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System Design of a High Speed Ground Vehicle Lifted by Air Bearings

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System Design of a High Speed Ground Vehicle Lifted by Air Bearings

by

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Thesis

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Dedication

Dedicated to my mother and father, for I could never have gotten to where I am or to where I am going without them.

Acknowledgements

I would like to thank all past and present members of Texas Guadaloop for their tireless contributions to this project. Without them, I never would have been able to write this paper, or get this far in the competition. It never ceases to amaze me that a group of volunteers can bring such passion to a project. This has been so much fun.

In particular, I would like to thank Patryk Radyjowski, who has been my partner in this from day one. He is the most brilliant engineer I have ever met, and without him we would not have even made it out of the planning stages. I cannot wait until he puts a human on Mars!

I would also like to thank my supervisor, Dr. Li, and my second reader, Dr. Claudel. Without Dr. Li and his help, I never would have been able to finish this Thesis, let alone graduate on time. Dr. Claudel has been our guiding hand throughout this whole project. His diverse background has made him an important architect in our systems and controls integration process.

Of course, I would like to thank my family. My Mom, Dad, George, and Richie have given me the faith and support necessary for the completion of this project and degree.

Abstract

System Design of a High Speed Ground Vehicle Lifted by Air Bearings

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The University of Texas at Austin, 2017

Supervisor: Wei Li

In 2015, SpaceX announced an international competition for student teams to design and build prototype pods to compete on a one-mile test track at their HQ in Hawthorne, CA. The track would be contained in a partial vacuum tube, and student teams were given near free reign in their design and build process. Of considerable interest in Hyperloop development is what mechanism of lift it should use—magnetic levitation or air bearings. In this Thesis, a novel approach is taken to the system design of a pod capable of levitating itself with compressed air, or air bearings. By doing so, drag is essentially eliminated from the system, and the pod will be able to travel at very high speeds with little power requirements. Building a half-scale pod and testing it on the track is considered a feasible way to test air bearings at high velocities. Since that has never been done before, the main goal of this research is to design and build a pod capable of doing so, given the input parameters provided by SpaceX. The prototype pod detailed in this thesis has been designed and built, and will be tested on the SpaceX test track. A new air bearing design is proposed for future work. While the SpaceX competition gave motivation for this work, the research conducted in this thesis, including evaluation of various levitation and braking mechanisms, design methodology, and parameter design, are applicable to other engineering challenges.

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Chapter 1: Introduction — The Proposed Hyperloop

The focus of this Thesis research is to develop a testing platform for air bearings, a technology that lies at the core of the Hyperloop concept. A review of the current modes of transportation, and their shortcomings, is offered in order to detail the need for an entirely new mode of transportation. This will discuss the benefits of a Hyperloop over the other modes of transportation in certain scenarios. While this research does not focus on the development of a full scale Hyperloop, it does focus on a new form of levitation technology that is essential to making it work. As such, in depth market research has not been performed in comparing these modes of transportation. Simply, an informal discussion will take place to lay the groundwork of the fundamentals of the Hyperloop concept. It will be later discussed the benefits of air bearings over other forms of levitation, such as magnetic levitation.

1.1: THE FIFTH MAJOR MODE OF TRANSPORT

Since the Wright Brothers' first powered flight in 1903, no more major modes of transportation have been invented. That means that for over 100 years, we have used the same four modes of transportation to travel large distances: cars, planes, trains, and boats. Despite obvious innovations in each of these categories, such as commercial jetliners in the 1950's or our progression up to current High Speed Rail (HSR) trains, the guiding principles behind these forms of transportation has remained the same. These modes of transportation each have their advantages and disadvantages, and it has become apparent that they have left a gap in the needs of the 21st century human. While discussion abounds around under water Hyperloops, boats will largely be left out of the discussion. The primary focus of the Hyperloop rests on the concept of shipping cargo by land, or with super commuters. As a result, it is necessary to first discuss the disadvantages of conventional modes of shipping and commuting by land—cars, trains, and planes. For ease, the discussion will be largely limited to the United States, even though the first commercial Hyperloop line will likely be built overseas.

1.1.1 Cars

The commuter industry in the United States is still largely dominated by infrastructure decisions made in the 1950's. That is, by building a national highway system, Americans were given the infrastructure necessary for wide-scale use of cars and trucks for both commuting and shipping. While it is very American to own a car and be able to drive anywhere one likes at any time, it is not the most efficient means of travelling long distances. Take, for example, travelling from Austin to Dallas. The trip is roughly 200 miles, and will take a passenger car 3 hours to make the trip, without any traffic. While cheaper than a bus, train, or plane, it is a considerably time-consuming journey compared to by plane and leads to greater CO_2 emissions than shared transportation. While effective for short distances, there is a better way of travelling on journeys of 200 miles or more.

1.1.2 Planes

Commercial air travel at scale was also introduced in the 1950's with the advent of the commercial jet liner. Planes are certainly one of the most important facets of our modern transportation lifestyle. We're able to travel close to 3,000 miles from NYC to LA in six hours, something that is impossible with the other modes. However, the trip from Austin to Dallas by plane does not look so favorable. While only about 40 minutes to an hour in the air, the majority of the journey takes place on either end of the flight. Planes cannot fly near large buildings, so airports generally have to be on the outskirts of major cities, as opposed to downtown. This leads to travel times of fifteen minutes or greater (sometimes an hour), by car, before and after the plane ride itself. Furthermore, it is necessary to arrive an hour or more before the flight to go through security and check-in. Door-to-door, the 200 mile journey by plane does not end up being drastically shorter than by car.

1.1.3 Trains

Deploying a high speed rail system of similar scale to our highway system would be the modern day equivalent of the decisions made in the 1950's. However, that seems increasingly unlikely to happen. While there are systems in place in areas like the East Coast (from DC to NYC and Boston), the capacity of these trains is nowhere close to what is seen in other parts of the world. In fact, the 200 mile journey does make most sense for a train. It can be downtown to downtown, and even a moderately fast High Speed Rail (HSR) system at 150 mph would have you there in an hour and a half. But does this justify the massive infrastructure spending needed to do so? Is it even possible given NIMBYism and the safety systems necessary to let a HSR train travel at 150mph through some small Texas town? It seems the answer is no, it is not justified, given the lack of HSR infrastructure upgrades currently taking place across the U.S. What if we could make that 200 mile journey in 20 minutes, and make it cheaper than a HSR system? Would that change anything?

1.1.4: The Hyperloop Concept

The Hyperloop Concept was born out of Elon Musk's frustrations with the questions being raised above. However, for him it was the trip from LA to San Francisco. With traffic problems up and down the coast, and plans to build an overly expensive "HSR" system, that is not even HSR speeds, Mr. Musk thought that there must be a better way. So, in 2013 he released what is known as the White Paper [1] detailing an entirely new mode of transportation called the Hyperloop. The basic premise is to build an evacuated tube and levitate a pod inside that tube on a bed of pressurized air. This would entirely eliminate drag from the system, allowing the pod to travel at speeds of up to 750 mph. Essentially, it would combine the low drag atmosphere of a plane (even lower, actually) with the downtown-to-downtown convenience of a train. Furthermore, it would solve safety concerns of a fast-moving object in towns because it would be fully contained. This sounded like the new, futuristic mode of transportation that would solve our infrastructure woes in the United States. All, he promised, at a price significantly lower than current HSR systems.

Obviously, there are quite a few large engineering challenges that would have to be solved in order to make this happen. The most obvious of which is the levitation mechanism. What Elon Musk proposed was an almost entirely new way of levitation—at least at this scale. It seems though that he fundamentally misunderstood the nature of what are called air bearings in this preliminary paper. He proposed a porous skid, shown in Figure 1, that has a slight angle of attack. It seems this implies that they would operate, at least to some degree, based off lift.

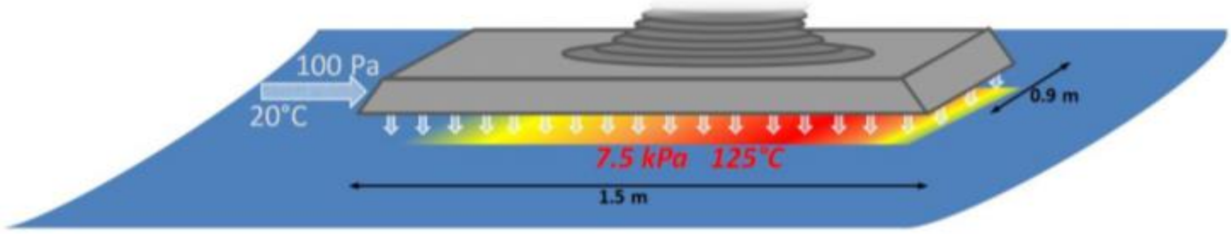


Figure 1.1: The air bearing originally proposed by Elon Musk [1]

In reality, current air bearings operate nothing like this. What he proposed is closest to what is today called a "rigid" air bearing, a porous piece of metal that pumps highly pressurized air at of the pores to achieve levitation. There are also "skirted" and "compliant" air bearings. It was decided to use urethane diaphragm compliant air bearings, or air casters, for reasons that will be discussed in Chapter 2.

The second engineering challenge stems from something called the Kantrowitz Limit. Because the pod is in a tube, a column of air can begin building up in front of the pod [1,2]. Even in reduced atmosphere, the air cannot clear over the pod fast enough due to a limited bypass area, which leads to forming drag. The way Elon Musk proposed combatting this is by putting a compressor on the nose of the pod. The compressor would clear the column of air in front of the pod, while also compressing it to be used as "fuel" for the air bearings. This lies beyond the scope of our abilities.

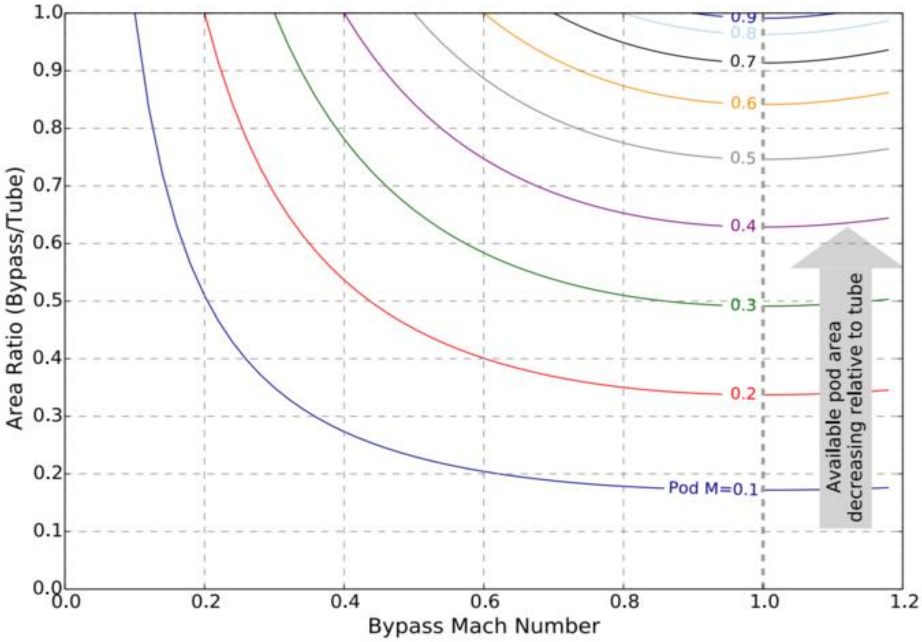


Figure 1.2: The potential velocity of bypass air over the pod increases as the area of the tube increases relative to the pod [2]

Lastly, the actual building of the Hyperloop track, or tube, is a massive engineering challenge. A flat track, kept at vacuum, over 100's of miles is no small feat. This also was clearly outside of our scope. Thus, the focus of this research is to develop the concept of air bearings that will be effective in high velocity regimes.

1.2 FURTHER MOTIVATIONS

1.2.1 Climate Change

One of the biggest challenges in combatting climate change is reducing our CO_2 emissions in the transportation industry. It seems that the only effective means to do so is by powering our transportation systems with electric power. This of course comes with the need to decarbonize the grid with resources that do not consume fossil fuels—solar, wind, nuclear, and hydropower, to name a few. If we decarbonize our grid, we can use batteries to power electric motors on our transportation systems.

