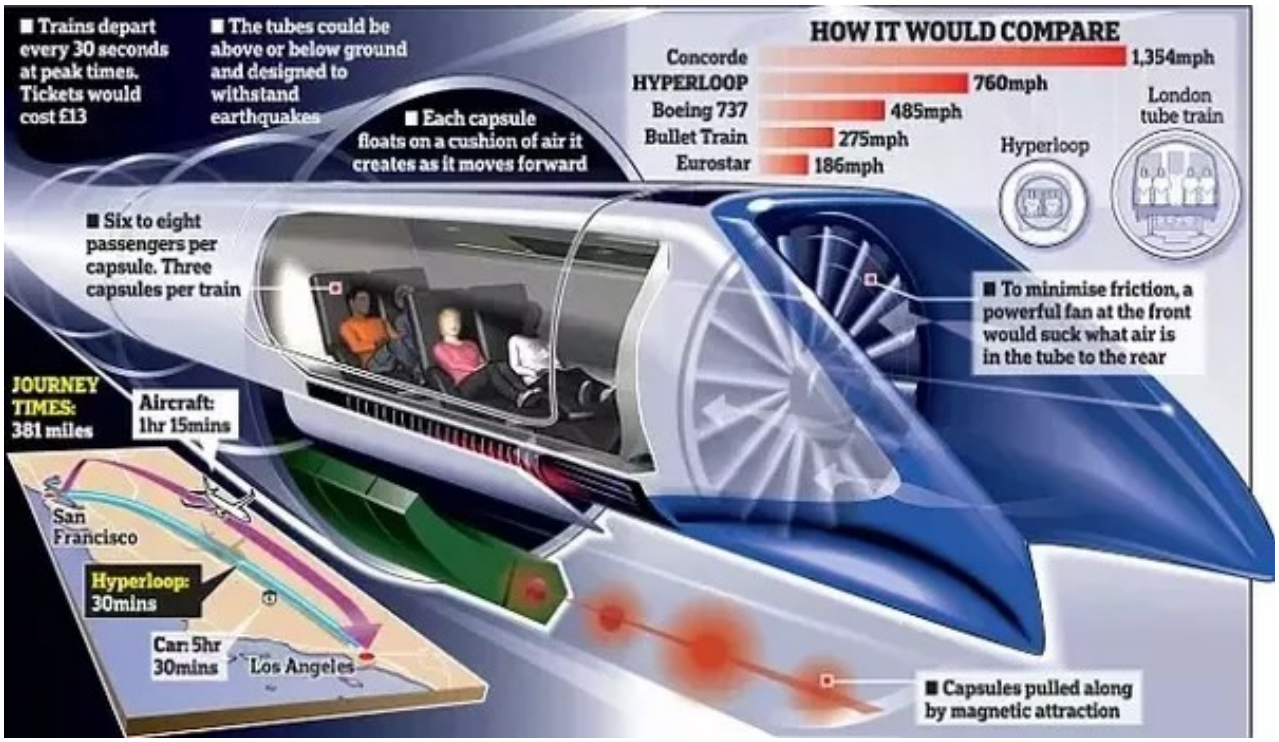
Hyperloop - The Black Paper



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1. Introduction

The Hyperloop is a notional scheme for high speed long distance land transport of passengers and small freight using small capsules running in vacuum tubes, the tubes supported on raised pylons or columns as much as possible. A working Hyperloop system would have at least two tubes, one for each direction of travel. It was described in a white paper with the title *Hyperloop Alpha*

[https://ia903209.us.archive.org/15/items/hyperloop_alpha/hyperloop_alpha.pdf] written in 2013 by Elon Musk, an eccentric and technically minded billionaire company owner, factory manager, salesman, and media personality. Musk owns *Tesla* and *SpaceX*, and several other less well known businesses including *The Boring Company,* a tunnelling company.

This "black paper" is a critique of Musk's white paper and aims to demonstrate the poor practicality and economics of the Hyperloop concept. It does not claim, as some have, that the Hyperloop is not possible. Anything is possible as long as it does not break the laws of physics and enough money is spent on it, and the history of technology has many schemes which have been claimed as impossible, but were nevertheless built and even worked, even if they ultimately failed because of technical factors or poor economics. There have been many unsupported claims made about Hyperloop by both its proponents and opponents, and it has proved to be a divisive subject.

Musk is writing from a North American perspective where the default mode of longer inter-city passenger transport is by airline. But commercial aircraft use carbon based fuel and there is at present no realistic prospect of replacing it with electrical power because of the poor energy-to-weight ratio of batteries. The existing, proven, carbon-free alternative to airlines for mid-range transport is electrically powered high speed rail, of which there are existing networks in most developed countries, although not in North America. In his white paper, Musk sees Hyperloop as a better option than high speed rail as a replacement for airlines for transport up to about 1500 km.

Some commentators confuse *Hyperloop* with *The Loop*. The Loop is a short underground tunnel for dedicated taxis in Las Vegas, with plans for extension, built and owned by The Boring Company. The Hyperloop on the other hand exists only as proposals and some very short test sections; the further developments since the white paper have been by companies not owned by Musk, although the word *Hyperloop* is held as a trademark by his SpaceX company. The most notable of these other companies are *Virgin Hyperloop One* which owns a half kilometer prototype single Hyperloop tube located in the desert outside Las Vegas called the *DevLoop*, and *HyperloopTT* which has a short test track in Toulouse and is pursuing the concept with somewhat less publicity. The fact that the Las Vegas area is the home of both Virgin Hyperloop One's test site and The Boring Company's The Loop seems to be a co-incidence.

While not being a board member of any Hyperloop company, Musk does make appearances at some of their publicity events, and SpaceX has sponsored some design competitions. He is a friend of Sir Richard Branson, who has a large investment in Virgin Hyperloop One and has been its chairman. Musk claims to have invented both the Hyperloop and The Loop, but he invented neither; I will deal with that later.

This paper primarily addresses Musk's white paper and refers only briefly to subsequent Hyperloop developments by other companies I have also concentrated on the potential competition between Hyperloop and high speed railways rather than with aircraft, partly because I know more about railways, having been on the engineering staff of one, but also because it is clear that railways are Musk's main target; he strongly dislikes them and states that he was motivated to write his white paper in opposition to the proposed Californian high speed railway line.

Like Musk's white paper, this is is not written as a formal technical treatise, and it is not peppered with references. Where possible, I use the same technical terminology as in the white paper, which tends to use American rather than British words. In particular the white paper refers to Hyperloop vehicles as *capsules*, but they are often referred to as *pods* elsewhere. I will indicate direct quotations by Musk from his white paper and elsewhere with blue highlighting.



Artist's impression of a Hyperloop tube crossing the Golden Gate illustrating the disconnection from reality of many Hyperloop advocates. The road bridge was built high and wide to allow ships to reach San Francisco's docks from the sea, but the Hyperloop blocks it. Ironically, the docks include an export wharf for one of Musk's Tesla car factories. Two or more tubes would be needed on a working Hyperloop.

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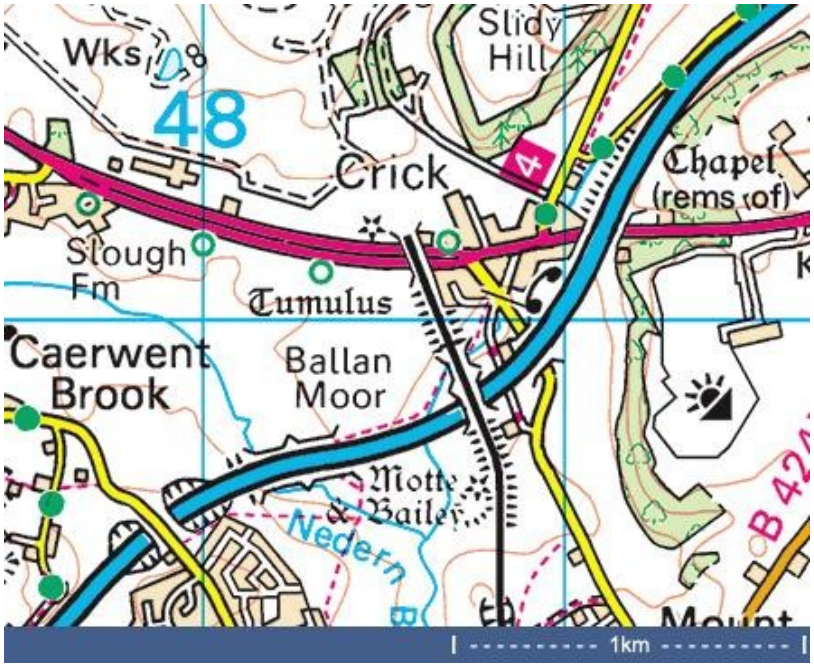
2. Route

Because of its high speed, Hyperloop requires very gentle curves, both vertically and laterally, so the line of route will be extremely restricted.

