod launch at any Hyperloop station throughout the day. More discussion about additional wear and tear of grid assets is provided below.

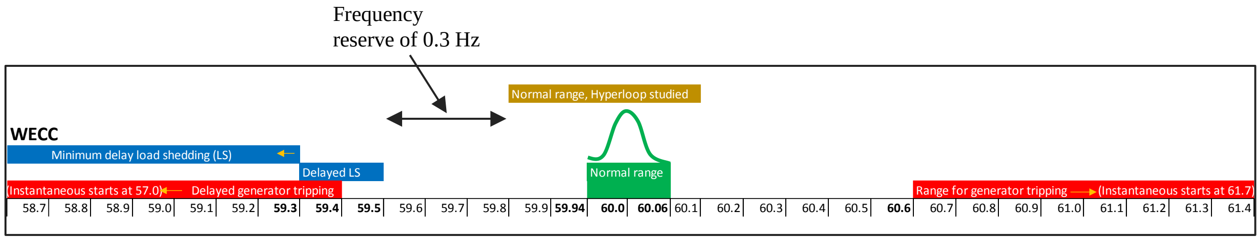

Figure 20. Frequency Range for Normal Operation for Hyperloop Nears the Ranges of Load Shedding. Note, a difference of only 0.3 Hz (59.8 to 59.5) exists between the Hyperloop-induced frequency and the load-shedding frequency.

Other Considerations and Concerns

Increased Wear and Tear in Grid Assets

The pulse nature of the Hyperloop system load will cause wear and tear in generators across all entire interconnections due to very rapid up and down ramping as shown in Figure 20. The increase ramp rates will have some impact on unit trips and start/shutdown cycles. While cycling-related increases in failure rates may not be noted immediately, critical components will eventually start to fail. Although it is difficult to quantify the wear and tear and the associated increase in maintenance cost or reduced life of a generator unit, it is likely that power plant owners would reject such stress on their units without significant compensation. Frequently occurring frequency deviations will induce a dynamic shear stress on the generator’s shaft as the generator speeds up and slows down. These torque changes will increase fatigue of the shaft material and place additional stress on the shaft bearings (Kumar et al. 2012, Tsao and Tsai 2004, EPRI 1996, Sürgevil and Akpnar 2009).

Wide Spread Adoption of Several Hyperloop Systems

In this study, only one Hyperloop system was studied at a time. The freight scenarios were considered because they represent highest power demands. If multiple Hyperloop systems are deployed in the future, the grid impacts analyzed in this report could be exacerbated unless effective mitigation measures are implemented. Give the pulse load nature of Hyperloop systems, load diversity benefits will not be realized with several Hyperloop systems connected to the same interconnection. In particular, frequency-related issues are likely to be cumulative (i.e., each source will exacerbate the problem) regardless of the locations within the interconnection. Voltage deviations and flicker issues are more local phenomena and may only worsen if sources of voltage deviations are located within “electrical” proximity. Additionally, if not mitigated, the pulsating load characteristic of several Hyperloop systems should be analyzed to avoid any inducement of oscillations near the natural frequency of the grid.

Summary of Simulation Results

The simulation results clearly indicate that a Hyperloop-like load needs compensation equipment to address the sharp pulses in active and reactive load profiles and the associated frequency and voltage variations in the grid. If uncompensated, the load characteristics for the Colorado case bring the power system’s normal operation closer to ranges of concern, leaving less margin to deal with contingencies. Frequency deviations under normal grid conditions may approach ranges where under-frequency load shedding may occur. Although the results do not result in load and generation tripping, the power system has less margin to absorb power system contingencies.

In other regions such as Ohio, frequency response was not a concern because of the larger connected inertia of the system.

Voltage deviations in some of the buses for the Colorado Hyperloop system violate typical power system planning criteria for flicker, which generally is considered a power quality issue that needs to be addressed. However, simulation results do not indicate voltage deviations of a magnitude that are likely to activate protection schemes. These insights, however, should not obviate any potential concerns that potential contingencies, such as unplanned outages of transmission or generation assets, may reduce the reserves of the grid to a point where protection schemes may be triggered.

In terms of voltage impact, Hyperloop systems impact grid operations more severely when connected to substations at lower voltage levels. The results suggest that interconnections to the transmission system should be at voltage levels above 230 kV.