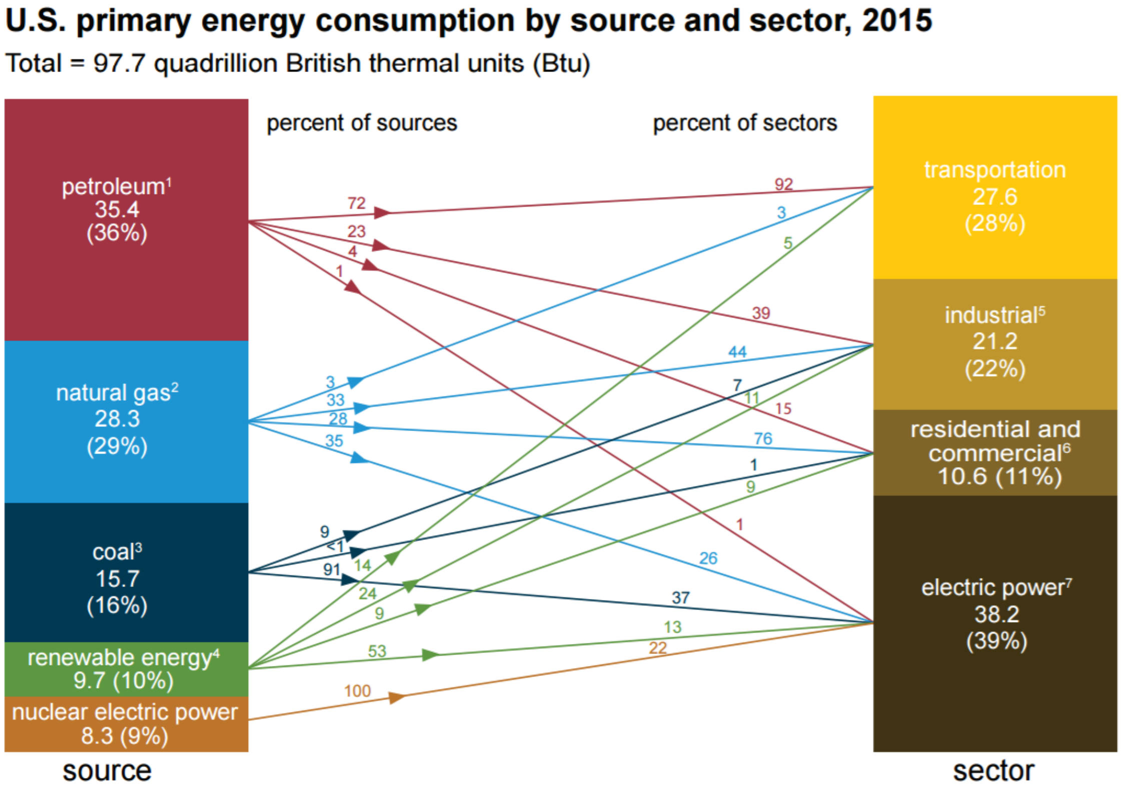


Figure 1.3: Transportation accounts for 28% of our total energy usage in the U.S., and is powered 95% by fossil fuels [3]

There are already steps being taken in the personal vehicle sector with electric cars (and eventually electric trucks), led in large part by none other than Elon Musk, but little has been done for mass transit. It is hard to conceive, with current technology, the number of batteries it would take to power a commercial jet or freight train. While subway systems are often powered electrically, and electric cars are currently effective at short distances, there does not exist a practical means of travelling long distances on electric power.

The Hyperloop aims to tackle that problem. While the compressor would be difficult to power with batteries, the low drag environment leads to a far more efficient way of travelling than current systems. The greatest enemy of the four major modes of transportation is drag. Because it is proportional to the square of the velocity, the problem gets progressively worse the faster the vehicle travels. This is the main reason why we fly at 35,000 feet, and why ground transportation encounters difficulty getting over speeds of 200mph. But, if that ground vehicle could travel in near vacuum environments on a bed of air, drag would be essentially eliminated from the system, leading to a vehicle that requires far less power. Figure 4 shows the Hyperloop's power consumption compared to other modes of transportation.

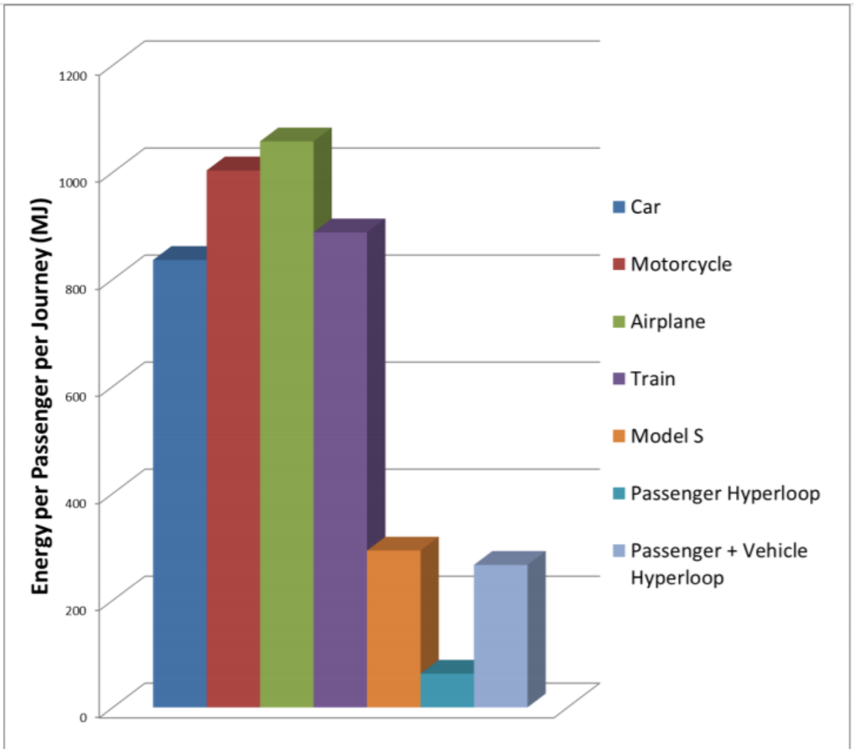


Figure 1.4: Energy consumption of Hyperloop compared to other modes of transportation [1]

Thus, the Hyperloop would lead to either lower emissions, or zero emissions. Mr. Musk even went as far to suggest that the tube of the Hyperloop be lined with solar panels, offsetting all of its energy consumption to the grid.

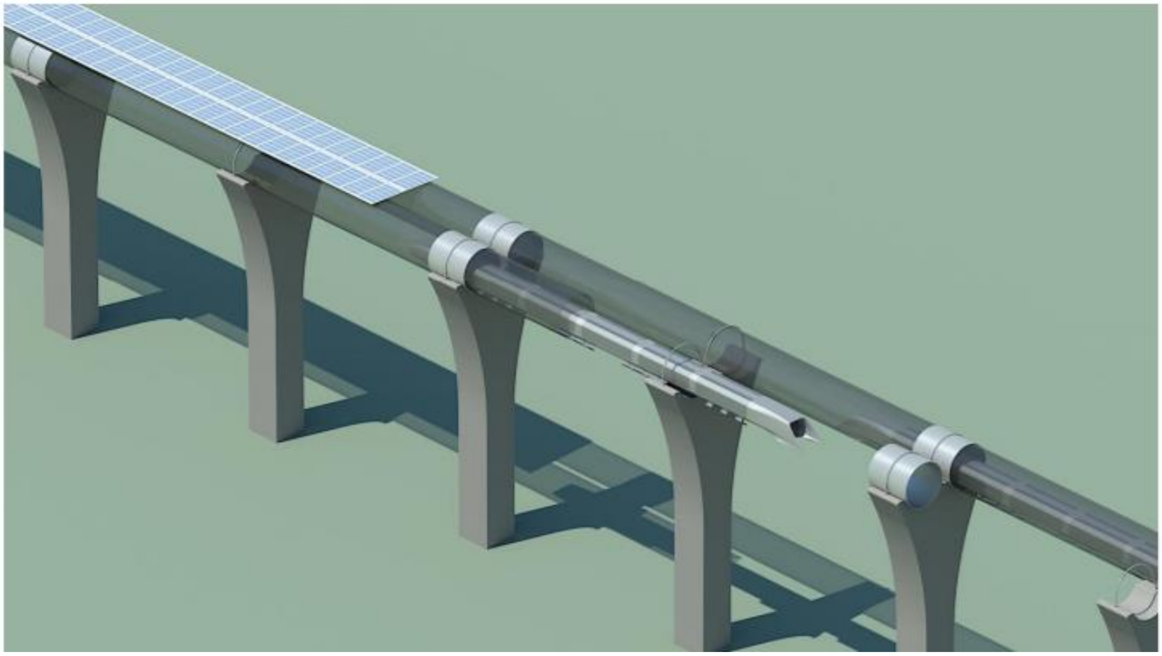


Figure 1.5: The original Hyperloop proposal included the idea of powering it off solar energy, making it the first zero-emission mass transit system [1]

It should be noted that the White Paper is by no means a rigorous scientific document. It’s lack of support for the claims made is at times laughable. The ideas presented above should not be taken as an attempt at “proof”, but a detailing of the preliminary stages of the ideas surrounding the Hyperloop. The next section will discuss which of these design challenges are tackled in this Thesis.

1.2.2 The Competition

In the summer of 2015, SpaceX announced the Hyperloop Pod Competition. This coincided with the start of the author’s first semester at UT, who decided to start a team to take on the challenge, named Texas Guadaloop. SpaceX pledged to build a one-mile long test Hyperloop track at their HQ in Hawthorne, California, and invited teams to design and build pods to race on that track. So, the Competition would have two parts: Design Weekend and Competition Weekend. Design Weekend took place at Texas A&M in January 2016, where over 120 international teams presented their pod designs in front of SpaceX engineers. 30 teams were selected to participate in the build portion of the Competition. Teams that advanced to the Build portion of the competition were invited to build the pod designs that they presented in front of SpaceX at Design Weekend. Competition Weekend I took place in January 2017, where only 3 of the 30 teams were selected to do runs on the actual track [4].

While not present at Competition Weekend I in January 2017, Texas Guadaloop was invited to compete in Competition Weekend II in August 2017. This follows the same rules as Competition Weekend I, but the emphasis is on top speed travelled by the pods. Thus, the Hyperloop pod designed by Texas Guadaloop is limited to the application of the SpaceX track. Track specifications were released in the fall of 2015, and the pod presented by the team at Design Weekend was meant to be built and tested on this track. These track specifications will be discussed in later sections of this Thesis, along with how and why design decisions were made related to these specifications.

1.3 RESEARCH OBJECTIVES

The central research objective of this thesis was to tackle the issue of air bearings for hyperloop pods. This was not only a central technological issue in the proposition of the Hyperloop, but also one that Texas Guadaloop was capable of exploring. Other teams focused on other necessary subsystems: stability, controls, braking, etc—all teams tried to focus on at least one issue that would need to be solved for the full scale Hyperloop. The Competition thus split into three main levitation camps: Magnetic Levitation, Air Bearings, and Wheels. Texas Guadaloop felt that the exciting nature of the original idea rested on the Air Bearings, but this will be discussed further in the "Design Phase" chapter of this Thesis. Current air-bearing systems are for low-speed, high-load applications. Thus, Texas Guadaloop has had to adapt the existing technology into a high speed, low load application. As such, the research was split into four phases:

- Design a Hyperloop pod capable of safely using air based levitation
- Build a Hyperloop pod capable of safely testing air based levitation at high speeds
- Test the built Hyperloop pod at speed (in the competition)
- Gather data and results from testing in order to design an improved high speed air bearing

The issue of this research is that due to their complex nature at high speeds, they cannot be simulated or convincingly tested in a lab. The best way to conduct this research is then to do a run on the actual track, and have the necessary safety systems in place in case of failure. The pod build has been completed, but as it has not had the chance to run on the track, this Thesis focuses on the design and build methodology of the project. Certain challenges include, but are no means limited to, tight tolerances of the track, running the vehicle in partial vacuum, the high-velocities desired, testing air bearings at these high velocities, and building the pod with limited resources. All of these factors were taken into consideration for the design and building of Texas Guadaloop's Hyperloop pod.

1.4 THESIS OUTLINE

The preceding sections serve only to provide context on the Hyperloop concept and SpaceX competition, while outlining applications. Chapter 2 will provide background on the parameters offered by SpaceX, and detail the design methodology used by Texas Guadaloop in the process. Chapter 3 will then present the design and fabrication process. This chapter will discuss the need to refine or change certain design aspects with the prospect of putting a fabricated pod on the actual track. The many challenges associated with both of these processes will be discussed throughout Chapter 3. Chapter 4 will present conclusions and future work. Most notably, Texas Guadaloop plans to use the data acquired in future test runs to collaborate with Air Float, LLC (a division of Align Production Systems based in Decatur, IL) on a high speed air bearing design. Air Float was founded by the inventor of Air Caster (compliant air bearings) technology 50 years ago, and are the leading company in the U.S. air bearing technologies.

Chapter 2: Design Methodology and Parameters

As stated in Chapter 1, the design parameters were offered by SpaceX. As they were building the one-mile track, Texas Guadaloop was forced to comply with their constraints. There was a two-way dialogue on these parameters, and Texas Guadaloop was able to offer suggestions on the parameters. This is simply stated to point out that the design by Texas Guadaloop for the SpaceX track is simply one potential Hyperloop. However, the technology and results found should influence all future Hyperloop development.

2.1 DESIGN METHODOLOGY

Texas Guadaloop set out to design the simplest pod possible. The goal was to have as few moving parts as possible, with as simple of a controls system as possible. The impetus for this came from the desire to prove that the air bearing concept was valid. As stated in Chapter 1, the Competition split into three major camps: Magnetic Levitation (MagLev), Air Bearings, and Wheels. In general, wheels would not be capable of operating at speeds up to 700 mph. Magnetic Levitation, while an already existing and compelling technical solution, presents problems that will be discussed in the following section. Thus, air bearings seemed the most promising levitation mechanism to explore for implementation into a full-scale Hyperloop. However, magnetic levitation could still be considered, for reasons that will be discussed in the following section. Due to the fact that air bearings have not been studied for an application such as this one, it was decided that a simple system would be necessary to prove their efficacy. That is, a test bed for air bearings needs to be developed to mimic a full scale Hyperloop pod.

2.1.1 MagLev

One of the driving ideas behind the Hyperloop is that a superior technology to HSR could also be cheaper than HSR systems as well. That is why, in the original White Paper, Elon Musk stated, “A viable technical solution is magnetic levitation; however the cost associated with material and construction is prohibitive” [1]. In fact, systems are estimated to cost \$50-\$200 million per mile [5]. This is one reason why very few MagLev lines exist worldwide, even though the technology has been around since the 1970’s. It is expensive and requires large amounts of power, if electromagnetically powered. Thus, it is not possible to build a magnetically levitated train, surrounded by a vacuum tube, that is cheaper than current HSR systems.