The White Paper proposes a speed of 760 mph, and some proponents have talked of even higher speeds. In metric units, for the purpose of engineering calculations, that is 340 metres per second (m/s). As centrifugal force is proportional to the square of the speed, this would lead to some very high forces if curve radii were used that are similar to those on existing motorways, freeways and even high speed railways. The White Paper claims that 0.5g is an an acceptable maximum centripetal acceleration of the capsules, and even if we take that questionably high value curve radii must be at least 23.5 kilometres.

The very large minimum curve radius is a serious issue for the Hyperloop because it makes it very difficult or impossible to thread it through typical European terrain, or that of many other areas in the world, while avoiding intermediate towns, villages, industrial plant, hills, lakes and nature reserves. The route planners will be restricted to drawing an almost straight line across the map. Musk attaches little importance to this, and believes that being raised on pylons will overcome any objections. He also believes Hyperloop can be routed in the median ("central reservation" in the UK) of major highways and gives the example of Interstate 5 in California.





A typical UK motorway (blue on map). These sweeping curves, to avoid settlements and a hill, would be much too sharp for a Hyperloop. They are about 1 km in radius, but a Hyperloop would need a radius of at least 23 km. Unlike Musk's example I-5 in California, UK medians are too narrow to accommodate a Hyperloop.

But 0.5g is too severe for passengers in a public transport system. White-knuckle fairground rides significantly exceed this but only for brief periods, and their passengers are *seeking* a thrill and tend to be young. The ability to tilt the Hyperloop capsules inwards on curves does not alter the fact that there are comfort limits for both vertical and lateral dynamic forces, and there are codes of practice (that can be legal requirements) for passenger systems. Conventional railways have a passenger

comfort limit for lateral centripetal acceleration, typically 0.1g, and also an absolute limit of the inward inclination of track (known as “cant”) of about 5 degrees. The maximum cant is specified out of consideration for passenger comfort on a train stopped on a curve, something that will also occur on Hyperloop when there is a queue to enter a terminus for example. There is also the fact that with passengers closely confined and unable to see a horizon from within the Hyperloop, their tolerance to tilting and accelerations may well be lower than with conventional transport. The psychological aspects are not addressed in the white paper and do not seem to have been since.

Combining the maximum lateral acceleration allowed for the passengers with the maximum cant allowed for the track used in railway practice means there is a limit of about 0.2g centripetal acceleration for the vehicle rather than Musk’s 0.5g figure. At 340 m/s, with this limit, the Hyperloop would require a minimum curve radius of nearly 60 km, which is a very severe design constraint on the route.

The limitation of curvature applies in the vertical plane as well as the horizontal. Changes of gradient will need to be very gradual, so the idea of supporting the tube on pylons of modest height will not survive the first encounter with undulating terrain. In those areas the height of the supporting pylons will need to vary enormously, and the tube will often be at ground level, in cuttings, and in tunnels. Like a conventional railway in fact.

But the restrictions on lateral and vertical Hyperloop curvature will be much greater than for a conventional railway, so the civil engineering will be more expensive, with longer tunnels and some spectacularly high viaducts over valleys.



New-build railways have lower civil engineering costs than a Hyperloop. Modern passenger trains have multiple driven axles so the track can follow undulations relatively closely. But, to limit the vertical acceleration, Hyperloop would require extra high pylons over this dip, and tunnels or deep cuttings into the rises.



A Victorian railway viaduct. A Hyperloop would need many more viaducts on this scale than a railway does. Even in a level area, long lengths of high viaduct would be needed to ease upturns towards higher ground.

Unsurprisingly, Hyperloop artist's impressions and CGI (Computer Generated Imagery) usually shows it in a flat featureless landscape.

The other advantage a high speed railway has over the Hyperloop is that beyond the high speed sections the trains can continue at reduced speed on existing railway lines, either as an interim measure (as the HS1 trains did in the UK), or as a permanent arrangement to reach an existing city centre station or further regions. This greatly enlarges the area that can benefit from the high speed sections of a railway. Hyperloop however would be restricted to its own infrastructure. This is a political as well as a practical consideration.

3. Land

Musk wrote :
The key advantages of a tube vs a railway track are that it can be built above the ground on pylons and it can be built in pre-fabricated sections that can be dropped in place

If those are the key advantages of Hyperloop, then its case fails here. Conventional railways can also be built on raised supports and often are (they are viaducts), and "dropping" tubes on pylons ignores the task of constructing the pylons first. The laying of railway track on its foundation is a relative speedy and largely automated process that is faster than placing Hyperloop tubes would be. Most of the time spent building a railway is on the civil engineering such as tunnels and bridges, and that would even more be the case for Hyperloop.

Musk wrote :
"… Hyperloop …. will cause minimal disruption to farmland roughly comparable to a tree or telephone pole which farmers deal with all the time. A ground based high speed rail system by comparison needs up to a 100 ft wide swathe of dedicated land"

It is clear that Musk does not expect Hyperloop to pay for the land under the tubes, only for the small footprints of the pylons. He seems not even to expect to pay for those if they are in "existing rights of way". This is nonsense. It is also clear that he does not know much about agriculture.



Railway track laying, a largely automated and relatively rapid process.

In principle, in both English and USA law a landlord owns everything above their property as high as Heaven and everything below as deep as Hell. In practice there are no hard vertical boundaries, but 500 or 1000 feet up have been used in legal cases in the context of aircraft. There is no way that a Hyperloop company could place tubes over property in a civilised nation without the purchase of a wayleave, or of the land itself.

In the case of elevated sections of motorway built in the UK, the land below is bought by compulsory purchase, and any buildings on it are generally demolished. These areas are now usually wastelands or, at best in urban areas, parking lots or scrapyards. When the original railways were built in inner South London around 1850, the practice was also to buy everything along the route, demolish it, and then build brick viaducts to carry the railway about 30 feet above ground level – a height similar to that in the Hyperloop proposals. The arches were then rented to sub-prime businesses who would brick or fence them in to make vaulted chambers. These railway arch premises have entered UK urban culture as being somewhat disreputable - possibly holding stolen or smuggled goods, or serving as gangsters' torture chambers. Not those in the picture below of course. Hyperloop tubes are not however amenable to making into premises of any sort. Agricultural land would be useless in the shadow of the Hyperloop tubes, and the shadow area, which moves around during the day, would be significantly wider than the tubes themselves and probably similar or more than the 100 ft that Musk mentions for railways, although a double-track

railway in the UK is more typically 50 ft between fences. Telephone poles and their wires, with which Musk claims his pylons compare, cast very little shadow, but even so in fields of crops they are usually surrounded by a patch of hardy weeds. It is astonishing that Musk complains about the "unsightly" fencing of railways, while proposing to cross the landscape with large tubes on stilts.

Hyperloop companies will need to pay for their strip of land just as a railway would. This huge cost is not included in Musk's estimates.



Railway arches in inner south London, supporting a viaduct carrying a main line into a terminus, at a similar height to Hyperloop pylons. Miles of these viaducts were built in the mid 1800's after demolishing existing housing along the way.



Waste ground under a UK motorway viaduct, a modern equivalent of the Victorian railway arches. Houses were demolished here because such areas are considered unfit to live in. It would also be useless for agriculture, even the weeds are sparse.

4. The Vacuum

Both advocates and critics of Hyperloop get tied in knots over the “vacuum”. So let us get the terminology out of the way.

No-one has ever produced a perfect vacuum (ie void of any substance), not even in laboratories. Even outer space has a few molecules in each cubic metre. But in engineering terms a vacuum means any volume containing gas at a pressure significantly below atmospheric. The word covers, among other things, industrial vacuum pumps, domestic vacuum flasks, the propulsion of Brunel’s South Devon Atmospheric Railway (which leaked like a sieve), and vacuum cleaners (which do not even get down to half atmospheric pressure).