While no direct reliability concerns were detected in the simulations, the sharp load pulses that may occur every 2 minutes with the departure of a pod at a station during the operating hours of a Hyperloop system do open up additional vulnerabilities under contingency conditions. Furthermore, the persistence of grid impact may place unacceptable burden on generator and voltage regulating devices with increased wear and tear. All of these insights suggest that effective mitigation strategies are necessary to compensate for the large load ramps. The next section discusses 1) compensation technology options, 2) examples of how large industrial loads have been connected to the grid, and 3) interconnection considerations for Hyperloop technologies.

Considerations for Interconnecting Hyperloop-Like Loads

Hyperloop technology represents a non-conforming load profile that changes significantly over a very short span of time (i.e., a pulsating load). There are examples of how non-conforming load customers have been successfully connected to the grid. PNNL reviewed technology solutions for non-conforming loads using the example of large arc furnaces that have Hyperloop-like intensive load profiles. Furthermore, PNNL outlined a concept for energy storage solutions that could serve as an illustrative example to flatten the undesirable real power pulses. Two examples of potential energy storage-based integration concepts are presented.

Arc Furnace/Steel Plant

Arc furnaces are characterized by rapidly varying loads as shown in Figure 21 (Andrei et al. 2011); therefore, they were considered to be representative of Hyperloop-like intensive loads. Because of the large input power requirements of arc furnaces and the nature of their load profiles, solutions implemented to mitigate power quality issues, such as flicker, voltage imbalances, harmonics, etc. (Dixon and Kendall 1972, Freeman and Medley 1978, Andrei et al. 2011), caused by their connection to the grid could be helpful in identifying a good solution for connecting Hyperloop systems to the grid.

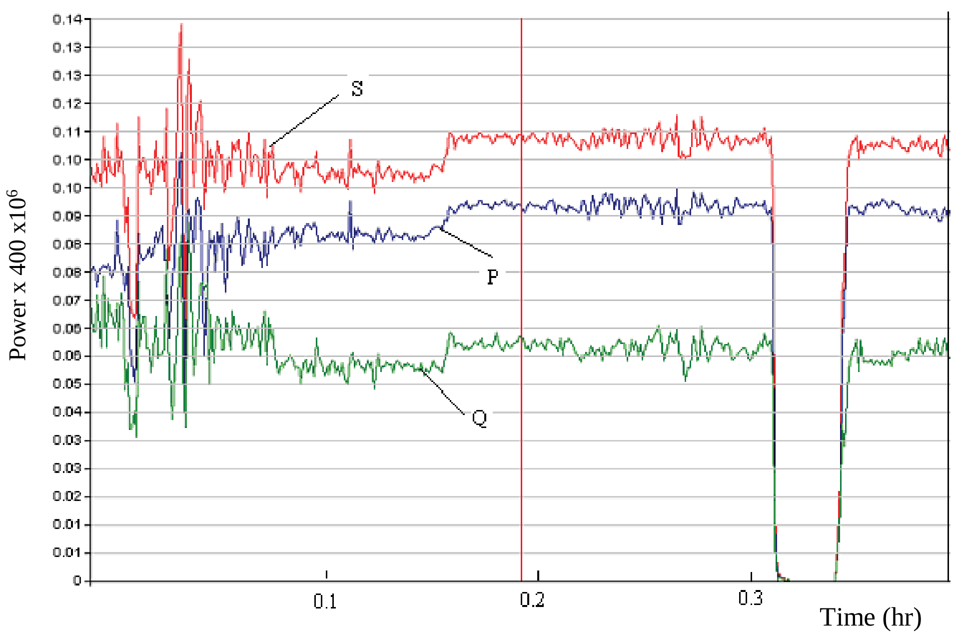

Figure 21. Real Measurements showing Variations in Active Power (P in watts), Reactive Power (Q in var), and Apparent Power (S in volt-amperes) of an Electric Arc Furnace. Note the maximum active power is 40 MW ($0.1*400*10^6$ W).

Because of the abrupt initiation and interruption of current flows associated with the non-linear and stochastic behaviors of arc-furnace operations, their impacts to the grid are significant (Shevchenko et al. 2015). In addition to the power quality issues mentioned earlier, other impacts of arc-furnace operations are torsional vibrations caused by variations of active and reactive power in an electric arc furnace on turbine-generator shafts and blades (EPRI 1996, Tsao and Tsai 2004, Shevchenko et al. 2015). These torsional oscillations can result in a complete failure of mechanical shaft system components of generators located electric arc-furnace plants over an extended period of time.