More recently, research has been done on passive magnetic levitation. Where electromagnetic levitation requires powered coils, passive magnetic levitation requires only fixed permanent magnets, like Neodymium. By having permanent magnets arranged in a Halbach Array move at speed over a conductive track, robust levitation can be achieved [6].

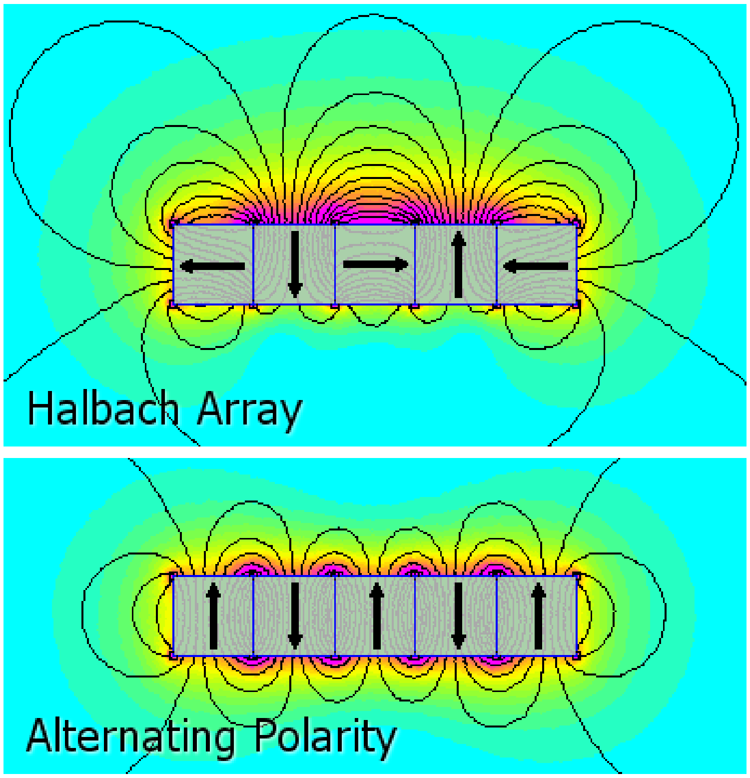


Figure 2.1: Image showing the function of Halbach Arrays [7].

Halbach Arrays refer to arranging the magnets in a certain wave to get magnetic field interference patterns beneficial to the use case—in this case, having a stronger field pointed at the conductive sub-track [6, 7], as shown in Figure 2.1.

While certainly a viable technical solution, especially owing to the fact that passive magnets over a conducting track do not require power, Halbach Array levitation still leads to cost and drag problems. It is unclear why others pursue the passive magnetic levitation approach. The Hyperloop is a simple (in theory) solution devised to get rid of drag—a vacuum tube and air-based levitation—now made elaborate with the reintroduction of magnetic drag. Because passive magnetic levitation operates based on the principle of induction, one can imagine that a pod travelling very fast over a conductive slab will also come with some amount of drag.

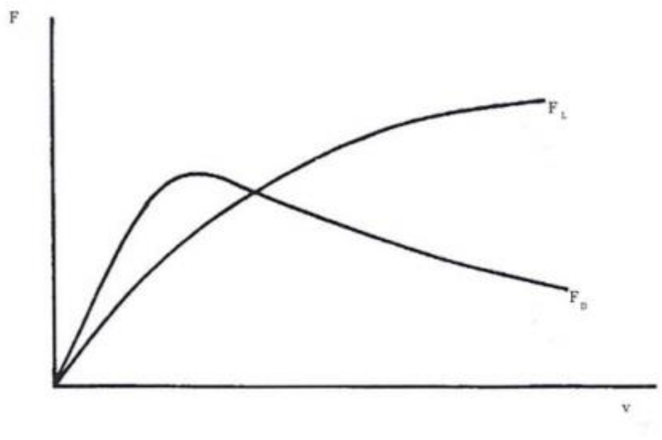


Figure 2.2: Drag force related to velocity of Halbach Array based magnetic levitation [8]

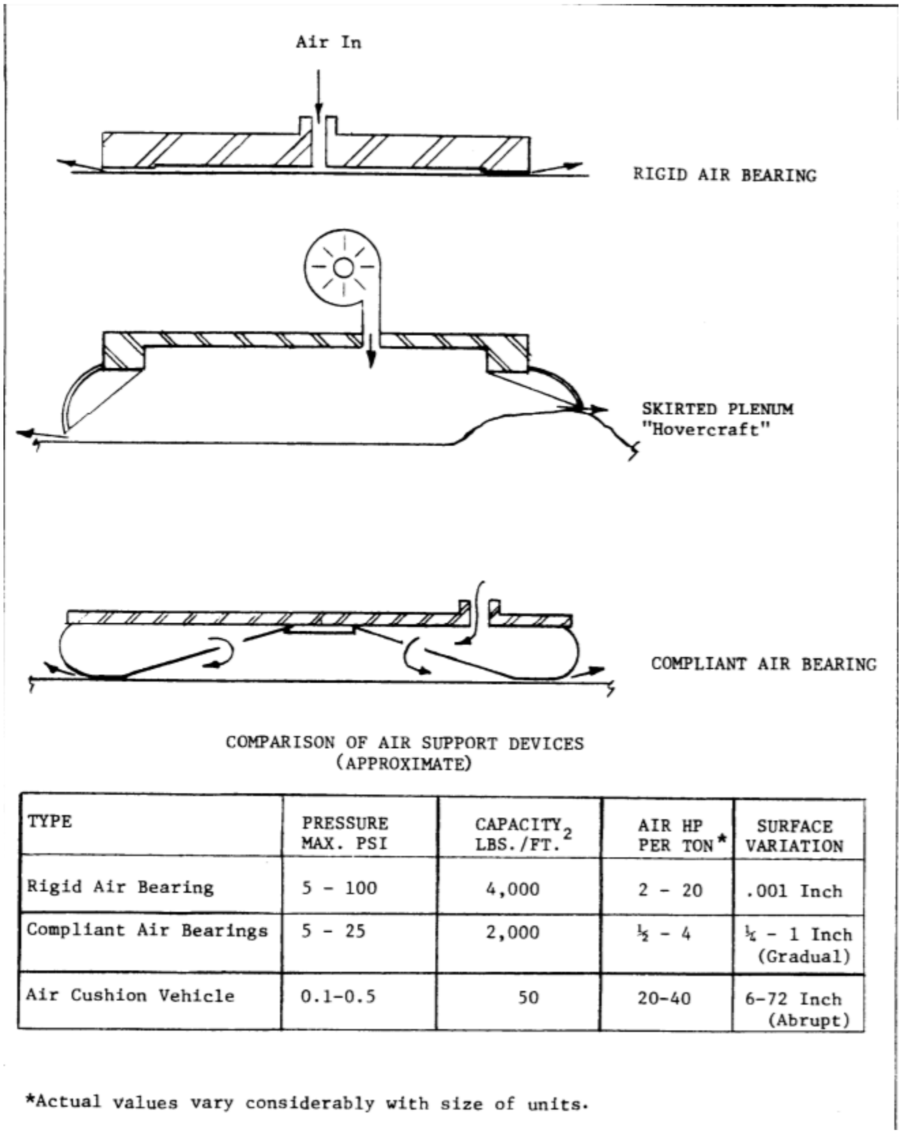
One can see in Figure 2.2 that while drag actually decreases as velocity increases, the effect is still non-negligible. Figure 2.2 does not show the magnitude of these forces, but they are significant. For example, teams using magnetic levitation were citing drag on the order of 1000's of Newtons of force [9]. The aerodynamic drag in the system—even with a modestly aerodynamic design, meanwhile, is on the order of 10's of Newtons.

Furthermore, Neodymium is a far more expensive material (and far more of it is needed) than the urethane that air casters are made of. From a cost and drag perspective, the answer is clear: air bearings. And while Neodymium may itself not require power, it is also clear that passive magnetic levitation indirectly requires more power than air bearings in order to overcome the drag that it creates. From a technological perspective, however, the answer is certainly not clear. Air bearings have never even been tested at velocities of 50 mph, let alone 700 mph.

2.1.2 Testing Air Bearings

Not only is there a very limited (or non-existent) amount of research done on the subject of high-speed air bearings, but there is also a number of difficult barriers to overcome in researching the topic. First, it is challenging to simulate the fluid dynamics of air bearings at high speed. This is due to both the geometry of the air bearing and the boundary conditions of the problem. Compliant air bearings have a “plenum”, seen as the empty space under the orifices in Figure 2.3. So, the material is urethane (or compliant), there is high pressure air being pumped into the plenum, the track underneath the plenum is moving at speed, and there is an oncoming pressure wave from ambient air. Thus, it was decided that simulation was not the best course of action.

An experimental method proves difficult as well. While many ways of simulating linear motion seemed possible: a treadmill like device running under the air bearing, a rotating disk, or even building a smaller scale test track, it was determined that the best way to understand the nature of air bearings at speed was to actually build a pod to put onto the test track that



COMPARISON OF AIR SUPPORT DEVICES
(APPROXIMATE)

TYPE	PRESSURE MAX. PSI	CAPACITY LBS./FT.^{2}	AIR HP PER TON*	SURFACE VARIATION
Rigid Air Bearing	5 - 100	4,000	2 - 20	.001 Inch
Compliant Air Bearings	5 - 25	2,000	½ - 4	¼ - 1 Inch (Gradual)
Air Cushion Vehicle	0.1-0.5	50	20-40	6-72 Inch (Abrupt)

*Actual values vary considerably with size of units.

Figure 2.3: Comparison of different air bearing technologies [10]

SpaceX was building for the competition. The one-mile track would allow the pod to reach speeds of 300mph or more. However, it was decided that air bearings reaching speeds of 150-200mph would be enough to prove the fundamentals of the idea. Thus, it was decided to build a working prototype for full speed testing.

It was also decided to build a 150 foot long test track that will allow the pod to travel at speeds of up to 30 mph. This enables testing and the proof of concept of all systems. By going 30 mph, braking controls can be tested. Most importantly, though, air based levitation can be demonstrated at low speeds. This is the primary objective of the project. While the SpaceX was motivation for the project, the objective became proving air bearings. Thus, the problem of building a full-scale Hyperloop then became very small and manageable: build a pod that would act as a load and compressed air supply for the air bearings, while also providing the necessary stability and braking mechanisms. It was decided to simply build a test platform for air bearings that will function at high velocities. The remaining sections focus on the design parameters of the system, as well as the safety systems in place to hedge against outright failure of air bearings at speed.

2.2 DESIGN PARAMETERS

2.2.1 Track Specifications

When Texas Guadaloop began designing in August 2015, there were no track specifications. Those did not come until the fall. Since then, there have been 11 revisions to the specifications. The latest version will be presented, and later, the latest design of the pod will be presented (there have been 3 generations, and currently the pod is in version 28 of the third generation).

Subtrack: Aluminum subtrack with central rail (all dimensions in inches)

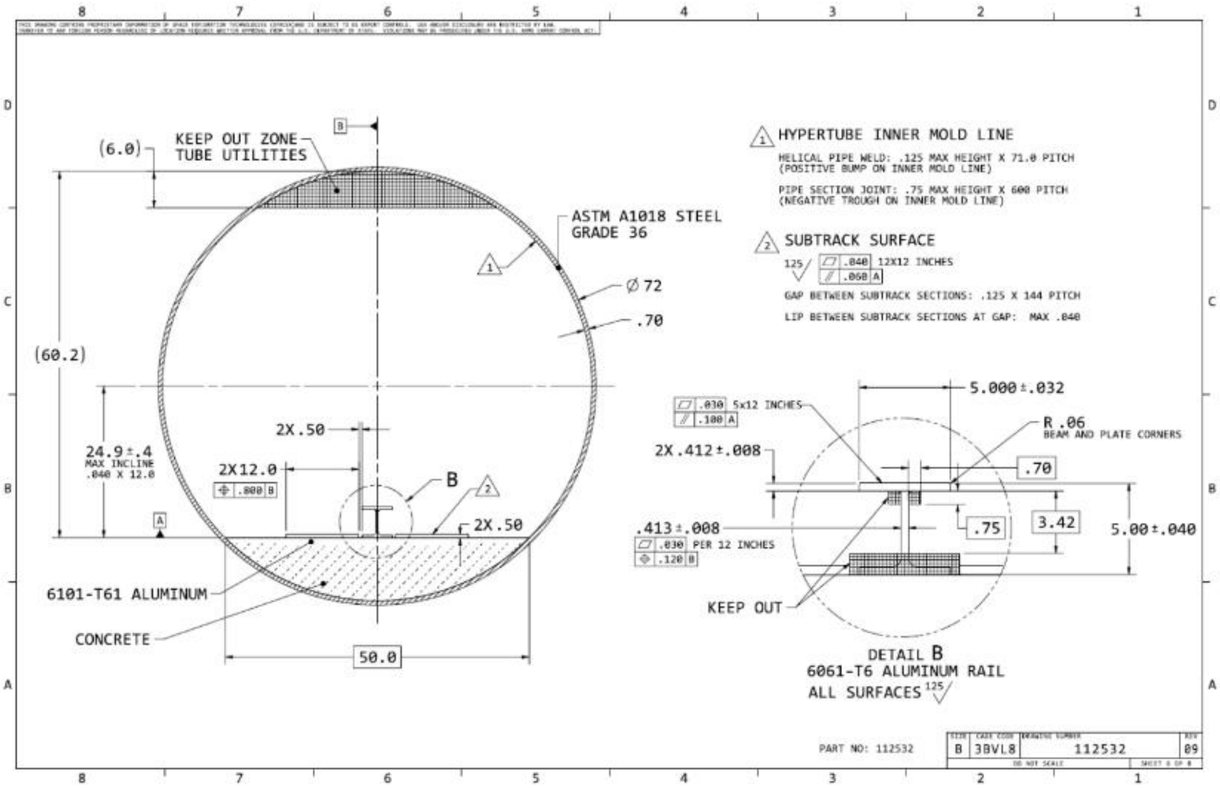


Figure 2.4: Track specifications of the SpaceX Hyperloop Pod Competition tube [11]

The tube itself is half-scale to the proposed full-scale Hyperloop. With an outer diameter of only six feet, it would be difficult to seat humans comfortably inside of a pod within this tube. The full-scale tube would be 12 feet diameter or greater. As no humans are allowed on these test runs, the goal of the competition is studying the fundamentals of half-scale systems that have the potential to be scaled to full scale systems.