The White Paper proposes an engineering vacuum in the Hyperloop tubes, actually air at greatly reduced pressure : 100 Pascals, which is about one thousandth of normal atmospheric pressure. Industrial vacuum pumps are capable of creating such a vacuum in closed containers, although even large numbers of them would struggle to do so in a kilometres-long Hyperloop tube with inevitably leaky airlocks. Nevertheless, a significant vacuum could be achieved and would significantly reduce the air resistance of the capsules.

Musk must have burned a lot of midnight oil worrying about the Kantrowitz limit and planning a way round it. This is the point at which the air flowing back between a speeding capsule and the tube wall reaches the speed of sound, when the air resistance increases significantly. Musk proposes to raise this limit by sucking in some of the frontal air, compressing it in an axial flow rotary compressor (similar to the front part of a jet aircraft engine), and ducting the air to the rear of the capsule for release. The intake of this compressor occupies much of the capsule’s frontal area, as depicted in the artist’s impression at the start of this Black Paper. Some of the compressed air is diverted to provide lift for the air skis, which I will cover later. The proposed air system is complex, heavy and expensive, but the companies now developing Hyperloop seem not to be worrying about the Kantrowitz limit and are omitting the system anyway.

The Kantrowitz limit could be deferred simply by using a larger tube to allow a wider gap around the capsule, but this would be contrary to Musk’s principle that tube and capsules should be as small as possible. We see this same principle in his small Las Vegas Loop taxi tunnels.

5. Stations

5.1. Airlocks

The white paper proposes that every platform at a terminus will have its own airlock. On this basis, every through station platform will need two. Each airlock will require two very large and very expensive gate valves, nothing like the flimsy diaphragms seen in the artists’ impressions. Passing through these airlocks would be a slow operation and would be a bottleneck in the system.

I do not want to be drawn into how Hyperloop should be designed, but it would have been more sensible to keep the capsule in the vacuum and provide access for passengers via a retractable sealed connecting tube from the station “transit area” (as Musk calls the platform). But then, unless the passengers are to crawl through it on all fours, the capsule would need to be much larger than

Musk proposes, contrary to Musk's "small capsule" principle. The artists' impressions in the white paper show passengers almost lying on their backs to fit inside.

5.2. Turntables

It is ironic that Musk proposes turntables for his capsules at the terminii. Turntables are slow and troublesome devices that railways eliminated long ago by the adoption of double-ended locomotives and double-ended trains. Hyperloop capsules could be double ended except that those proposed in the white paper have the large and expensive air compressor on the leading end, and to have one at both ends would double that expense and further reduce room for passengers.

6. Suspension

Musk proposes that the capsules run on air skis, like pucks on "an air hockey table" , except that the air is being fed from the puck rather than from the table. The air gap would be only 0.5-1.3 mm. This proposal shows a serious lack of engineering practicality.

According to the white paper, the air pressure under the skis (28 skis per capsule!) would need to be 3900 Pascals on average, about 40 times higher than the 100 Pascal ambient pressure in the tube, which is a medium vacuum by technical standards. It claims this can be met at speed by the aerodynamic effect. It seems unlikely that the skis could scoop in enough of the very thin air for this effect, and I have not done the sums, but in any case Musk proposes to supplement it with air pumped into the skis by two axial compressors in series drawing on the thin ambient air in the tube, the first stage being the one mentioned earlier that is also used to overcome the Kantrowitz limit. These compressors would be powered at 330 kW by 1½ tonnes of on-board batteries that need recharging every trip. For comparison, the battery of an internal combustion engined car can produce about 1kW, briefly.

The compressed air requires cooling. Being in a vacuum, air cooling cannot be used, so Musk proposes to do this by boiling water from an on-board tank into steam that is stored in a further tank until it can be emptied at a station. The steam presents a major technical difficulty and safety issue, but this is not addressed further. The steam cannot be released from the capsule because it would compromise the vacuum and cause longer term corrosion within the tube.

The white paper seems to propose tubes that are entirely smooth internally, except for blade-like stators for linear induction motors and retarders at the beginning and end of the route. In mid-journey, a capsule on its air cushion could adopt any position around the tube circumference according to its speed to make the lateral g-force zero.

The idea of air skis riding directly on the tube wall is a bad one for several reasons. One is that the tube would be manufactured from lengths welded together and the weld beads would protrude into the proposed 0.5-1.3 mm air gap. The beads would therefore need to be ground smooth at considerable extra expense. A second reason is that the tubes would need to be built, placed, and kept in place with extreme precision because slight variations from line would cause unacceptable jolts at the high speed, and metal-to-metal contact of the skids with the tube would occur. A third reason is that there would be nothing to stop pendulum oscillation of the capsules from side to side within the tube as they went.

Rails on the other hand, whether on conventional railways or a maglev, can be made much more accurately and can shimmed into precise location during construction, and adjusted if necessary

after that. They would also locate the capsule to prevent pendulum oscillation. But Musk is intent on avoiding rails to avoid any association of Hyperloop with conventional railways. Moreover, if rails were provided for air skis, they would need to be very wide to provide the lift area .



A large pressure vessel showing circumferential and longitudinal weld beads. There will be similar beads on the inner surface.

The more practical Hyperloop projects now being pursued are not using Musk's air ski system or the associated system for raising the Kantrowitz limit. More sensibly, they propose maglev systems, which use rails (or a monorail) to support the vehicle via a small magnetic gap. It has been used in some trials and small schemes, and the most significant is the Shanghai Transrapid system, a 30 km stretch with a top speed of 430 kph.

But Musk wrote :
" A viable technical solution is magnetic levitation: however the cost associated with material and construction is prohibitive"

He may be correct .

7. Thermal Expansion

Musk makes light of this. He believes that being on pylons :
where the tube is not rigidly fixed at any point you … avoid the need for expansion joints … inside each pylon you could place two adjustable lateral (XY) dampers and one vertical (Z) damper

and that
a telescoping tube, similar to the boxy ones used to access airplanes at airports would be needed at the end stations to address the cumulative length change of the tube.

Musk does does not seem to have done any expansion calculations. Take the example of a relatively short Hyperloop between London and Birmingham UK, about 90 miles or 150km. The coefficient of expansion of steel is about 0.000012 per degree C. In a UK heatwave the metal temperature could reach about 60 deg C and in the coldest weather it could go down to -10 deg.

That difference of 70 deg would cause a change of length of 126 metres, or 63 metres at each end if you are lucky enough for it to be equally distributed. That is a lot more than an airport access connector could accommodate and it poses a serious engineering problem. In other climates the temperature range could be even greater.

Musk's dampers could not be attached directly to the tube. No dampers exist that could accommodate up to 126 metres of movement. They would need to be attached to an intermediate cradle with rollers in it ... but I don't want to drawn into designing this stuff for him. Musk also assumes that the tube will behave well and stay on the pylons as it expands. But the accumulated friction along thousands of pylons means that the tube will try to buckle sideways, particularly where it is curved, even slightly so. Musk claims that dampers in the pylons will "absorb the small length changes" due to thermal changes and that the "damper neutral position" can be adjusted to compensate foundation settlement. He does not seem to know what a damper is, and his word "absorb" implies that the expansion will somehow disappear. But dampers cannot "absorb" a length change, on the contrary they would pass it on, and while they have a mid position they do not have a "neutral" position like a spring. Dampers respond to velocity, not position. Perhaps Musk does know this, but is trying to convince his readers that he has a solution to the expansion problem when in fact he does not.

It would be more practical for the Hyperloop to have intermediate thermal expansion joints, lots of them, each capable of handling say 200mm, so about 600 would be needed between London and Birmingham. I have dealt with flexible joints in large ducts in power stations, similar to those that Hyperloop would require. They use convoluted steel bellows and are very expensive.



A thermal expansion bellows for a large duct. Hundreds like this would be needed along a Hyperloop tube, but Musk appears not to know of them.
Hyperloop has much more serious thermal expansion problems than a railway does.

There is also the problem that the more exposed upper sides of the tube will get hotter in strong sun than the lower. This will tend to make the tube hog in shape as the upper part expands more; not a lot, but enough to give a very bumpy ride at speed.
Musk again shows his ignorance of railways when he writes : ".. a rail system … needs frequent expansion joints to deal with terrmal expansion/contraction ...". On the contrary, the problem is solved for railways, while Musk is offering no real solution for the Hyperloop.