Power utilities have certain requirements for connecting industrial loads to the grid so that the residential customers remain unaffected. Some of the solutions often implemented to mitigate the power quality issues caused by arc furnaces are listed below (Shevchenko et al. 2015):

1. *Series equipment* – Series equipment such as reactors, capacitors, smart predictive line capacitors (SPLC) and thyristor converters (Freeman and Medley 1978, Spasojević et al. 2011) to reduce flickers and voltage fluctuations by smoothing out current variations. Series reactors are often avoided as they can introduce significant harmonics (Shevchenko et al. 2015). Series capacitors also are not used as they result in significant increase in the voltage. As described by Shevchenko et al. (2015), using these devices can solve power quality issues and, thus, help gain approval of the grid connection by the utility.
2. *Shunt equipment* – The shunt equipment, such as power factor compensation capacitors and harmonic filters, static var compensators (SVC), static compensators (STATCOM), and energy storage equipment, are designed to maintain power quality parameters at the power supply bus of the furnace.

As shown in Figure 22, modern arc furnaces often use SVCs to reduce their impact on the grid (i.e., to meet utility electrical requirements) (EPRI 1996, Silva et al. 1996, Morello et al. 2015). Examples of facilities where SVCs are used to mitigate power quality issues are the Lukens steel plant, described in EPRI (1996), and Sumitomo Metals/Standard Steel in Burnham, Pennsylvania, as described in Morello et al. (2015). In addition to mitigating power quality issues, the installed SVCs also help with enhancing power factors, making noise levels within an acceptable limits, and improving overall arc-furnace operation and productivity (O'Kelly et al. 1992, Silva et al. 1996, EPRI 1996, Morello et al. 2015).

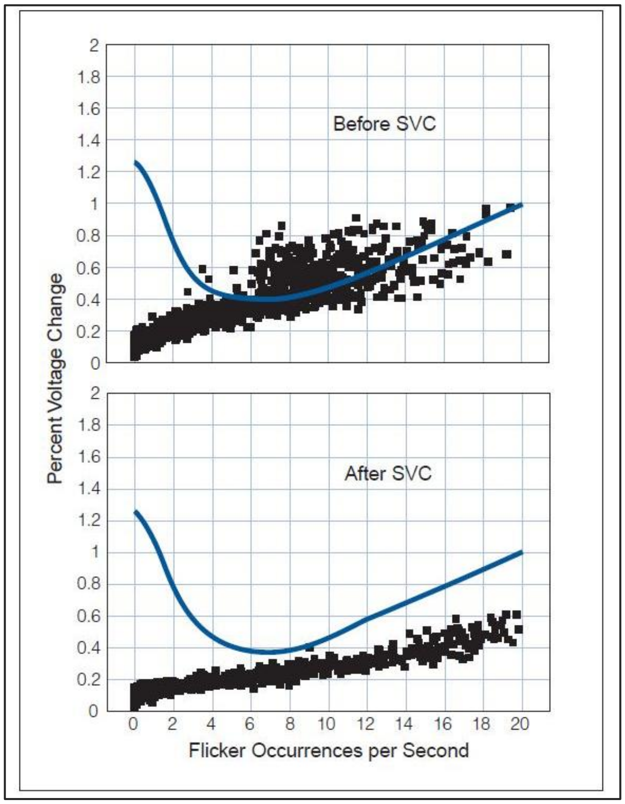

Figure 22. Installation of SVCs at the Utility Substation Supplying Power to the Lukens Plant Reduced Flicker from Objectionable to Non-Objectionable Levels. The blue curve shows the threshold (EPRI 1996).

Energy Storage as an Interconnection Device for Hyperloop Technologies

An additional or alternative technology option to capacitors, SVC, STATCOM, and dynamic VAR devices, which can help mitigate voltage and flicker problems, is an energy storage system that can reduces the amplitude of pulsating active power consumption at the PCC. There are many energy storage technologies available. Because of recent cost reductions and the potential further reductions, battery technologies have received the most attention recently. All energy storage systems can provide real power stored in their storage medium and also reactive power through smart inverters that convert the stored DC power to AC power. Energy storage technology alone or in combination with the other technologies discussed above are a potential solution to the main challenge facing Hyperloop systems.

It is important to highlight that regarding mitigation of voltage fluctuations, energy storage and SVC or STATCOM are equivalent solutions. They all are dynamically controlled voltage and reactive power compensation approaches. The additional benefit of energy storage over SVC or STATCOM is that an energy storage system also can mitigate frequency fluctuations. Energy storage also can dynamically compensate for the rapid active power fluctuations seen in Hyperloop load profile, thus addressing concerns about widening the normal operation range for system frequency and additional wear and tear on generator assets.