The proposed track by SpaceX includes a few important factors. First is the addition of a "subtrack", or flat bed for pods to levitate on. It would not work so well with a round bottom. This track consists of a concrete bed, a monorail, and the aluminum subtrack. The track was organized in this way to accommodate all three levitation mechanisms. The outer concrete part, seen in Figure 2.4, can be used for wheeled systems. The 12” wide (on either side of the monorail) aluminum subtrack can be used for both magnetic levitation—as aluminum is conductive—and air bearings—as aluminum is smooth and conducive to air based levitation. The aluminum has certain things to note. It is composed of 12.5’ long plates, with a maximum .125” gap width in between them. The maximum step height is .04” between these plates. The gap width effects air bearings, as there are moments where there is no subtrack for the air to push against. Similarly, the gap height matters, as the air bearings must have a sufficient levitation height to not make contact with subsequent aluminum plates during the run. This will be further discussed in Chapter 3.

The monorail was one of the most notable additions to the subtrack. This helps teams with stability and braking mechanisms. Previously, there was no good way to combat air bearing instability and to enact braking. Air bearings have no directional bias; since there is no friction, the pod can drift in any 2D direction. Thus, the monorail can be used to keep the pod going straight. However, this offers constraints to the system, since all stability and braking mechanisms must take place within the web of the 5” I-beam monorail. Furthermore, there is a SpaceX “Keep Out zone”, outlined in the web of the rail in gray in Figure 9. This is to allow for proper clearance, so that pod subsystems are not scraping the monorail—especially given that, even with a robust suspension system, it is impossible to entirely eliminate travel height of the pod.

2.2.2 Rules

To protect their own track, SpaceX has made certain rules that teams must comply with in order to compete. The first mentioned is the "Keep Out" zone. The second is the manner in which teams are allowed to brake, shown in Figure 2.5. This is for obvious reasons, to not wreck the rail by providing an unbalanced force or moment on the rail. Similarly, the materials used on the rail must not cause damage to the rail. The pod cannot exceed 14 feet in length, or 2,000 pounds in weight. Some of the most challenging rules, however, involve the so-called SpaceX "pusher plate".

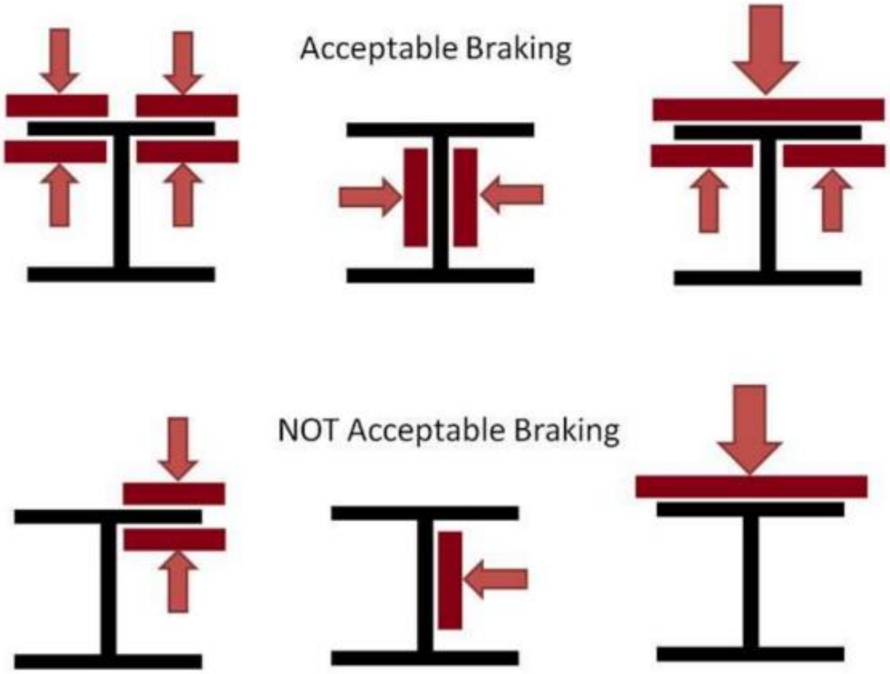


Figure 2.5: SpaceX allowed, and disallowed, braking mechanisms

The SpaceX pusher plate is a means by which teams can avoid having to implement complicated propulsion mechanism. For the full-scale Hyperloop, it is quite obvious that thx electromagnets. The difference is that, due to how little drag air bearing systems offer, the induction motor will have to be used very infrequently to accelerate and to keep the pod at top velocity. The more drag introduced into the system, the more this motor needs to operate, which increases the power requirements and overall cost of the pod. Because it is known that this is the likely propulsion mechanism, and it is near impossible for teams to implement on half scale models, SpaceX is offering a simple mechanical push to accelerate pods.

The pusher plate appears to be a wheeled vehicle, and hitches in with the back of the pod. The mechanism can push at a maximum of 2.5g's, but will be limited to 1g for the competition, with an acceleration profile of 1600 feet. The interface can be seen in Figure 2.6, but the important aspect of the rules surrounding the pusher plate is how it affects the braking profile. Because SpaceX does not want their expensive pusher plate to be damaged, teams must be able to prove with overwhelming certainty that their braking systems will not engage on the rail while the pusher plate is engaged. If the brakes engage, the pod will be decelerating as the pusher plate is accelerating. Obviously, this means a crash, and the destruction of SpaceX property. This becomes a very difficult design challenge to overcome, discussed in Chapter 3.

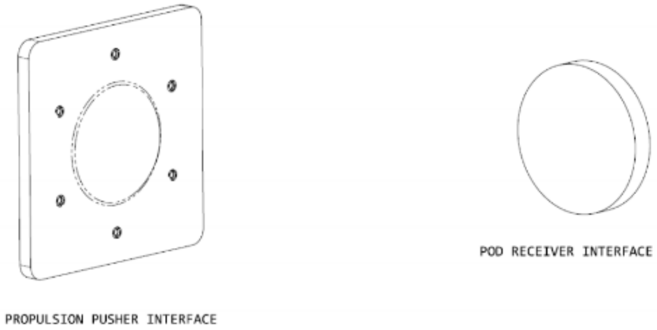


Figure 2.6: The mechanical interface of the pusher plate

2.2.3 Vacuum

Another important design factor is the available operating pressures for the competition runs. SpaceX can offer to go as low as .125 psi, and as high as 14.7 psi. The team is allowed to select any operating pressure within that range. To combat drag, the pod must be prepared to operate at the lowest possible pressure environment, or .125 psi. This presents a design challenge for the electronics and controls systems. It must be insured that all components will operate in this low pressure environment. For mechanical systems, certain materials, such as lubricants, cannot be used due to outgassing. Furthermore, all "stored materials" must be vacuum compatible, or kept out of the vacuum environment. In the case of the designed pod, "stored materials" includes a battery as well as four 2400 psi compressed air tanks. Due to the lack of compressor on this pod, the air supply must be entirely on board the pod for the run. The designs built to address the vacuum environment will be further addressed later on.

2.2.4 Navigation and Communications

Due to the fact that the pod will be contained in a steel tube, Navigation and Communications becomes a difficult design constraint. Teams cannot use GPS, or other outside mechanisms for navigation purposes. They must use mechanisms internal to the Hyperloop. As such, SpaceX is providing retro reflective tape placed at increments within the tube, in order for teams to be able to detect these pieces of tape in order to know their position within the tube. This can be seen in Figure 2.7. While there is a "foam pit" at the end of the tube in case a team does not brake properly, a team should be able to properly initiate their braking sequence based off their positon in the pod.

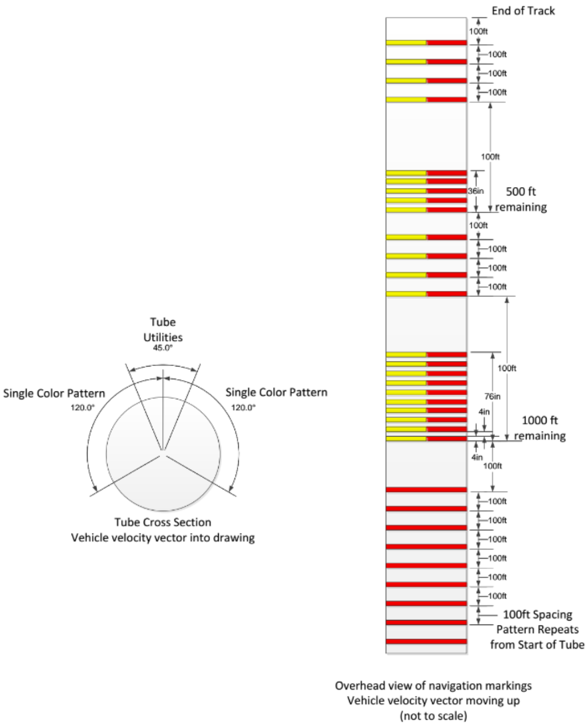


Figure 2.7: Counting or detecting retro-reflective tape can be used to know the pod's position within the Hyperloop

SpaceX is also providing a Network Access Panel (NAP) to be mounted on the pod. Teams must interface with the NAP via Ethernet, in order to have communications with their pods. The NAP communicates through a Spacex provided communications network that can operate within the steel tube. However, it is upon teams to provide their own internal communications networks. That is, while the NAP can communicate from the pod to the "outside world", all controls systems on the pod must be of the teams' creation. This will also be discussed in Chapter 3.

Chapter 3: Fabricating the Pod

3.1 STRUCTURE

The first and most obvious problem to address was creating a robust structure. This structure would have to handle lateral forces for stability purposes, and linear forces to handle pusher plate and braking forces. Originally, a fully cylindrical shape was to be pursued, like an airplane fuselage. However, after recognizing that there was no need to pressurize the cabin (as no humans would be on board for test runs), the structure was designed as a half cylinder. From that point, the various subsystems, like braking and levitation, could be added onto the frame. The primary goal was to handle the pusher plate force. This was first addressed with a simple FEA model, as shown in Figure 3.1a, and then became the fully realized.

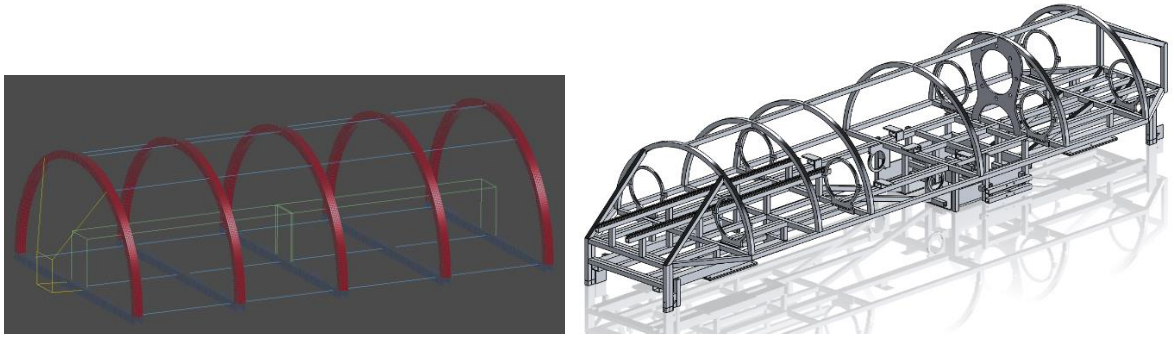


Figure 3.1a) Preliminary FEA showing T6-6061 aluminum could be designed with Factor of Safety greater than 3 for pusher plate forces. Figure 3.1b) The final structure design, after addition of all subsystems.

The secondary problem was deciding how to assemble the frame. Riveting the frame together would add a lot of weight, while not being sturdy. It was decided that welding was the best option regardless. The pod was designed to be modular and accommodate loose tolerances, as much as 1/16th of an inch. The goal was to have a Factor of Safety (FOS) of 3 or greater, even with conservative estimates of the forces that would be experienced.

Full thermal, structural, and vibrational analyses were also performed on the finished pod. For the thermal profile, heating from braking and electronics were analyzed. Even assuming that all power consumption would be dumped into the frame (essentially 0% efficiency), and no cooling from radiation, the frame does not see yield issues from heating. Similarly, assuming that all kinetic energy of the pod at top speed is dumped into itself as heat—again with no cooling from radiation— no part on the pod will reach the melting point of aluminum and all critical structural members remain well below temperatures that will affect the young's modulus, or their integrity. It turns out that the aluminum structure itself acts as quite a good heat sink.