Rail expansion on modern railways is accommodated mainly by pre-tensioning the rails, and sliding joints are used in some circumstances such as near pointwork. The pre-tension avoids buckling and is calculated to tend to zero on the hottest days. The tension does try to pull the track inwards on curves but this is resisted by the heavy sleepers and "shoulders" of ballast which are at ground level. If similar pre-tensioning were attempted on the Hyperloop tube, not only would the tension force be far greater than in a rail (because it has a much larger area of metal in its cross-section), but because the force is high above the ground it will have leverage on the pylon foundations. To resist this the pylons would need massive lateral buttressing and foundations.

Musk proposes that "Two tubes will be welded together in a side-by-side configuration … ". This would not only be pointless, but would create residual weld shrinkage stresses, and induce further unnecessary stresses with ambient temerature changes. This statement again shows a lack of engineering understanding.

8. Safety

Musk wrote of the Hyperloop :
"… Very few safety concerns remain" and "In many cases Hyperloop is intrinsically safer than airplanes, trains, or automobiles.".

Yet there is no statistical data on Hyperloop safety. These bold claims seem to be based on the fact that the system is enclosed in its tube so is not vulnerable to weather or stray animals, and being up on pylons it is hard for terrorists to climb up .

I will break safety aspects into sub-headings :-

8.1 The Tube

Being in an enclosed tube cuts both ways with regard to safety. Musk makes light of the scenario of a capsule stopped in the tube, where it will be very difficult to rescue passengers. He says nothing of any emergency exits in the tube, or how they would be accessed via a vacuum, but he does make a vague claim that there will be a "great enough" air supply on board for the stranded passengers and that other capsules would be brought to an emergency halt. He does not say what would happen after that and he seems to regard a capsule stoppage as a non-event.

It is also questionable whether the claustrophobic and lurching environment will be tolerable to many passengers - there could be panic attacks. To avoid claustrophobia I believe that the capsules would need to be large enough to allow a passenger to stand, even if they might not do so, and this would allow even less agile ones to take and leave their seats without assistance. Research would be needed in this area. Larger capsules and therefore tubes would add greatly to the costs.

8.2. The Vacuum

One of the worst scenarios the Hyperloop needs to address is loss of air pressure from the capsule. This is a real danger in view of the area of sealing involved (Musk writes of gull-wing doors) and also the possibility of a tube-side scrape if the capsule loses engagement with its track (whatever form it takes). The white paper claims that the tube will always keep the capsule contained, but a brush with the tube wall at such speeds would probably open a gash. The tube would not have an entirely smooth interior because there would be service cables and their brackets.

Musk writes :
"In the case of a more significant depressurisation, oxygen masks would be deployed as in airplanes. Once the capsule reached the destination safely it would be removed from service."

The passengers' bodies would also need removing. The idea that they would be saved by oxygen masks is fatuous, otherwise astronauts could take space walks with scuba diving equipment. An aircraft pilot can make a rapid descent into higher pressure air. Moreover, the decompression of a capsule is likely to be much faster than that of an airliner because its volume is much less.

Humans would not survive a vacuum for the remaining minutes a capsule will take to reach the destination and pass out through the air lock.

8.3. Control (ie Signalling)

People who know little about railways might think of signalling as old mechanical semaphores. Forget them. The most modern signalling does not even have trackside colour lights because the signals are on the driver's console, or go straight to the on-board train controller if the train is driver-less, such as on the London Docklands Railway and the Hyperloop as proposed.

The main function of the signalling control systems is to keep trains from colliding with each other. Even when they are on the same track going in the same direction, the long braking distance of railway trains means that they must be kept well apart, usually beyond the driver's line of sight. In this, a generous safety margin is added the basic stopping distance. The Hyperloop, with even longer braking distances, will need such a control system.

Musk proposes to despatch capsules as close as 30 seconds apart (the "headway" in rail terminology), so the spacing between capsules at 760 mph (340 m/s) would be 10.2 km. It is a principle of transport systems that a vehicle should be able to stop in the distance clear ahead, and to stop in this distance, even with no safety margin, would require a retardation of 0.58g.

Between the motored zones the capsules will coast, but Musk refers to an emergency braking system. He gives no indication of how this would work except that it is mechanical, in which case 0.58g is very tall order considering that this is in a vacuum and there will be a tremendous amount of energy to dissipate. Normally, vehicles dissipate braking energy by air cooling. Perhaps he envisages friction pads on feet that extend to rub on the inner surface of the tube, like a cyclist with no brakes scraping their foot on the ground, but the heat generated in the feet will be enormous. All this assumes the braking is applied the instant trouble arises ahead, but again there is no explanation of how that trouble be detected and how quickly. There will be little time to spare.

To keep trains safely apart, railways use a block system in which a train cannot enter a section (the "block") until the previous train has left it. On some modern railways the block moves with the train

like a safety bubble. These systems have evolved to become among the most reliable safety systems of any kind in existence, and they are very expensive - a significant part of the cost of a conventional railway. Yet Musk makes no mention of control, and it is not even in his list of costs.

8.4. Earthquakes and Subsidence

At the speed of the Hyperloop, a very small deviation from alignment caused by an earth tremor will cause a severe jolt or worse. Musk claims that dampers in the supports between the pylons and the tube will mitigate this, and this has some merit as far as short and relatively small tremors are concerned. For some reason he believes that railways are more susceptible to earthquakes than the Hyperloop would be; but in fact tall structures such as pylons amplify earth tremors.

For severe earthquakes that might lead to large dislocation of the feet of pylons, Musk proposes signalling the capsules to apply their emergency brakes, presumably following detection by dedicated seismic instruments along the route, although that will not save the capsules closest to the dislocation. Similar systems are used on some high speed railways. A local earth subsidence causing a displacement of one or two pylons would require a seismometer on every pylon in order to be detected. As noted, it remains unexplained how the capsules' emergency brakes would work.

8.5. Safety Comparison with Other Transport Modes

Musk writes :
The train … would be less safe by two orders of magnitude than flying

and
In many cases Hyperloop is intrinsically safer than airplanes, trains or automobiles

Musk's claims about the safety of the Hyperloop are made without statistical basis, and with regard to trains are ludicrous. Perhaps he has been watching Roblox game train crash videos. I will not delve into automobile crashes; they do have a bad safety record but are not public transport, but it can be noted that there are about 4 deaths per day on UK roads and over 100 per day in the USA.

Both air and rail safety statistics vary widely, depending on the context and how they are presented. Airliners are much safer than light aircraft, and European railways are much safer than those in developing countries. The global table below suggests that air is an order of magnitude safer than rail in deaths per km, but how Musk can claim *two* orders of magnitude is possibly by including fatalities outside the train such as suicides, and fatalities to road users at grade (ie level) crossings.

Type	Deaths per billion		
	Journeys	Hours	km
Space Shuttle[14]	17000000	70000	6.6
Skydiving	7500[12]	75000[13]	
Motorcycle	1640	4840	108.9
Pedal cycle	170	550	44.6
Air	117	30.8	0.05
Water	90	50	2.6
Car	40	130	3.1
Foot	40	220	54.2
Rail	20	30	0.6
Van	20	60	1.2
Bus	4.3	11.1	0.4
Paragliding		8850[10] [11]	