Example 1: Storage Solution that Produces Flat Load to the Grid

To illustrate a potential use of a storage device as a mitigation strategy to the pulsating load demands, we discuss two simple storage concepts. It should be noted that these illustrative examples are conceptual and are by no means the only technological options. Nor should it imply that energy storage is the most cost-effective mitigation strategy. More detailed analyses would need to be made to explore economic solutions that would comply with NERC and design and planning guidelines.

The first example focuses on flattening the variable components of electrical demand for a Hyperloop system. For the California case, a high-power, low-energy, storage system (capable of moving large quantities of power in and out but with limited power storage capacity) could address the varying electrical demand and present a relatively constant 13-MW load to the grid using a 179-MW, 50-MWh storage system. An approximate cost for such device, if it was a lithium-ion battery system, would be $88 million.

This example illustrates the use of an energy storage system to absorb all variability in the Hyperloop load profiles. The power profile drawn from the power grid is constant. The flat power profile of the grid results is 13 MW to cover for average power and battery efficiency losses. Figure 23 shows the power profile used to charge and discharge the storage system. Figure 24 shows the state of charge of the storage. The maximum state of charge determines the energy capacity of the storage of 50 MWh. The power-to-energy capacity results in a 17-minute storage system (50 MWh/179 MW).

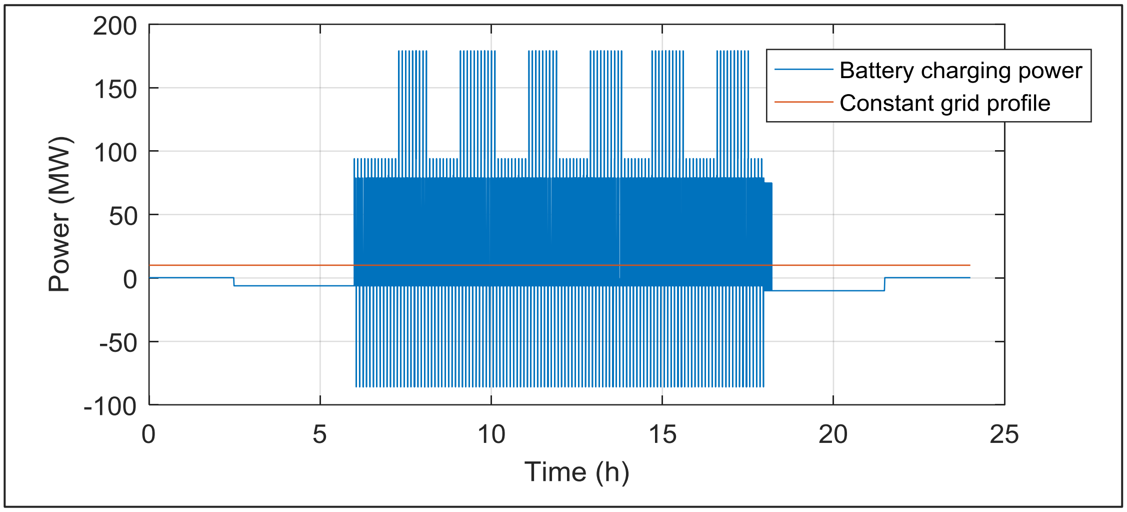

Figure 23. Power Profile Absorbed by a Storage System. Maximum power is 179 MW, while the grid observes a flat power profile of 10 MW