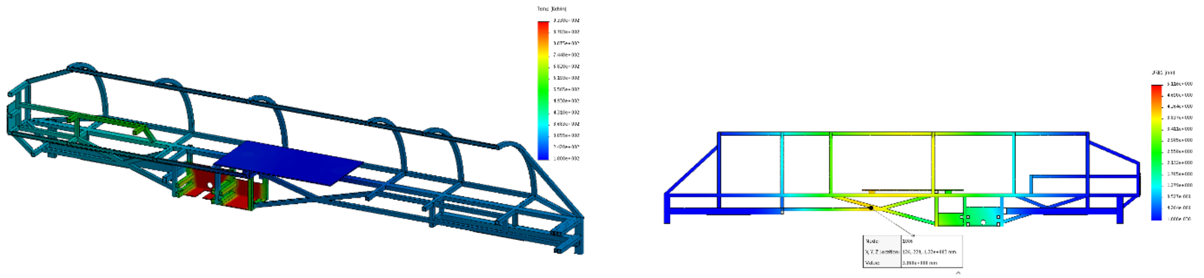


Figure 3.2 a) Thermal profile during braking with all kinetic energy at 225mph going into the braking frame shows only a non-structural member reaching a concerning temperature. Figure 3.2 b) No structural yield concerns during braking, only deflections in the middle of the pod on the order of millimeters.

All aspects of the structure have been completed, save the welding of the hoops that will attach the skin to the pod, as shown in Figure 3.3. Of most concern in the actual welding

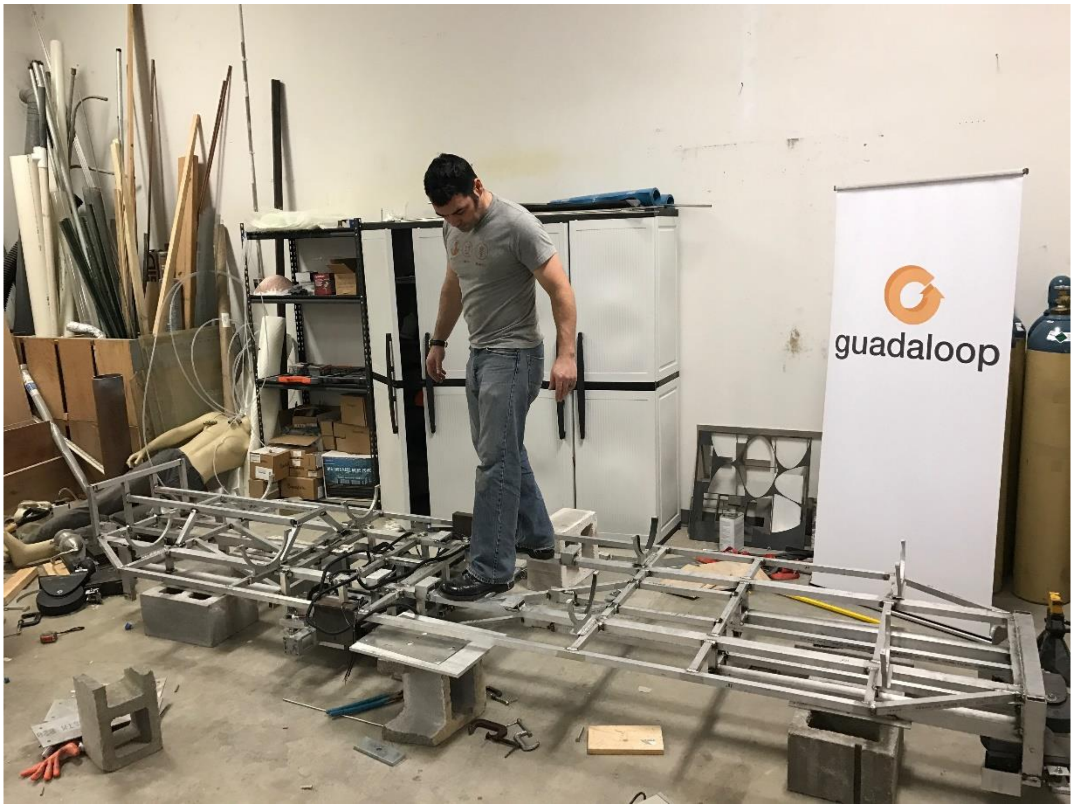


Figure 3.3: Texas Guadaloop's welder standing on the frame, showing its robustness and lack of deflection at its most vulnerable point

of the frame was tolerance. The web of the rail is less than five inches. Thus, any variation of more than 1/16th of an inch in the welding of the braking frame could prove costly. The welding process took place in stages over many months, with great care. "Mechanical fit" tests performed in the lab on a track mockup show all structural elements sitting within the allowed portions of the mono-rail detailed in Chapter 2.

3.2 BRAKING

Braking proved to be the single most challenging aspect of the pod to design. The goal of simplicity and having as few moving parts as possible was most difficult to achieve with this subsystem. Originally, off-the shelf solutions were sought, from caliper brakes to linear actuators. With no reasonable solution found, it was decided to design the system from scratch. Seeing as no modern transportation solutions use a monorail, there was not much literature to draw off of. The braking system had to be controlled simply, and be entirely fail-safe. While SpaceX is providing a "foam-pit" at the end of the track to catch pods so their track does not get damaged, being forced to use that foam pit should be avoided at all costs.

There were two main forms of braking available: friction based, and eddy current based braking. Eddy currents operate off the same principal as magnetic levitation: a magnetic field is induced in a conductor, which then provides a magnetic force on the magnet causing the induction. Friction, or caliper, brakes on a Hyperloop would operate just like a bike brake. While far more robust, they simply clamp on the web of the rail. After Design Weekend in January 2016, SpaceX encouraged all teams to pursue eddy current brakes as their primary method, to avoid damaging the track. With a desire to appease SpaceX and provide a redundant, fail-safe braking system, it was decided to move forward with both ideas. The eddy current brakes would be the primary brakes, and the friction brakes could take over at lower speeds, or help in the event of a failure.

The mechanics of both braking systems are designed on the exact same principles. That is, they are both electromagnetically released, and pneumatically reset. Having an electrical and pneumatic system involved in both serves two purposes; the redundancy leads to a very low probability of the brakes releasing while the pusher plate is engaged, and it also leads to a very simple controls system. An off-the-shelf electromagnetic "door lock" is used as the actuation control. These are used primarily for locking doors. There is a set of coils embedded in a piece of steel mounted to the door frame, and then a separate bar of steel that mounts to the door itself. When these are in contact with each other, and a current is applied through the coils, the “electromagnetic circuit” is sealed, and a holding force of 1650 pounds is established. In this case, the coils are mounted to the frame of the pod, and the steel bar is mounted to the arms that engage with the rail. A spring is used as the actuation mechanism.

Thus, when power is on and the engaging arm is near the maglock (the coils), the spring is compressed and held in place. Since the electromagnet being on holds the corresponding arm only when they are very close to each other, this necessitates another force to actually compress the spring. In this case, a pneumatic piston was chosen. The mechanism for each brake pair—there is one magnetic brake and one friction brake on either side of the rail—is detailed in Figure 3.4 below. The pneumatic piston is activated, compressing the spring to store enough energy to release the brakes near the rail when desired. Once close enough, the maglock completes the circuit and also holds the spring compressed as well. The piston can then be vented after the

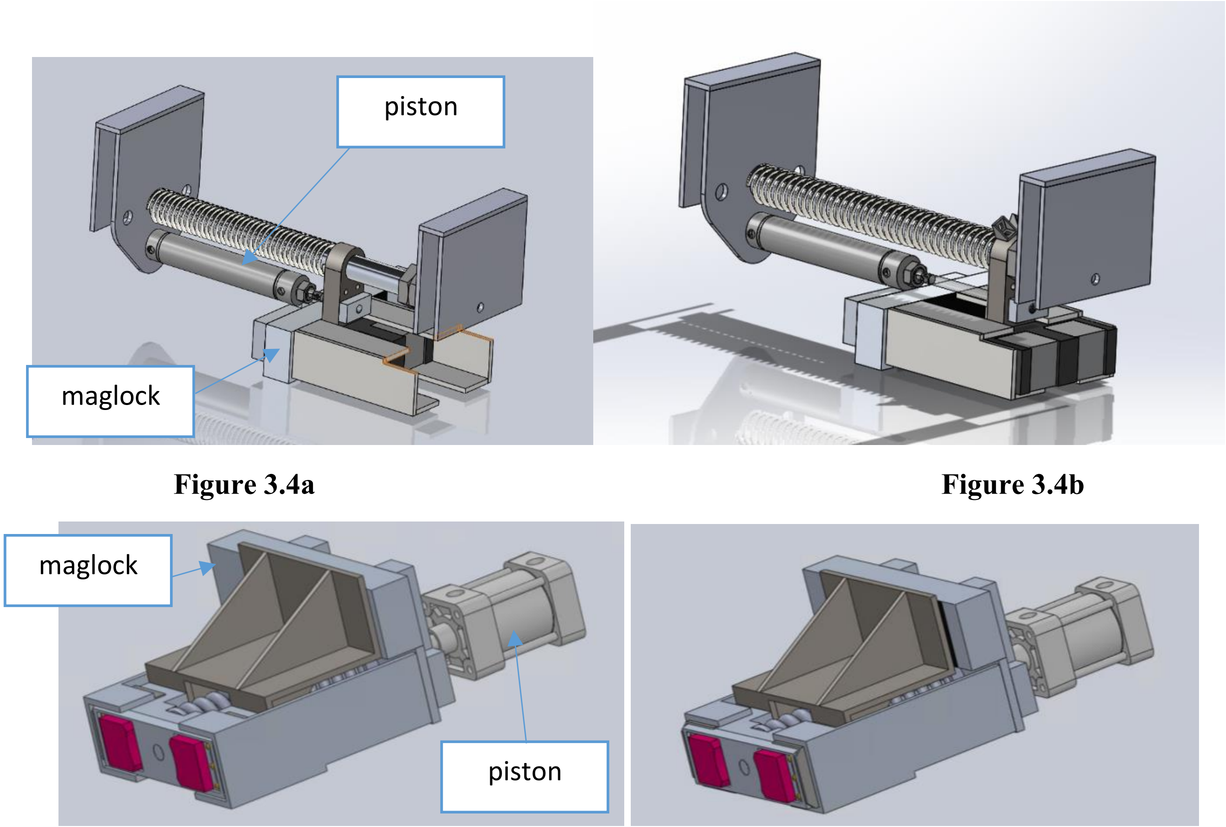


Figure 3.4a **Figure 3.4b**

Figure 3.4c **Figure 3.4d**

Figure 3.4 a) The pneumatic piston compresses the spring, which is then held in place by the maglock. 4b) Power to the maglock is cut, releasing the magnetic brake. c) The friction brake, while having a bigger spring to deal with, operates off the same principles as the magnetic brake in a) and b). d) The friction brake only moves ½" when released.

pusher plate detaches, and only the maglock holds the spring compressed. The controls, which will be discussed more in a later section, are now simply killing power to the maglocks when braking should be achieved. This is fail-safe because, in the event of a power failure, the brakes automatically release.

There are a few variations in the designs of the friction and magnetic brakes of course. The friction brake, in order to work, requires being compressed into the rail. Thus, when in the "engaged" position, the spring is compressed by two inches into the rail. The spring also has a much higher k value of 500 lbs/in, in order to provide sufficient normal force to the braking pads. On the other hand, it is not desired that the magnetic brake touches the web of the rail at all. Thus, a spring of much lower k value can be used for the magnetic brake. Both braking systems have already been completed, welded into the frame, and tested. Figures 3.5, 3.6, and 3.7 all show various aspects of the build process related to this.

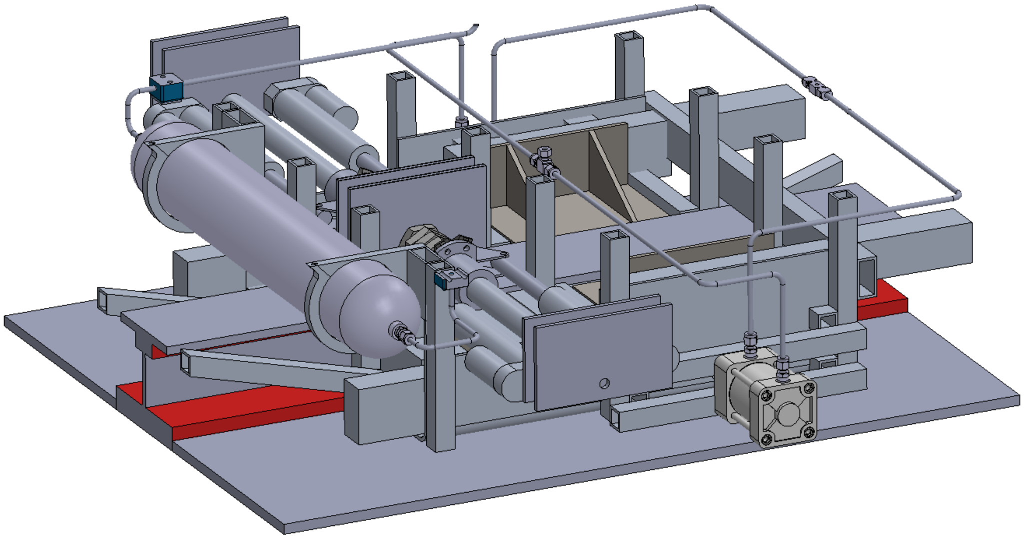


Figure 3.5: The entire "brake frame", with both braking systems within, is shown as designed in SolidWorks.