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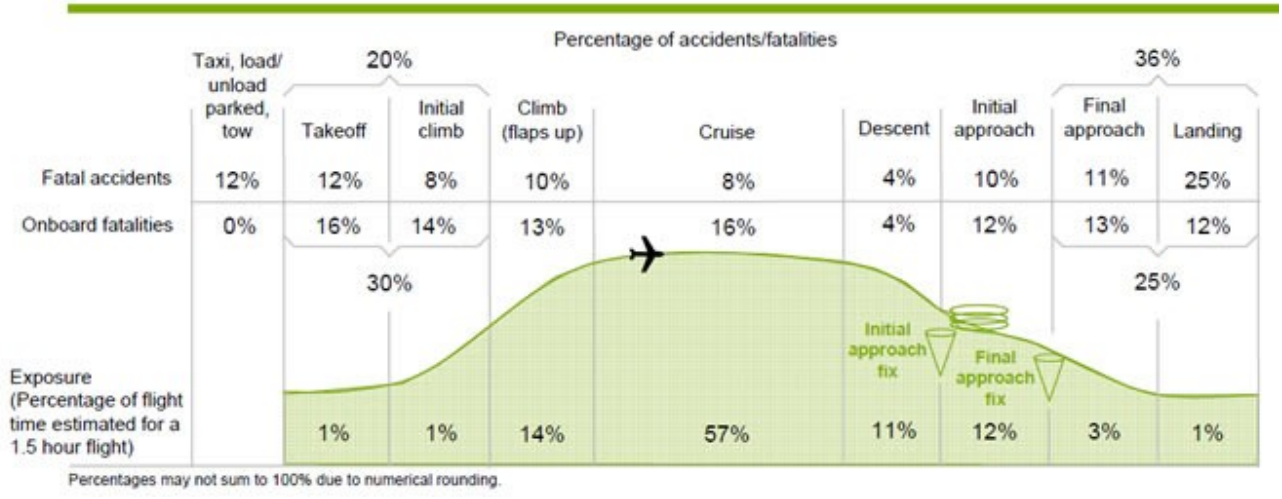
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Motorcycle	1640	4840	108.9
Foot	40	220	54.2
Pedal cycle	170	550	44.6
Space Shuttle[14]	17000000	70000	6.6
Car	40	130	3.1
Water	90	50	2.6
Van	20	60	1.2
Rail	20	30	0.6
Bus	4.3	11.1	0.4
Air	117	30.8	0.05
Skydiving	7500[12]	75000[13]	
Paragliding		8850[10] [11]	

But generalised world statistics on train crashes are not applicable either in well-regulated nations or to new high speed lines. On the other hand, global airline safety standards tend to be more consistent because even third world airlines must meet the standards of the nations they fly to.



Global railway accident statistics are adversely skewed by poor 3rd World practices. They are not relevant to well regulated countries or modern high speed lines.

However, comparison between the death rates of air flights and ground level travel is not best understood from the per km figures, because, unlike ground level travel, the air crash rate is highly non-linear in relation to distance. The vast majority of air crashes occur during the take off, climbing, descending and landing phases, not during the high level cruising phase, so the per-journey figure is more consistent than the per-km figure. This means that if air flights were as short on average as train journeys (about 60km in the UK), air would be the less safe form of travel.



	Taxi, load/ unload parked, tow	Takeoff	Initial climb	Climb (flaps up)	Cruise	Descent	Initial approach	Final approach	Landing
Fatal accidents	12%	12%	8%	10%	8%	4%	10%	11%	25%
Onboard fatalities	0%	16%	14%	13%	16%	4%	12%	13%	12%
Exposure (Percentage of flight time estimated for a 1.5 hour flight)		1%	1%	14%	57%	11%	12%	3%	1%

Aircraft crashes by flight phase. Only 16% of deaths occur during cruise.

The numbers of deaths of passengers *on board trains* on UK railways in the 2000-2020 period is easily summed up: 6 in 2001, 7 in 2002, 5 in 2004, 1 in 2007, and 1 in 2020. Each of those figures is from a single crash. The whole 20 year average is 0.025 per billion passenger-km, and the last 10 year average is 0.0025. These are significantly lower than the figure of 0.05 for air travel in the table, in fact the more recent average is lower by a factor of 20. This is a long way from Musk's ridiculous claim that rail is two orders of magnitude less safe than air.

Most passenger deaths on legacy railways occur in "platform edge" incidents, which are passengers standing too close to the edge of the platform being struck by a train. Any individual can of course avoid this by not standing close to the edge. A new build railway can almost eliminate these accidents by the use of platform doors or, at intermediate stations, not having accessible platforms by the non-stop tracks.

Many deaths, mostly of road users, occur at "grade" or "level" crossings between a road and a railway at the same level, of which there are an extraordinarily large number in the USA, over 200,000. There are far fewer in the UK, about 7000. Almost all of these accidents are caused by road users ignoring the stop signs. A modern high speed line has no such crossings.



Train crash caused by a truck obstructing a grade crossing in North Carolina.
A modern high speed line would not have grade crossings.

Musk adds :
Risk of [train] derailment is also not to be taken lightly, as demonstrated by several recent fatal train accidents

In my engineering career I was at one time (among other things) the derailment specialist for a major railway. I calculated the dynamics of potential derailment of new train designs and investigated any occurrences in service. I had only one actual derailment to deal with, and it was a slow moving event in a depot where the cause was obviously the badly maintained and very uneven track.

It is difficult for a train to derail on properly maintained track. The media often attribute a crash to a derailment when in fact the derailment is caused by the crash, such as the one at the grade crossing pictured above. In the USA where Musk is writing, railways are predominantly used for freight and the standard of the track is generally lower than on European passenger railways, and certainly below that of a modern high speed line. Perhaps that is how Musk gets that impression.

9. Economics and Operation

9.1. Costs

I am not an expert on economics, but you don't need to be one to realise that a transport system that requires a large enclosing steel tube, a large number of high grade vacuum pumps, large airlocks, and thousands of support pylons, and must maintain an almost straight line across the landscape whatever obstacles are found in its way, will be more expensive to build than a transport system that is not burdened with those requirements.

As proposed by Musk (although he does not give figures directly), the pair of tubes themselves, plus fittings such as expansion joints, will need 3000-4000 tonnes of steel per kilometre, and the pylons (in level areas) at least 2000 tonnes of concrete per kilometre. Even more concrete and steel will be required in areas of undulating terrain. Manufacture of steel and concrete are both prolific producers of CO_2. These figures would be greatly increased if it is found, as is likely, that larger capsules (and hence tubes) are needed for ergonomic reasons.

The white paper also ignores the legal, planning and regulatory costs of building and operating the system. The new high speed rail link (HS2) now being built between London and Birmingham met with massive opposition, with challenges on the grounds of ecology, safety, amenity, national economic policy, national transport policy etc being made at all levels, by the public (local and otherwise) and from within government itself. Numerous very costly consultations and concessions needed to be made. But Musk seems to think that people will have no objection to his ugly pair of tubes on concrete pillars crossing the landscape and even over their property - but they won't, and the notion in the white paper that the land underneath will be provided free of charge is fantasy.

The paper also fails to consider the cost of the system needed to control the vehicles.

The Shanghai Transrapid system, mentioned earlier, is the operational system that offers the nearest comparison with Hyperloop. It does not have a vacuum tube around it with the associated pumps and airlocks etc, but even so it cost about twice as much to build per kilometre as a conventional high speed railway. This is despite being in an authoritarian nation where it would not have had such high legal and planning costs that any new system in the West must face. In operation the Shanghai Transrapid loses money.

9.2. Speed

The Hyperloop has the advantages that it is fast and, being in a near vacuum, has a low air resistance. The latter means that it would require less propulsion power than equivalent vehicles in the open, particularly at high speed, although the power used by the pumps to maintain the vacuum would need to be offset. These advantages are undeniable, but are over-rated.

The fact that Hyperloop would travel at three times the speed of a modern high speed train does not mean that people would get from their door to their destination in a third of the time, unless both

locations happened to be adjacent to Hyperloop stations. Hyperloop will have the same problem that air and rail have, but even more so, which is that a significant part of the journey time is spent getting to and from the airport or station. Even with a fully developed Hyperloop network, its stations will be very few and far between for reasons I will come to. In the UK, which has a relatively small area, there are several thousand railway stations and yet few people live within a reasonable (say 15 minute) walking distance of one – even within London outside the central area. The benefit of speed has diminishing returns.

With regard to the rolling resistance, it should be realised that Musk demands small vehicles for travel on principle. He expresses a strong aversion to travelling with strangers - in one interview he said they could be serial killers. But vehicles in the open air have a much higher air resistance individually than if they are in a close line ahead like a conventional railway train or a team of racing cyclists in a team pursuit event. The air resistance of a long railway train is so low compared with its momentum that it will roll for 30 km or more on the level if the power were to be shut off. But a short vehicle at high speed in the open has a very high air resistance for its size, so Musk puts forward a vacuum tube as the solution to a problem which is largely of his own creation.

At such a high speed, the periods of acceleration and retardation occupy a significant part of the journey and have a strong influence on journey time. Musk proposes routine acceleration (and by implication, retardation) of 1g, by means of linear induction motors at only a few locations. This is an absurdly high acceleration level for a public transport system (for comparison the HyperloopTT Great Lakes feasibility study proposes 0.1 g). Apart from the nausea that 1g lasting for over half a minute) would induce among the passengers, it could cause items such hand luggage and even spectacles to fly across the cabin. The journey times he postulates are therefore questionable. One must wonder how much thought went into even this basic considerations in the white paper.