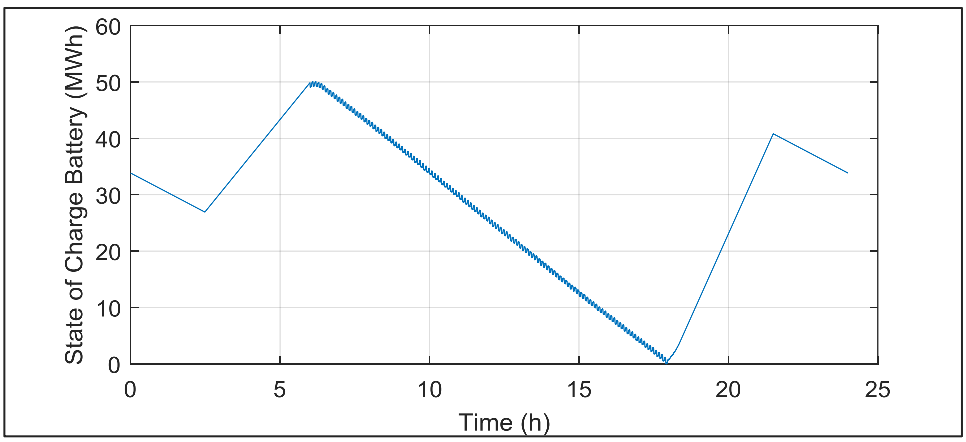

Figure 24. State of Charge of Storage with a Maximum Size of 50 MWh

Example 2: Storage Designed to Absorb Some Variable Power Requirements

As an alternative to the fully flat load profile described in Example 1, an energy storage system could be designed to absorb only the fast component of the Hyperloop load characteristics. The remaining slower component of the Hyperloop load profile would be absorbed by the grid. By only absorbing the fast component, the storage system could be smaller in size and less expensive.

The storage system for the fast component (faster than 1 minute) is a 113-MW and 9.5-MWh system (5-minute storage system) that would cost, if assumed to be a lithium-ion battery system, approximately $47 million. The remaining slow power component to be absorbed by the grid would not exceed 117.5 MW.

Figure 25 shows the decomposition of the original active power load profile into a fast load component (to be provided by energy storage) and a slow component (to be exposed by the grid).

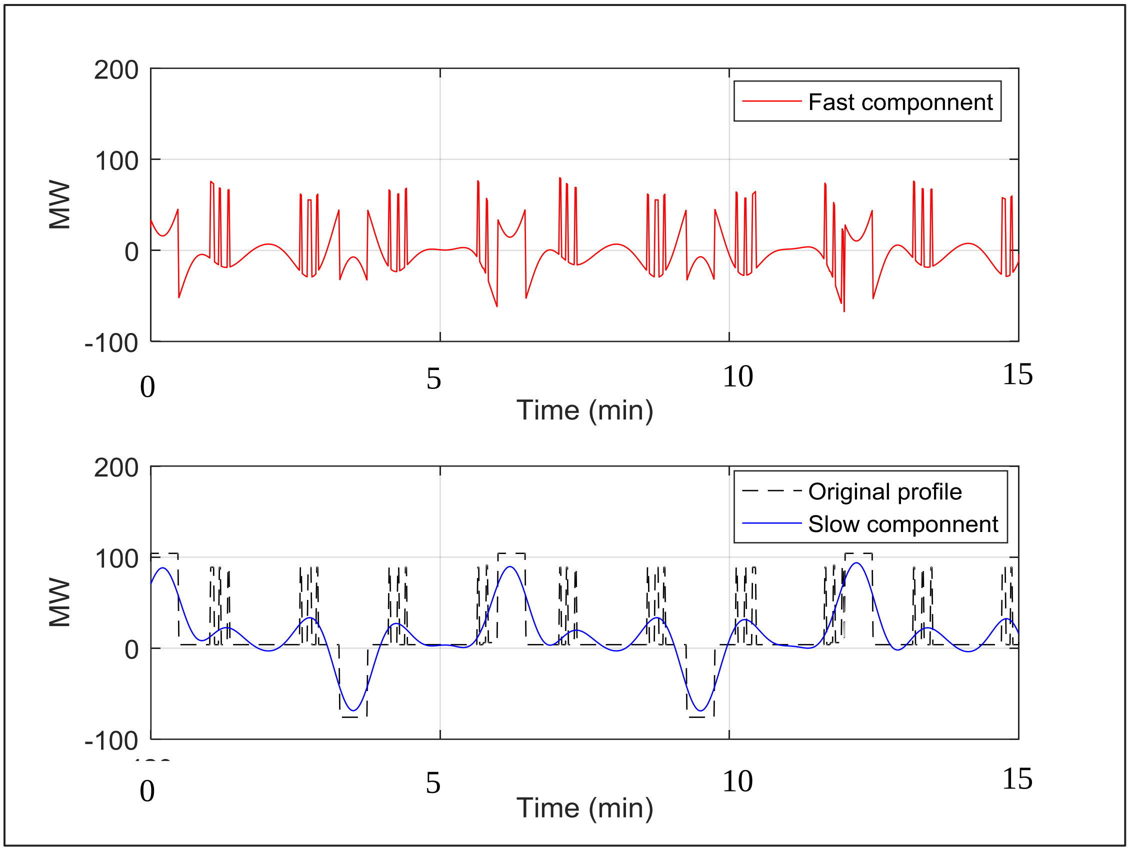

Figure 25. Decomposition of Hyperloop Load Power Profile into Fast and Slow Components. The fast component will be absorbed by a battery storage system. The slow component can be absorbed by the grid.