Figure 3.6: The magnetic brake assembly is shown in a youtube video demonstrating the actuation mechanism

Figure 3.7 a) The brake frames (left) are shown having been installed into the full pod (right)

3.3 LEVITATION AND SUSPENSION

While levitation is achieved via off the shelf air bearings, a considerable amount of design had to go into the system surrounding the air bearings themselves. Two factors were of primary concern in this design: 1) effectively balancing the load to the inflated air bearings and 2) an automatic secondary levitation mechanism in the case of air bearing or air supply failure. A suspension system then had to be designed to limit or eliminate travel height due to bumps in the pod, in order to ensure that the braking system could engage on the web of the rail inside the SpaceX defined limits at all times. These mechanisms will be discussed in this section, while the pneumatic distribution system will be discussed in the following section.

The original idea for levitation was to rigidly attach the four air bearings to the frame. As the track specifications detailed a very flat track, only rubber inserts would act as vibrational dampeners. The rigidity of the frame would actually help the air bearings self-equilibrate, as all suspension would essentially be limited to the air cushions. However, as the track specification changed (building a track that flat proved difficult), it was decided to add a standard—albeit adapted—bell-crank based suspension system. In fact, released videos of the MIT and Delft test runs revealed that his new design would be absolutely critical to success [12, 13]. The original design is shown in Figure 3.8, while the later system is shown in Figure 3.9. The new suspension is designed to minimize travel height, and eliminate the worry of the braking system knocking into the web of the rail.

There are other important features to point out in Figure 3.8. The first are the four (three that can be seen) wheels shown on the air bearing skid. The black diaphragm shown touching the track is the air bearing, while the wheels are connected to the skid itself. This is a passively integrated safety system. That is, the wheels are touching the track only when the air bearings are deflated. In this way, if the air supply or air bearings themselves fail, the pod will automatically land on the wheels, allowing the control system to bring the pod to a stop without any crashing.

Also of importance in Figure 3.8 is the hop tank. This is the tank seen connected to the air bearing by a ½" tube. In Figure 3.8b) it has the "Air Float" sticker attached to it. These are critical in the use of air bearings at high speed. Their function is to hold a volume of air at the same pressure in the lines coming into the air bearing. This acts as a capacitor to equilibrate at all times the pressure in the lines. As the bearing travels at speed, up and down, there will be minor pressure waves or variations in the line. This tank effectively absorbs them, or acts as a high frequency dampener. These are used in normal high-load, low velocity applications to keep the load from "hopping". They have been adapted them for high velocity applications.

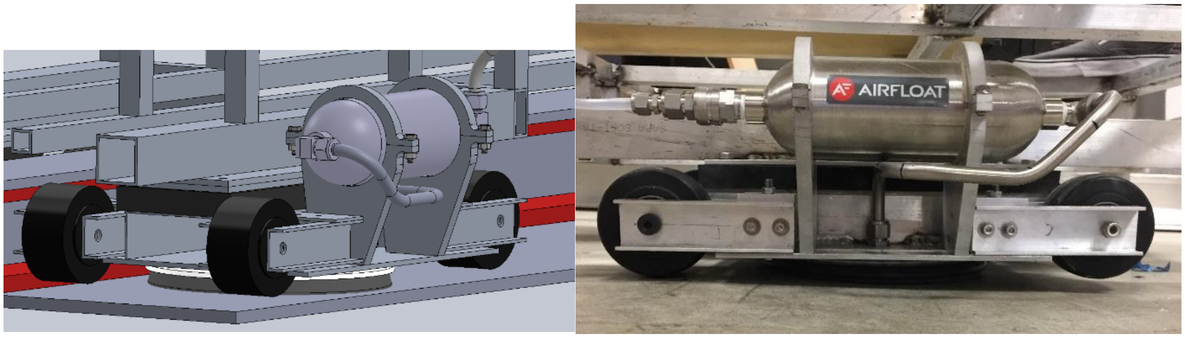


Figure 3.8 a) SolidWorks design of air bearing skid showing secondary wheels and hop tank. b) Picture of actual air bearing skid built to specifications, attached to the pod with rubber inserts.

However, it became apparent that a dampening mechanism for lower and medium frequencies would be necessary. After witnessing the results and videos of other teams suspension systems on the track at Competition Weekend I, it was decided that something better than rubber was necessary. A simple bell-crank based spring dampener system has been designed, shown in Figure 3.9.

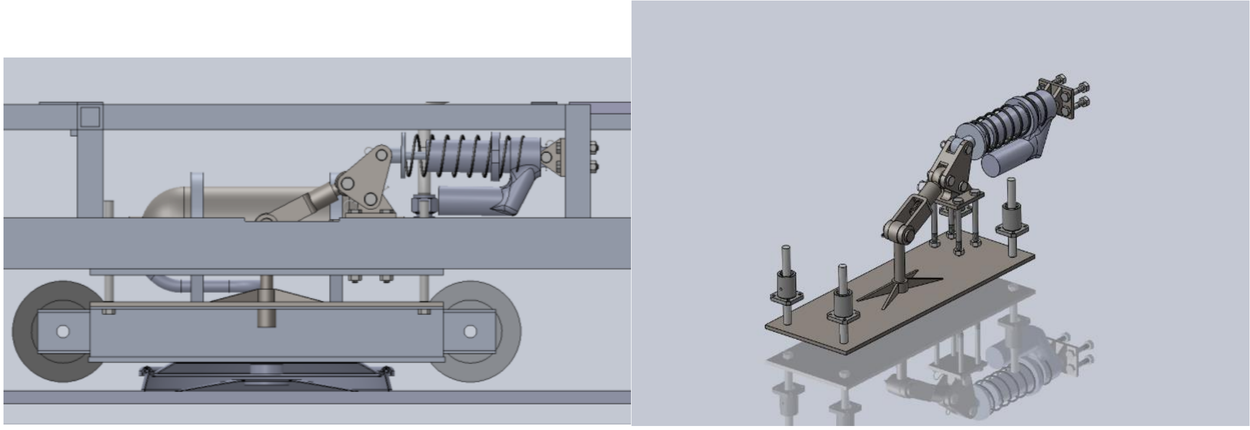


Figure 3.9 a) profile view of new suspension system fitting into the existing frame. b) Isometric view of the new suspension system assembly, which will be installed into the frame in the coming weeks.

The new suspension system is designed to be integrated into the existing frame, so that no major structural changes will have to take place. Furthermore, the geometry is such that, with the expected vibrational environment, the “travel height” of the pod should be minimal to non-existent. This is important in keeping the braking frame and stability system firmly within the desired range on the web of the rail.

3.4 PNEUMATICS

As evidenced in the prior section, pneumatics are not only used for levitation. It was concluded that with a large supply of air on board and the need to divert pressure from above 2400 psi tanks to a 40 psi air bearing controller, that small amounts of pressurized air could be repurposed for various subsystems. This led to the development of a sophisticated yet simple pneumatics design that could distribute various pressures to both the braking and levitation system. Thus, this section will cover the pneumatics design of both.

The primary function of the pneumatic system is to regulate down and distribute air from four 2400 psi industrial standard air tanks to about 40 psi for delivery into the air bearing controller. The four tanks themselves are on-board to provide sufficient levitation time. Preliminary tests indicate that each tank should last more than 6 minutes, giving a total levitation time of up to 30 minutes. Redundant safety measures, such as check and relief valves, and remote venting capacity are also included on the main pneumatics board. There is a high pressure regulator which can regulate the 2400 psi incoming air to 200-400 psi, or “utility level”. The utility level air supply is used for the braking panel.

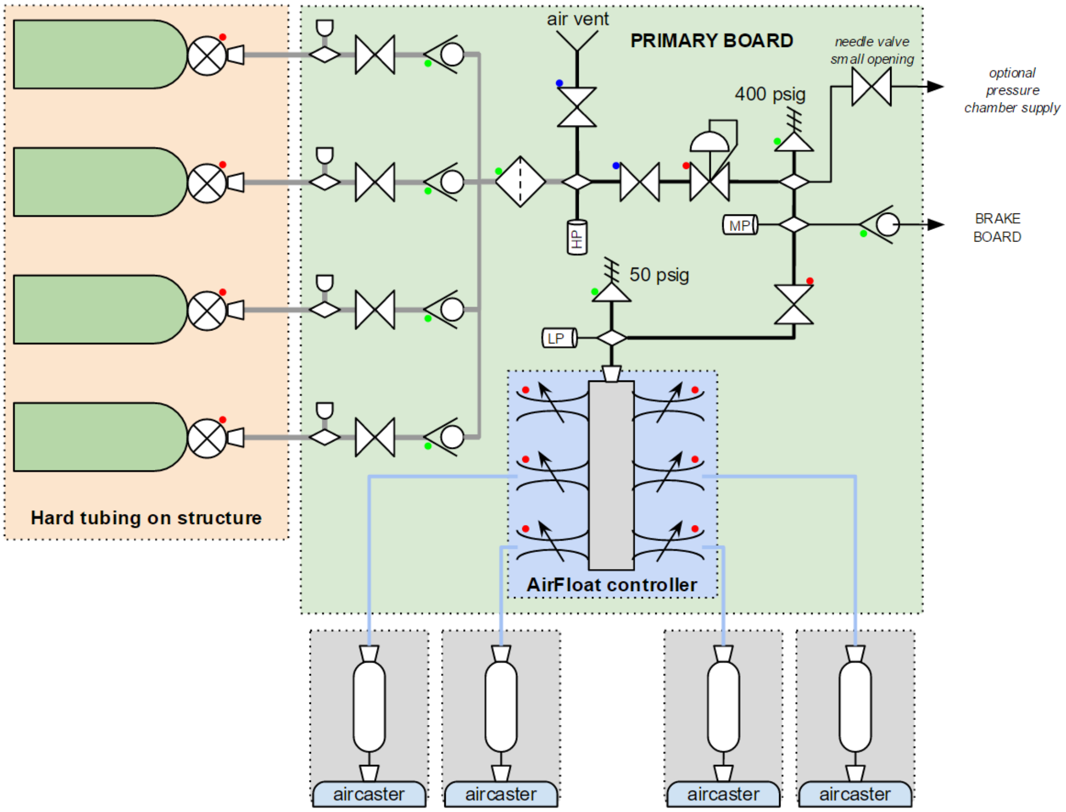


Figure 3.10: Main pneumatics panel

There is then a low pressure regulator, which is a needle valve and takes the 200-400 psi air down to 40-80psi. This pressure is delivered into a controller supplied by Air Float. This controller allows the pressure for each air bearing to be manually preset, and includes a flow controller to keep the same set flow rate going into the bearings at all times.

Furthermore, the pneumatics panel is a mix of both remote and manual controls. The regulators and flow controllers themselves are preset, but various stages of the pressure board are activated by remotely controlled valves. It was determined that no active feedback controls would be necessary during the run of the actual pod. However, the actuators give control over various stages of the flight that will be discussed in detail in the Electronics and Control section of this Thesis. This is most important for the braking panel, which is shown in Figure 3.11. The braking panel distributes air to the braking system, and provides control over its functionality. It can also operate completely independently of the main panel in the event of an air supply failure, given the "volume tank" shown in Figure 3.11.

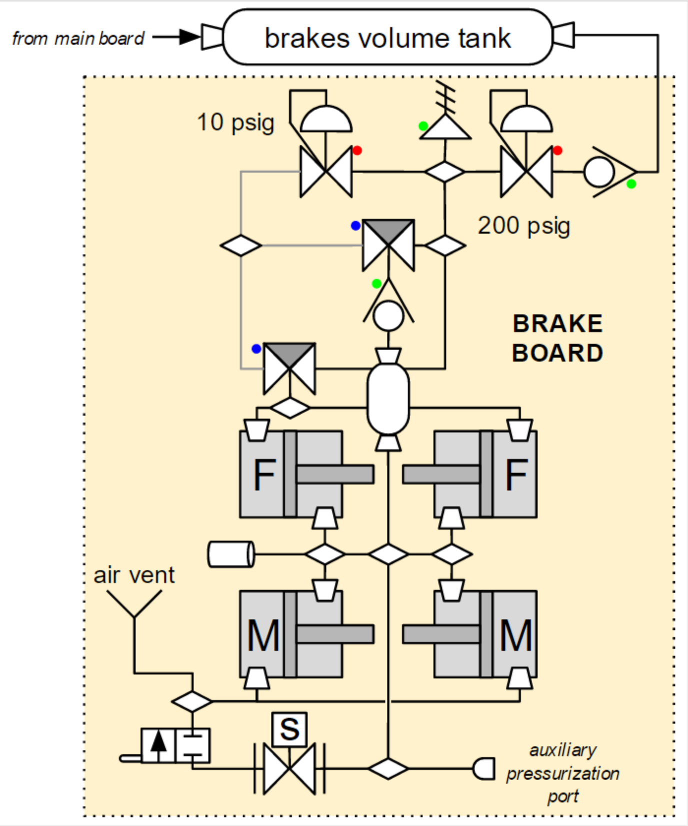


Figure 3.11: Design of the braking panel, which distributes and controls air into the four pressure pistons for the four braking elements

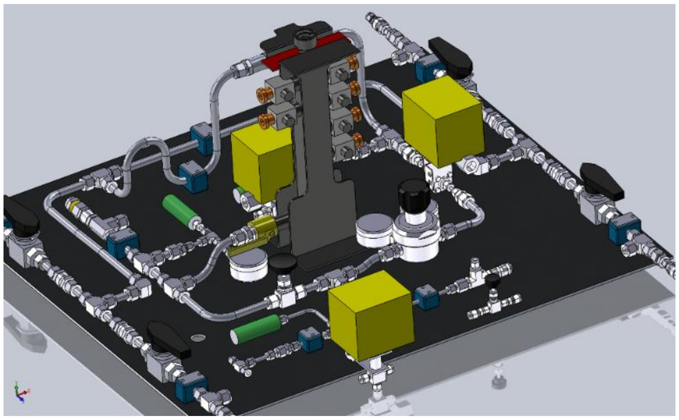


Figure 3.12: SolidWorks design of the main pneumatics panel, which has already been built in full and tested on multiple occasions.