9.3 Station Capacity

Musk proposes an average departure time of 2 minutes (the “headway”) between capsules of 28 people. But there will be more than one platform and he estimates that loading and unloading of each capsule will take 5 minutes. It is not clear if 5 minutes is supposed to be the total, including (in addition to passengers getting on and off) the operation of the airlock for the capsule to enter the platform area, turning the capsule on a turntable, and then passing back out through the airlock on departure. He also seems to have forgotten that the 1½ tonne on-board battery to power his air ski system will need recharging or swapping. 5 minutes is an impossibly optimistic figure.

But assuming 5 minutes nevertheless, with capsules arriving every two minutes, a station would require a theoretical minimum of three platforms (or “stopping locations” to avoid railway terminology). Musk mentions six capsules being at the terminals which is three at each terminal. That might work as long as nothing goes wrong, such as a wheelchair stuck in the door; such delays will happen sometimes and then the timing of the whole system will fall apart. On conventional railways it is typical to provide four platforms at a busy twin-track terminus, even at stations mostly used by hurrying commuters who are familiar with the routine, and they do not have air locks, turntables or battery changes to create delays. I would estimate that for a two minute headway the Hyperloop would require ten platforms at each terminus and a large rolling reserve of capsules.

Intermediate stations on the Hyperloop would be problematic. If every capsule stops, such stations will require a similar number of platforms as the terminus. But if all capsules stop it would severely impact the average speed of the journey, so intermediate stations would only be at major centres, such as Birmingham on a line between London and Manchester.

On conventional railways, intermediate stations often have a loop (that word again) into a platform to allow non-stop trains to overtake stopping trains. For those not familiar with railways this is equivalent to a lay-by on a road. This would be either impractical or costly for the Hyperloop because of the very long stopping distance the capsules require – slowing to stop in the platform loop long before entering it would require all capsules behind it to slow too. Conventional railways do not have this problem because the trains are further apart, but carry more people in each one.

Some Hyperloop advocates have looked forward to commuting long distances to London, Paris, or Brussels while living in cheaper or more pleasant areas such as small Shropshire towns or by scenic Scottish lochs. That will not happen, Hyperloop will only go non-stop between major cities. Even if it did stop in such locations it would raise local house prices and, like certain railway towns in the 19th century, they would probably cease to be pleasant. Even if Hyperloop were fully developed, in the UK for example there would never be more than a couple of dozen stations. It would not stop for commuters in small country towns or by Scottish lochs.



Intermediate railway stations can have loops into platforms for stopping trains, leaving the main tracks clear for non-stop trains. With their large capacity, trains can run sufficiently far apart for the stopping train to reduce speed without forcing following trains to do so.

9.4. Line Capacity

Counter-intuitively, other things being equal the faster that vehicles travel on a road, railway, or a Hyperloop, the lower the capacity in passengers per hour. This is because, although vehicles pass at a higher speed, the rate in vehicles per hour must be reduced to maintain the separation in which they can stop safety, the stopping distance being related to the square of the speed. Part of the reason for imposing lower speed limits on some motorways at busy times is to increase the capacity.

Musk proposes capsules of 28 passengers despatched at intervals (the headway) of 30 seconds at peak times and 2 minutes off-peak. The peak equates to 3360 passengers per hour and effectively assumes that capsules can stop within 10.2 km, the separation between capsules at 30 second intervals at full speed. I am not sure he has *consciously* assumed that, but that would be the requirement. As I said earlier, this would require an emergency retardation rate in excess of 0.5g, even without any additional safety margin to allow the systems to detect and then react to an emergency (or the "*thinking distance*" as the UK Highway Code calls it in a human context).

The subsequent HyperloopTT proposal is for routine acceleration and retardation to be a more realistic 0.1g, and their linear motor is available over the whole length of the tube, not just the start and finish. However, if 0.1g is also used for emergency braking the stopping distance increases to 59km which in turn increases the headway to nearly three minutes, plus a safety margin.

The HyperloopTT linear motor/retarder could be made stronger than needed for the normal 0.1g, but there is an economic balance between the cost of the hardware for this and the loss of revenue due to increasing the headway. It is for a Hyperloop builder to decide this, but if we assume a reasonable 0.2g emergency retardation level, the stopping distance would be 29 km giving a headway of 86 seconds plus a 50% safety margin – say 2 minutes, which happens to be Musk's off-peak figure. That would give a maximum capacity of 840 passengers per hour.

Now compare that with high speed trains each carrying 500 passengers at 225 mph (100 m/s). The maximum retardation of a train is about 0.1g giving an emergency stopping distance of 5km The minimum headway needed to maintain this separation is 50 seconds. Adding a 50% safety margin as we did for the HyperloopTT above gives a headway of 1¼ minutes. That means that the high speed trains could carry 24,000 passengers per hour.

To be clear, this is the absolute maximum theoretical capacity of the high speed railway, but so is Musk's claimed capacity of the Hyperloop, even his off-peak capacity. In this like-for-like comparison, the high speed railway has 28 times the capacity of a Hyperloop, or 7 times even if we take Musk's implausibly ambitious 30 second headway.

In practice, for one thing to keep the level of foot traffic reasonable at the stations, the high speed railway would be limited to about 15 trains per hour, or 4 minute headways. This gives a capacity of 7500 passengers per hour, still well above the Musk's most extreme theoretical Hyperloop figure.

Musk sees small bore tubes and tunnels, and small separate vehicles, as fundamental to his scheme. These principles are seen in the Hyperloop white paper and also in his built Las Vegas Loop. The small bores are needed to support his claims of low building costs, although his costs are significant under-estimates anyway. But these self-imposed principles severely limit the capacity of the system, as well as creating other problems which require elaborate solutions.

As mentioned earlier, the principle of small separate vehicles seems to arise from Musk's personal dislike of sharing public transport with "strangers", and in particular of trains. He has also said that he wants to "defeat" rail, and he severed the rail freight connection into his Tesla factory in Freemont. In the white paper he avoids anything resembling a railway, such as coupling capsules together (which would increase capacity) or using a guidance rail in any shape or form.



At peak times in the central area, The London Underground railway moves passengers at a rate of up to about 30,000 per hour in each single track tunnel.
This is the flow on just one escalator flight leading to and from the platforms.

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10. Inapplicable Issues

10.1. Implosion

Some Hyperloop critics have shown spectacular video clips of oil tanks imploding when subjected to a vacuum for which they were not designed. They have postulated that if for example someone fired a shotgun at it, the tube would suddenly flatten itself over hundreds of miles from end to end. On the other hand, a popular Hyperloop advocate on Youtube produced some simple calculations of the acceptability of the primary compressive stress (which were correct) but failed to consider the issue of structural instability.

Structural instability is the run-away failure of a structure that begins from geometric factors that do not involve material breakage or even exceed the material's elastic limit in the first stages. A tube containing a vacuum becomes progressively less strong as its geometry departs from the perfectly circular, so a dent or manufacturing deviation could trigger an implosion. However, designers would take this into account, within reason. But there *is* a potential issue of implosion, if for example a rock fall or crashing light aircraft made a large dent in the tube; but even if an implosion followed, the effect would not be likely to pass the next substantial external flange or thermal expansion joint. But such a dent, whether implosion follows or not, is likely to cause a devastating obstruction to the next capsule to pass anyway, so this is not primarily a vacuum related issue.

10.2. Terrorism

Musk claims that because the Hyperloop is on raised pylons it makes it difficult for terrorists to attack. His actual words are "Tubes located on pylons would limit access to critical elements of the

system.". In fact in undulating terrain there will be plenty of places where the tubes will be at ground level. In any case, if you had a bomb to place, the Hyperloop would not be a very "efficient" target in terms of effect, although the publicity which would inevitably accompany it might make it seem attractive to a terrorist.

10.3. Bullet holes

Some have claimed that one small hole in a Hyperloop tube, caused by a red-neck's pot shot or a saboteur with a drill, would cause a shock wave of air along the tube that would kill all capsule occupants. This is nonsense, the leak would be gradual and would hardly register on the instrumentation. There will be routine leaks larger than bullet holes, such as from the air locks.

10.4. Solar Panels

Musk proposes that the Hyperloop is self-powering. He has not invented a perpetual motion machine, but is saying that he would use the Hyperloop tubes to carry solar panels, which he claims would be more than enough to power the system. Musk owns a solar panel company.