Summary of Energy Storage as an Interconnection Device for Hyperloop Technologies

As demonstrated in the two illustrative examples, storage systems can be sized and designed to mitigate grid-side load profile. It is now a matter of design optimization to find the most economic technology solution set and control strategy that will meet grid interconnection rules and guidelines while containing cost.

Conclusions

PNNL performed a grid study that assessed the potential grid impacts of an at-scale Hyperloop system at four U.S. locations. The assessment was performed for each location separately. No cumulative grid effects when operating four systems simultaneously were considered. The selection of the four locations were based on existing conceptual geographic layouts connecting two or more cities in the United States as published by Hyperloop technology developers. One of the four locations represented a smaller system as an illustrative example for an intra-city transportation application. San Francisco was arbitrarily chosen to represent an intra-city application. Furthermore, consideration was given to represent some diversity in the Hyperloop system size (small versus large) and geographic placement in the U.S. bulk power system. Three systems were located in the Western Interconnection and one was in the Eastern Interconnection. Given the short study period, the grid assessment focused on the worst-case scenario that was defined by a heavy Hyperloop pod (freight application) and at a high rate of acceleration (1g). These assumptions resulted in a very high pulsating load profile in both active and reactive power. Part of the worst-case scenario definition was a deliberate assumption that no compensation technologies were applied, but rather that the full impact of the pulsating load profile was imposed onto the grid. In choosing this assumption, the worst-case impacts would be revealed. PNNL's assessment provides estimates of the worst-case impacts and describes considerations of how grid impacts could be mitigated by a set of compensation technologies that would reduce the impacts to an acceptable level for grid integration.

The results of this study clearly indicate that the continuous power pulses for inter-city transportation applications are sufficiently large in magnitude and ramp rates such that they are likely to induce system voltage disturbances that, in some cases, may violate commonly used planning guides for voltage fluctuations and flicker conditions. Furthermore, system frequency disturbances would be of significant magnitude and could be "felt" throughout the entire or major portion of the Western and Easter Interconnections, respectively. Although the modeling results did not indicate frequency trips, the margins between the under-frequency excursions and the under-frequency load-shedding thresholds became very small. In other words, the range of the system's frequency under normal operation becomes wider, thereby reducing frequency reserves in cases of high stress conditions during grid contingency conditions. This may present additional vulnerabilities of the grid during large contingency conditions when a large generator or transmission asset trips unexpectedly. It should be noted that the analysis did NOT consider contingency conditions. Only normal grid conditions were simulated.

The persistence of these pulsating load profiles during regular Hyperloop operating periods (with high power pulses every 2 minutes when a pod starts up at a station) imposes constant voltage and frequency deviations that are not acceptable for grid interconnections from the perspective of planning guidelines for voltage variations and undue wear and tear on generator assets primarily due to frequency variations.

The simulation results clearly indicate that Hyperloop technologies will require compensation devices to address or preempt the pulsating characteristics of the expected load profile both for active and reactive power. There are examples of how industrial loads with similar load characteristics (e.g., arc-furnace installations) have been successfully connected to the transmission grid in the United States and worldwide, using dynamic compensation equipment, such as SVC and STATCOM devices. These examples, however, are not quite of the size (MW and MVar) and persistence of a large Hyperloop implementation; therefore, larger compensation devices might be needed. Other technologies such as energy storage systems may offer unique capabilities to preempt the pulsating characteristics that the grid would need to absorb by compensating and dampening the sharp power requirements encountered during pod acceleration and by absorbing electric energy during regenerative braking.

While a full compensation strategy for a Hyperloop technology was beyond the scope of this study, concepts of potential storage solutions to fully eliminate or partially reduce the pulsating load characteristics are provided in this report. For the California case, a high-power, low-energy storage system (capable of moving large quantities of power in and out, but with limited power storage capacity) could eliminate the variable component of the electrical demand. The results would be a constant load of 13 MW. The system storage size would be 178 MW and 50 MWh. The system cost was estimated to be approximately $88 million, assuming a lithium-ion based battery system is employed. A smaller storage solution that reduces the amplitude of the load pulses was estimated to cost approximately $47 million (again assuming a lithium-ion battery system is used).

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