3.5 CALCULATIONS

While pressure is important, the flow rate is actually most important for both loads and the pneumatic system itself. Each air bearing from Air Float requires a flow rate of 6.9 SCFM, given that the track is considered a "good" floor condition [14]. With four air bearings, this results in a total of 27.6 SCFM. Theoretical air supply time on board is then 33 minutes. Preliminary tests in the lab reveal around 25 minutes of levitation. This minor discrepancy could be due to poor floor conditions, or air tanks that slightly deviate from the spec sheet. Meanwhile, each air bearing can provide up to 3,000 pounds of lift [14], for a total payload capability of 12,000 pounds. With an overall pod weight of 1,200 pounds, payload capacity is certainly not an issue. In fact, this is evidence that these air bearings have a great potential to be able to accommodate a fully loaded passenger vehicle, and trips of much greater duration. The trip in the tube will take less than a minute, while there is currently a proposed Austin to Dallas trip that is expected to take 20 minutes [16].

Each compressed air tank on board has a total air volume of 232 cubic feet, giving a total volume of 928 cubic feet [15]. The pneumatic system, then, must be capable of handling pressures of 2200 psi or more, as well as high flow rates. The design and calculations of the system were aided by Swagelok Houston (Houston, TX), as well as their catalog [17].

One may wonder if dumping air into the Hyperloop vacuum tube will lead to increased atmosphere in the tube, or more drag for subsequent pods. In short, it is too negligible an amount of air. For example, Dekker Vacuum Technologies (Michigan City, IN) offers a vacuum pump capable of pumping 60-150 CFM at a maximum of 10 HP [18]. Four air bearings have a combined flow rate of only 27.6 SCFM, meaning the pump rate exceeds that of the rate of air being added to the system, allowing equilibrium to continue. Of course, the size of the pumps at the

Hyperloop track are actually substantially larger. Furthermore, at conditions of .2 psi in the test track, there is a total mass of air in one mile of the track of roughly 68 kg. This is calculated using the volume and density of air equations below [19], with a track length of one mile, a

$$V = \pi r^2 h$$

$$\rho = \frac{P}{R_s T}$$

diameter of 6 feet, a pressure of 1400 Pa, and a temperature of 295K. The mass of air in one air tank is roughly 7 kg. Of course, to travel one mile at the speeds considered will take less than 10 seconds, when the volume of this air would not be drained from our system for 7 minutes. This is to say, the total amount of air entering the tube is not only negligible, but the rate at which it is entering the system is also negligible. These numbers get even more negligible as the total volume of air increases with a longer (200 miles), larger diameter (12 feet) track.

3.6 STABILITY

The stability system is the most straightforward subsystem on the pod, designed to provide lateral control to the pod. The wheels and bearings were chosen to have a FOS of 3 or more at 200 mph in both strength and rotational speed. The concept of the design was taken from roller coaster wheels. With simple rubber inserts providing some cushion, the system is designed to simply pin the pod to the track. The design and finished product can be seen in Figures 3.12 and 3.13.

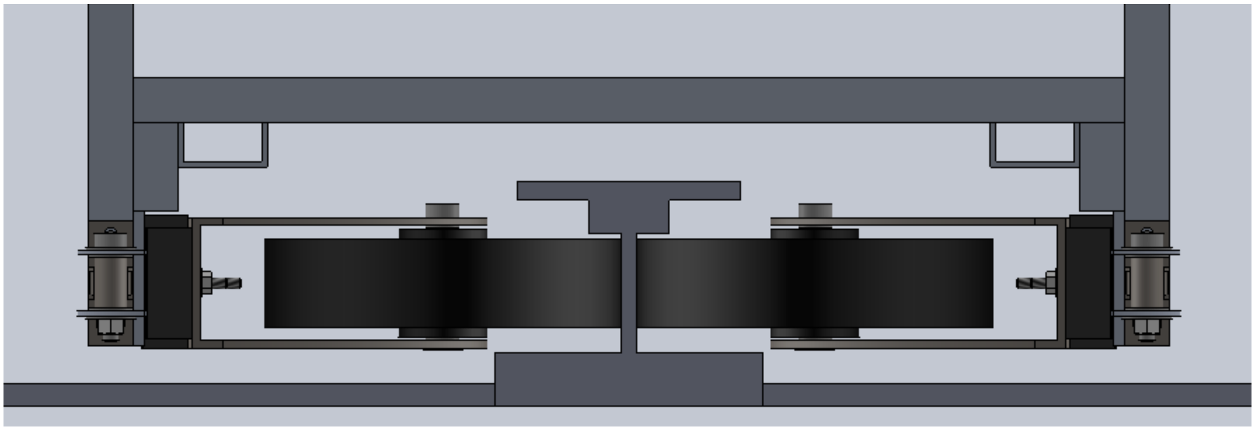


Figure 3.13: SolidWorks design of the stability system, showing the wheels not infringing on the SpaceX "no-go" zone. These are shown as gray blocks on the web of the rail

Figure 3.14: The stability system built to specification and integrated into the frame of the pod

3.7: ELECTRONICS AND CONTROLS

While the mechanical systems proved enough of a challenge in and of themselves, of equal importance is the electronics and controls systems. The pod of course will not have any human riders on it during the competition, so it must be able to operate completely autonomously. The challenge was to create a system that is both sophisticated and simple. An overcomplicated system would expose itself to multiple single points of failure, and a system that is unsophisticated would not have the functionality necessary to complete the run. Thus, the problem had to be broken down into its most fundamental parts, and then a system had to be built with as few moving parts as possible from those fundamentals.

This was done by separating the pod into five top level states, shown in Figure 3.14. The first is pre-flight, where the pod will be sitting in vacuum, ready to go. In this state, everything must be powered and there must be two way communication between the pod and the team outside the tube. It is here that the team can make sure all systems are go, and can levitate the pod. This is also where all the braking presets can be made, which will be discussed shortly. The second state is acceleration, or when the pusher plate is connected. The main control here is that braking cannot occur, until the pusher plate detached. In State 3, or flight, the pod only brakes in the event of the problem and should otherwise “coast”. State 4 is the braking phase, when the normal navigation controls should take over and bring the pod to a stop, based on the speed and position of the pod relative to the end of the tube. Lastly, in state 5, the team can manually vent the remaining air pressure and make sure that it is safe to approach by checking critical systems. This is all done with a simple National Instruments MyRio with an array of sensors, shown in Figure 3.15. The actuators operate based on simple relay switches because it was decided that this would lead to the simplest system possible. Each actuator basically has two states: “on” or “off”. These will not be covered in much depth in this Thesis.

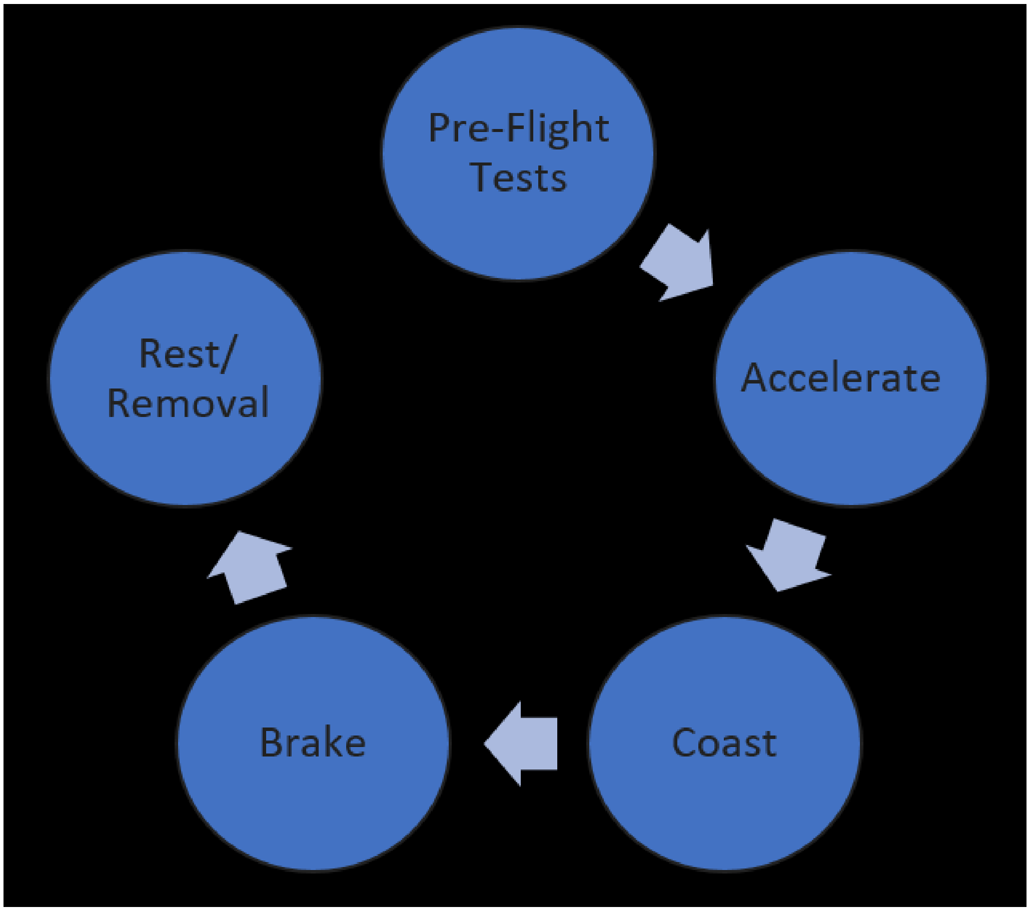


Figure 3.15: Pod top-level state map—pre-flight, acceleration, coast, brake, and rest.

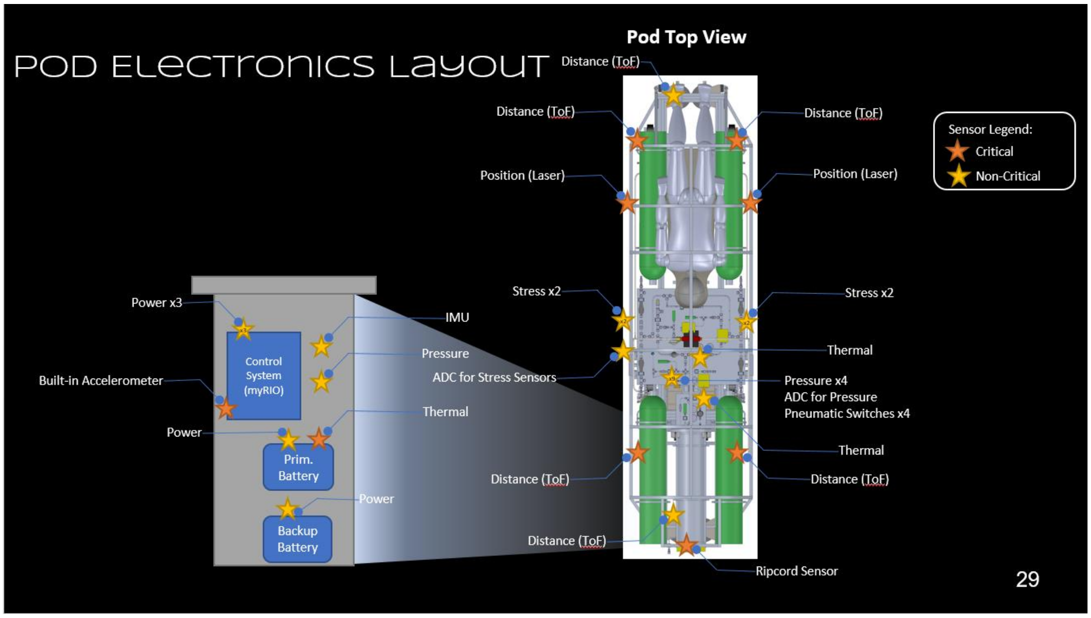
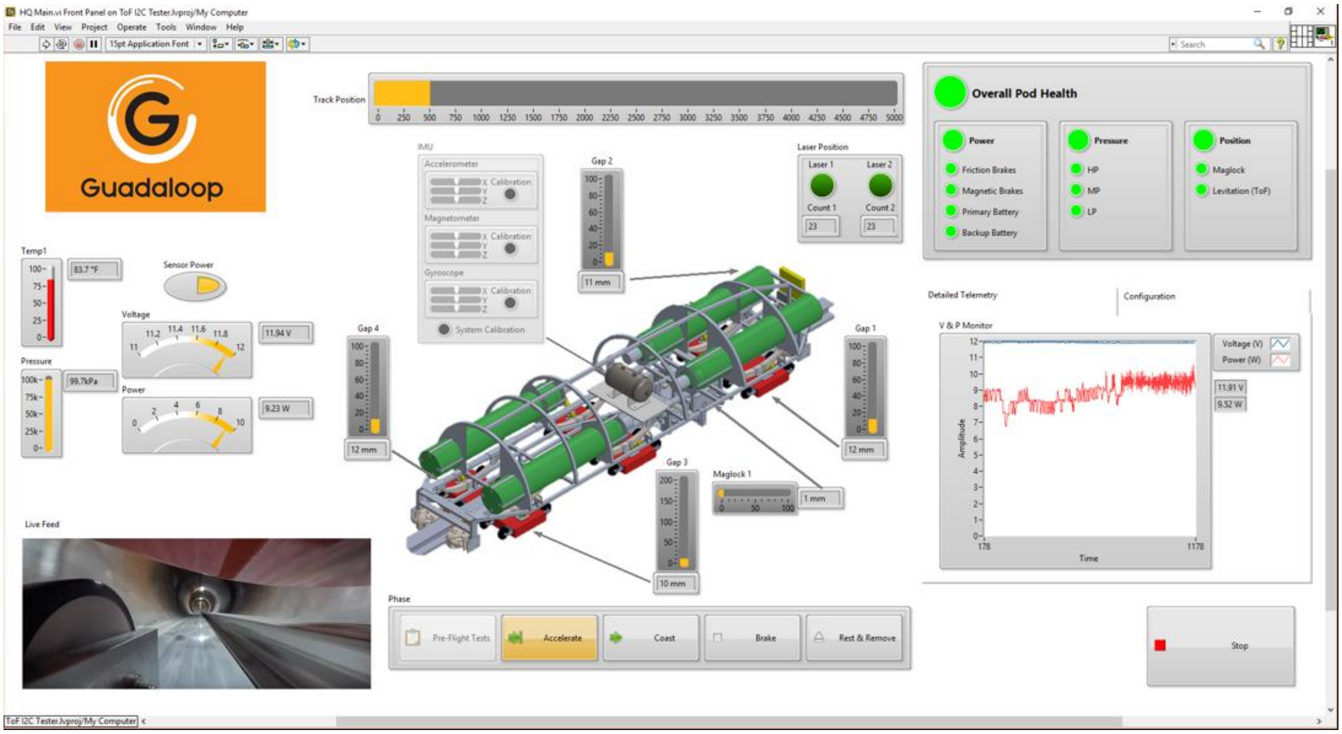


Figure 3.16: Sensor map of everything on board the pod.