This is only thrown in as an environmental sop. You do not need to build a Hyperloop to have solar panels, you could put them straight on the ground in the spacious median of the Californian I-5 highway where Musk proposes a Hyperloop. Or over or alongside many roads, railways (electric or not), roofs, or almost anywhere.

Reducing carbon emissions is usually high on the list of claims that Hyperloop proponents make for it. But there are far simpler, quicker, and cheaper ways to achieve that aim, for example filling in some relatively small gaps that exist in the electrification of European railways, or electrifying the many longer railway lines that still rely on diesel haulage, including most lines in North America. Such schemes can use existing proven technology and can use electricity generated in any way you want.

Of course, aircraft use carbon based fuel, and many people who know little about railways assume that any long distance railway must also do so. To those people, including many in the USA where Hyperloop is first proposed, the idea of the Hyperloop running on electricity powered by solar panels is an impressive novelty.

10.5. The South Devon Railway

Comparisons (both favourable and unfavourable) have been made with Brunel's South Devon atmospheric railway. However, the only technical similarity was that it employed a vacuum, but it was in a relatively small tube between the rails and contained only a propelling piston. It was a short-lived expensive failure, as the Hyperloop might be, mainly because of the expense of running the vacuum pumps to counter the continuous leaks.

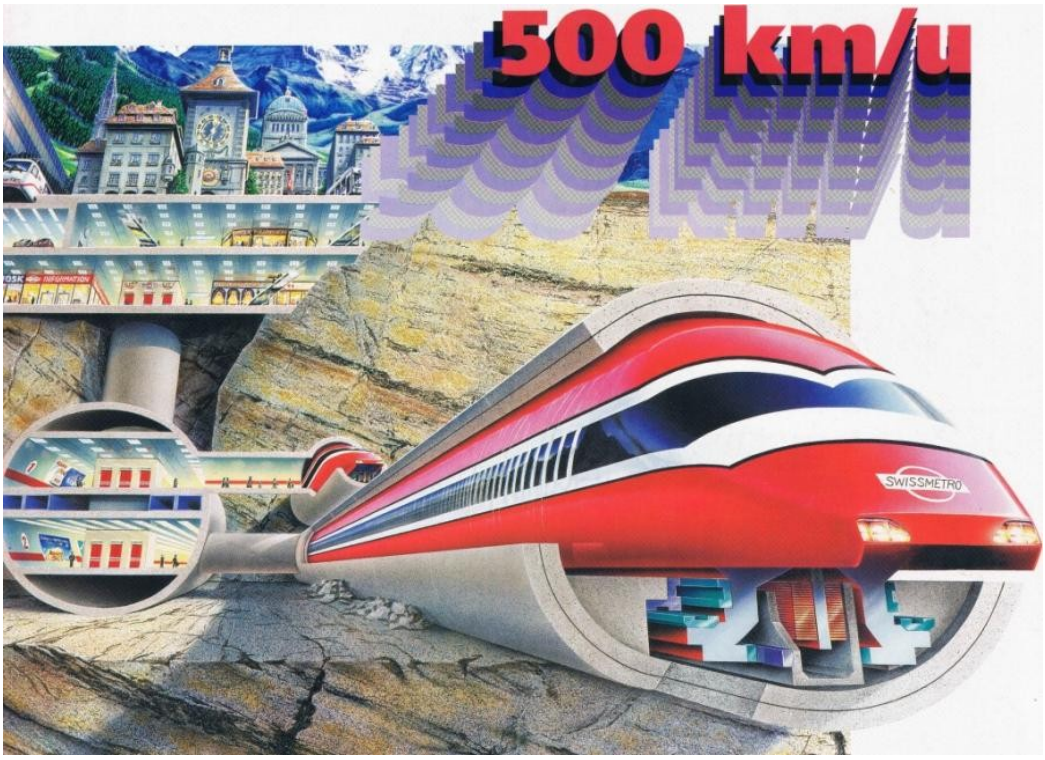
Brunel was a brilliant civil engineer, but he was not a good mechanical engineer. Now, a hundred and fifty years later, the Hyperloop should have more efficient pumps and better seals than Brunel could find, but the power to run the vacuum pumps, and their maintenance, will still be a major burden.

11. Open Source

Musk declared “his” idea to be “open source”. This has a particular meaning in the world of software in that the program code underlying a working application (such as a word processor or a computer game) is published and others are given permission to copy it and even modify it as long as a credit is given to the original writer.

Non-working items that are only *ideas* are not proper subjects for open sourcing. For example if I announce “*… an idea for a new video game where you float around in space and and shoot little green men with a ray gun*”, the announcement itself is not material for open sourcing. Only its actual computer code would be. Musk’s White Paper is the mechanical engineering equivalent of the announcement of the little green men game. He offers no blueprints, no detailed calculations, and of course no working example. Apparently to impress, he does throw in some results in graphical form of someone’s structural analysis of the pylons, but without any useful numerical values. No-one doubts that we can calculate stresses in support pylons. The White Paper is at the level of what engineers call *on-the-back-of-an-envelope*, or if deserving some contempt, *back-of-a-fag-packet*. Engineering projects other than software are not really amenable to open sourcing.

In any case, it was not within Musk’s entitlement to open source Hyperloop (other than the name). The idea of vehicles in a vacuum tube existed already. He even mentions a couple himself, and there were others of which the Swissmetro (conceived in 1980) was (or is) one of the more practical schemes – more practical than the Hyperloop as Musk proposes it. Musk tries to differentiate Hyperloop from these others on the grounds that the level of vacuum in the Hyperloop is either more than, or less than, in those other proposals. However the principle is just the same – vehicles in a vacuum tube going faster and using less power because of reduced air resistance.



Artist’s Impression of the 1980 Swissmetro - underground, in a vacuum and using maglev. Fantastic, but more practical than Hyperloop as described in the white paper.

The only aspect in which Musk might have some originality (as far as I know) is his elaborate system covered earlier for overcoming the Kantrowitz speed limit. But if so, it would have been more appropriate to have o*pen patented* it rather than *open sourced* it. The ongoing Hyperloop projects seem to have ditched the system anyway..

What remains after these points are taken out are only some general dimensions like the weight and length of the capsules, the degree of vacuum and the tube diameter. Those are not patentable and hardly worth open sourcing, and in any case I have never worked on an engineering project on which many, if any, of those back-of-an-envelope figures have made it into the final design.

12. Developments since the White Paper

Several companies have pursued the Hyperloop concept since 2013. Some have since vanished, and within these companies many of Musk's ideas have been abandoned. Air film suspension has been replaced by maglev, and the axial flow compressor on the front of the capsules has gone. One scheme proposed capsules that continue beyond the vacuum tube by driving on outside roads, and some have negated Musk's claimed advantage of cheap tunnelling by enlarging the tube diameter to a more sensible four metres, which is about the same as used for the London Underground tube tunnels. The most significant of these companies at present are *Virgin Hyperloop One* and *HyperloopTT*, to use their current names, each of which have a short length of tube for trials.



The HyperloopTT capsule does not feature Musk's air intake and compressor

The websites of these companies and other Hyperloop projects are certainly impressive. Considerable effort and expense appears to have been put into the artists impressions and animations.

SpaceX, one of Musk's companies, built a short length of prototype tube outside its Los Angeles premises and here it sponsored competitions for student project capsule prototypes. Most entrants, even among the minority selected to attend, did not get the opportunity for a run in the tube. These events seem to have held mainly for publicity, and as a platform for announcements that the future had arrived, Hyperloop would solve global warming, and so on. The event due in 2020 was meant to have been held using a longer tube, but nothing materialised, and the original tube has since been

removed. Nevertheless, Hyperloop related technology continues to be a subject for academic theses and other student projects.

Some contracts have been placed for feasibility studies for routes, usually with much publicity, including in the USA, India, and the UAE. Hyperloop TT has been involved in a Great Lakes Hyperloop proposal for a route between Pittsburgh and Chicago. This latter proposal limits the accelerations imposed on passengers to levels similar to conventional rail practice. Fortunately, Musk's vision of a strapped-in, nausea-inducing, white-knuckle ride is fading away as more attention is paid to reality. The Great Lakes study also recognises the need for serious civil engineering including a lot of tunnelling, which of course greatly increases expense and also weakens the solar panel side-project, if there is one.