3.7.1 Pre-flight

The pre-flight phase is when SpaceX needs to know if all systems are “go” for launch. The “pod health system” shown in the top right of the Graphical User Interface keeps track of power consumption of each subsystem, the pressure amount of each pressure stage, the position of the brakes, and the levitation height of the pod. Each of these show “green” if the values are nominal, and “red” if they are not. All systems must be green in order to launch. When ready, the team can remotely levitate the pod with the turning of a single valve. This makes the pod ready for take-off.



Temp1: 83.7 °F
Pressure: 99.7kPa
Voltage: 11.94 V
Power: 9.23 W
Gap 2: 11 mm
Gap 4: 12 mm
Gap 1: 12 mm
Gap 3: 10 mm
Maglock 1: 1 mm
Count 1: 23
Count 2: 23
11.91 V
9.52 W

Figure 3.17: The Guadaloop “GUI”, showing the health of the system and giving manual actuation control over the pneumatics panel and braking circuits.

3.7.2 Acceleration

As stated previously, it is absolutely critical that the pod does not brake in this state. Thus, there is a mechanical and electrical redundancy in the braking setup. As shown in Figure 3.17, the valves are manually (but remotely) pre-set such that the pneumatic pistons in the braking circuit are pressurized at 200 psi. This is shown in green. The valve labeled "S" is closed when powered. When the pusher plate detaches, the electrical circuit is broken and this valve becomes open, allowing now for the brakes to activate controlled only by the maglock.

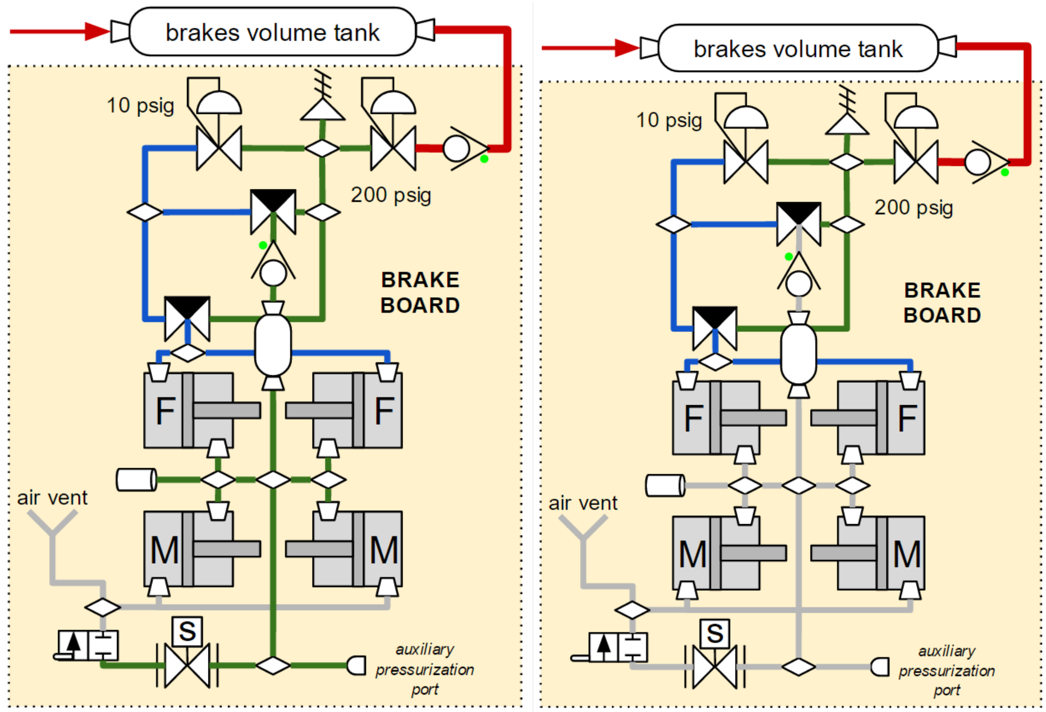


Figure 3.18 a) The green indicates the pistons being pressurized at 200psi during acceleration b) After the pusher-plate detaches, the pistons vent so that the brakes can engage.

3.7.3 Coast

Coasting should be the simplest of all states, and does not involve any complicated controls. If the power fails, the maglocks release automatically and the pod is brought to a stop.

If anything within the “pod health” system looks troubling, the brakes can be engaged automatically by autonomous software controls. Thus, in this state, the pod simply coasts on the air bearings (or wheels, if they fail), and brakes only in the event of a problem.

3.7.4 Braking

As explained in Chapter 2, the brakes are engaged using retro-reflective tape that is counted using a laser. That is, the laser counts the tape to detect the pod’s position within the tube. Based on preset calculations, the braking phase will initiate once the proper number of tapes has been counted. There is also a redundant, industry-grade accelerometer on board that will integrate along the pod’s flight to measure the distance traveled. If the laser fails, this system can initiate braking. Braking can also be initiated manually via a remote “pod-stop command”.

3.7.5 Post-flight

In this phase, the team makes sure that it is safe to approach and ready to remove. First, the team will remove the brakes from the rail using a command to the pneumatic piston valves. Then, the maglocks will be turned on again to hold the brakes in place. After that, the air tanks can be vented in order to make sure there is no pressurized air on board and no danger in approaching the pod. The pod can then be wheeled out by hand to safety.

Chapter 4: Conclusions and Future Work

4.1: SUMMARY AND CONCLUSIONS

The Hyperloop concept offers a new transportation method that is increasingly necessary for 21st century life. With promised speeds faster than a plane, while still being as convenient to ride as a train, the Hyperloop is an exciting possibility. As it was only announced in 2013, there are still a number of technical and engineering obstacles to overcome. In order to facilitate the solving of these problems, Elon Musk opened an international competition to design and build prototype pods to test on a one-mile track that SpaceX has built. A team was formed at UT in order to design and build a prototype pod. While the research conducted was for the full-scale Hyperloop concept, the competition served as motivation for many of the design decisions.

As the Hyperloop rests on the idea of cheap, drag-free transportation, what levitation mechanism to use is at the core of the research being conducted. The two main possible forms are magnetic levitation and air bearings. Due to the fact that magnetic levitation is expensive and introduces drag, it was decided that air bearings would be the best system for the Hyperloop. However, air bearings have never been tested at high velocities, and as such present considerable design challenges. While there is some literature on high velocity applications for rigid air bearings, it was decided that compliant air bearings were the only viable solution for the Hyperloop due to their superior gap height.

No team has yet been successful demonstrating air bearings at speed, as their designs have been, according to SpaceX, too complicated. From the beginning, the goal was to design and build the simplest system possible, as it was thought that this would be most reliable and give the best chance of using SpaceX's half-scale test track. A design methodology of “sophisticated, yet simple” was established. That is, the systems are fully functional for the goal of using the test track, but using the fewest moving parts possible. For example, safety systems are passively integrated where possible. A few components critical to the testing of air bearings at speed, that are in this design, follow

- In the case of levitation, there is the possibility of the air bearings failing at speed. Thus, a system was designed such that, in the event of failure, the pod would land on wheels with no controls necessary
- The pneumatic system has remote and passive venting capabilities, among other redundant safety systems and controls
- The braking systems function even in the event of communications and power failures, and cannot brake even if this occurs during acceleration phase
- Hop tanks dampen out high frequency vibrations that otherwise make air bearing travel at high velocity untenable
- A suspension system capable of providing dampening while keeping the air bearings loaded properly
- Robust lateral stability to keep the pod travelling in the proper direction

Due to this methodology, it is expected that this design will be able to demonstrate compliant air bearings at speeds of 100-200 mph. By doing this, the fundamentals of air bearings will be proven, and further work can be done to develop an air bearing of even greater speeds.

Most importantly, it was learned that a viable air bearing test platform can be built within these parameters. What is important is that the system design is safe and sophisticated enough (and also capable of being constructed) to truly have a way of studying air bearings at high velocities. Furthermore, it was concluded that using a one-mile (or longer) test track is a viable way of studying high velocity applications of air bearings. Simulations, whether it be in a lab or computational, are not currently capable to address this problem.

4.2: FUTURE WORK

As the test bed for accelerating air bearings up to high speeds has already been designed and built, the testing itself is left for future work. That is, with the sensors equipped on the pod, any runs on the track will be monitored and data will be acquired. Using this data, it will be able to be determined the performance of the air bearing. For example, time of flight sensors will measure the gap height as the pod travels down the tube, and accelerometers will measure the velocity. This will allow for effective lift vs. velocity and lift vs. drag profiles to be developed. Other elements can be discovered based on the location of sensors on the pod. For example, it may be found that lift is lost in the front of the air bearing (due to shear forces from the track), and not the rear. This will aid in optimizing geometry of and flow rates delivered to the new air bearing design. It may also be revealed that there is no loss of lift, and the air bearings as are perform very well in the tested velocity regimes. As such, even higher velocities would be sought.

References

1: Musk, Elon. *Hyperloop Alpha*. Tech. Spacex, 12 Aug. 2013. Web. 1 May 2017.

2: Chin, Jeffrey, Justin Gray, Scott Jones, and Jeffrey Berton. *Open-Source Conceptual Sizing Models for the Hyperloop Passenger Pod*. Tech. Nasa Glenn Research Center, 5 Jan. 2015. Web. 1 May 2017.

3: "U.S. Primary Energy Consumption by Source and Sector." *Energy Information Administration*. Web.

4: Muoio, Danielle. "Here are the big winners of Elon Musk's Hyperloop pod competition." *Business Insider*. Business Insider, 29 Jan. 2017. Web. 04 May 2017.

5: "Why Current Maglev is not viable." *MTS - Why Current Maglev is Not Viable*. N.p., n.d. Web. 04 May 2017.

6: Post, Richard. *Towards More Efficient Transport: The Inductrack Maglev System*. Issue brief. Lawrence Livermore National Laboratory, 10 Oct. 2005. Web. 04 May 2017.

7: "Halbach Arrays." KJ Magnetics, n.d. Web. 04 May 2017.

8: Hribar, Jure. *Magnetic Braking*. Tech. University of Ljubana Department of Math and Physics, 4 Nov. 2008. Web. 4 May 2017.

9: *Badgerloop Presentation*. Texas A&M, College Station, TX. 28 Jan. 2016. Performance.

10: *How Air Bearings Work*. Issue brief. AirFloat, LLC, n.d. Web. 04 May 2017.

11: *Spacex Hyperloop Track Specification Revision 11.0.* Issue brief. Spacex, 3 Mar. 2017. Web. 3 Mar. 2017.

12: "MIT Hyperloop Flight Jan 29th 2017 - First Ever Low Pressure Hyperloop Run." *MIT Hyperloop.* YouTube, 30 Jan. 2017. Web. 04 May 2017.

13: "Delft Hyperloop - First Run Undercarriage." *Delft Hyperloop*. YouTube, 01 Feb. 2017. Web. 04 May 2017.

14: *Minimum Estimated Air Consumption for Air Bearings*. Issue brief. AirFloat, LLC, n.d. Web. 04 May 2017.

15: Compressed Air Tank Specifications. N.d. Raw data. Praxair.com, n.p.

16: Ballor, Claire. "Dallas to Austin in 15 minutes? It's a long shot, but new high-speed system could make it happen | News." *Dallas News*. N.p., 07 Apr. 2017. Web. 04 May 2017.

17: "Product Catalog." *Product Groups | Swagelok*. N.p., n.d. Web. 04 May 2017. <https://www.swagelok.com/en/Resources/Product-Catalog>.

18: "Products & Parts." *DEKKER Vacuum Technologies, Inc.* N.p., n.d. Web. 04 May 2017. <https://www.dekkervacuum.com/store/?id=dv0200b-kb4>.

19: Munson, Bruce Roy, T. H. Okiishi, Wade W. Huebsch, and Alric P. Rothmayer. *Fundamentals of fluid mechanics*. Hoboken, NJ: John Wiley & Sons, Inc., 2013. Print.