The DevLoop, Virgin Hyperloop One's 500 metre straight and level test facility

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The EU has shown mild interest in the Hyperloop, allocating in 2021 a small fund towards development on paper. The publicity was about reducing carbon emissions, without mentioning that it was most likely to take traffic from Europe's existing high speed rail lines which run on electricity already. The UK government on the other hand have been dismissive of Hyperloop.

In 2020 Virgin Hyperloop One conducted a test run at the DevLoop with two passengers in a capsule in a near vacuum. However, in February 2022 they announced that they were ceasing development of a passenger Hyperloop in preference to freight, citing the difficulties that would be involved in obtaining safety approvals for public transportation (saying nothing of *actual* safety concerns). This is a major blow to the Hyperloop idea, coming as it does from a leading Hyperloop company.

No scheme has yet progressed beyond studies and small trials. I believe the developers are finding the technology far more difficult than Musk claimed it would be, if they ever believed him. To any experienced engineer the difficulties being found were entirely foreseeable, as are the ones ahead.

Musk does have a tendency to underrate technical challenges, at least to the ears of the audiences attending his high profile presentations. He is a natural salesman and showman.

13. Conclusion

The white paper is a technical whitewash, and makes little economic sense. It appeals to environmental credentials that are already available with electrically powered railways, which are the real alternative to Hyperloop. Routing, both physically and legally, is a major problem. Safety is only addressed with vague claims and misleading figures. Public transport regulations and passenger comfort standards are ignored. The carrying capacity is an order of magnitude less than a high speed railway. It assumes that Hyperloop will be given free land to build over. It claims to be cheaper than a high speed railway on the basis of absurdly underestimated costs. And the value of speed itself, the main positive attribute of Hyperloop, has diminishing returns because journey times to the boarding points would dominate, and it will have very few boarding points.

In places, the white paper shows engineering naivety, lack of technical understanding, and plain misinformation, particularly about conventional railways. Real difficulties are addressed with metaphorical arm waving, or not at all. Moreover, the basic idea, of vehicles in a vacuum tube, is not a new one.

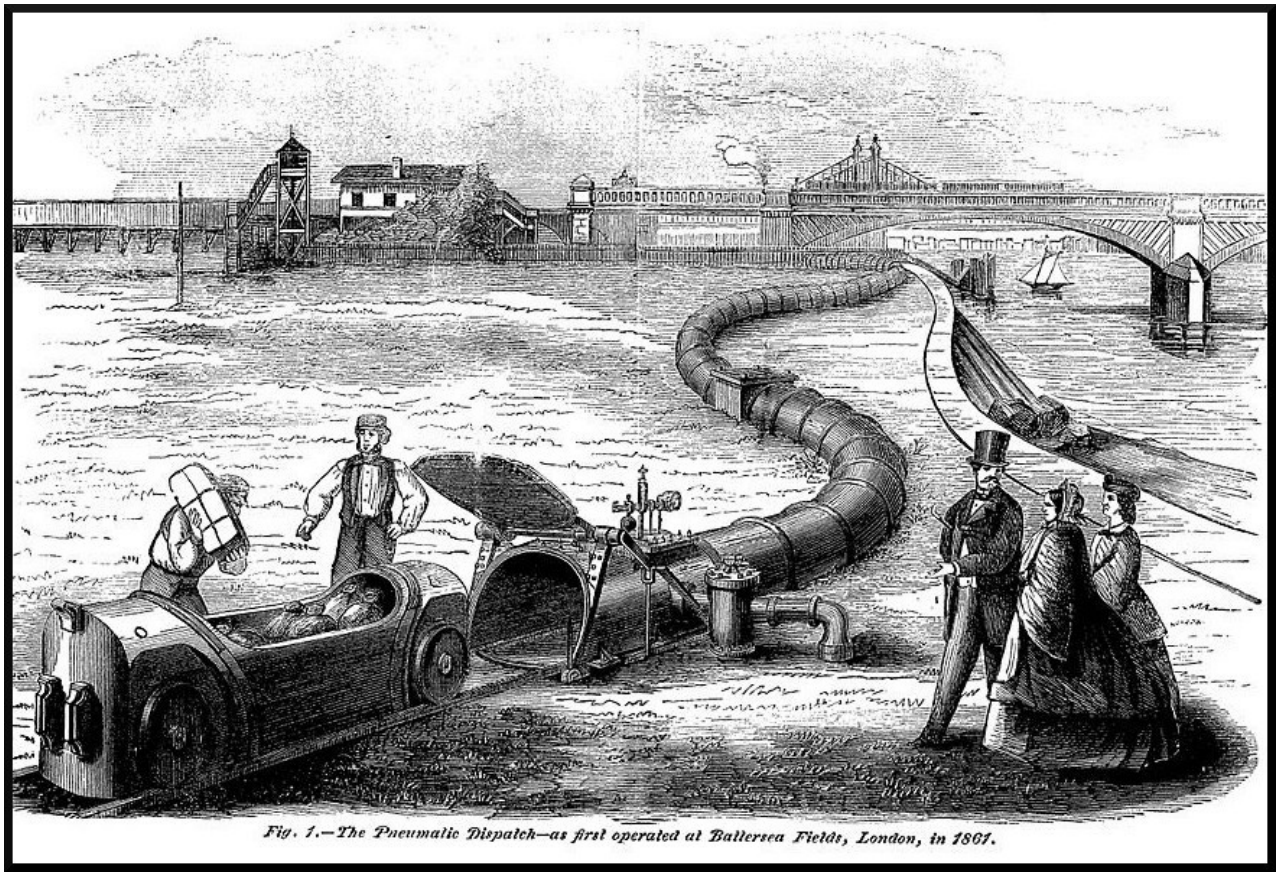


Fig. 1.—The Pneumatic Dispatch—as first operated at Battersea Fields, London, in 1861.

Ideas are never successful on the basis of innovation alone

It is clear from the white paper, and other statements made by Musk, that he has a strong personal dislike of railways, almost to the point of it being a vendetta. The Hyperloop is therefore his proposed alternative to rail for mid-range passenger travel, in particular to the Californian High

Speed railway under construction. He accepts aircraft for journeys longer than about 1500 km, and for shorter journeys he presumably accepts cars - he manufactures them.

North American railways are primarily used for freight and few people there travel by train. Most have never done so. But many American towns are bisected by railways with grade crossings, so many see them only as a nuisance. It is tempting to think that Musk's Hyperloop on pylons arose from frustration waiting at these crossings, just as he said that his idea for the Loop (the Las Vegas underground taxi tunnel) arose while he was stuck in a street-level traffic jam. The possibility of railways and roads crossing each other at different levels seems to be a novelty to some.



This is the only perception of railways for many - long slow diesel-hauled freight trains cutting through towns and causing long delays at dangerous level crossings

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With all the flaws in the white paper, it is possible to think that Musk did not even take Hyperloop seriously himself, and meant it only as a a foil to portray railways as old fashioned, and as a weapon "in being" in his opposition to the Californian high speed rail project. Musk has a history of announcing "disruptive" and "outrageous" ideas in media interviews and at spectacular presentations in show-biz style, followed up by futuristic artists impression and animated computer graphics. The media love it of course

These ideas have included a colony on Mars (usually in around ten years time) over which he will rule, international travel by ballistic spacecraft carrying 1000 people at a time, 150 mph underground city car transporters ("Loops"), and a cryptocurrency. However, the Las Vegas Loop was revealed to be only a small tunnel for taxis, and he later admited that the cryptocurrency was intended as a joke.

There would be no need to take Hyperloop seriously, and I would not have needed to write this black paper, if it were not for the fact that some people do. Unfortunately these include some politicians, financiers, and the media – people who do not in general have a strong grasp of technology. In addition, objectors to high speed rail schemes in the UK have used the possiblity of Hyperloop "coming soon" as one of their arguments, but of course this is only a play for time - they

would oppose a Hyperloop too. Hyperloop diverts attention and funds from more realistic transport improvement projects.

A Hyperloop *could* be built, but probably in a fairly flat and featureless area to keep down the legal and civil engineering costs. I doubt it would be a commercial success, and the operational limitations and problems would soon become very apparent. What is certain is that a built system would have little technical resemblance to that described in Musk's white paper, apart perhaps from the name.

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The Author

The author of this black paper has a masters degree in engineering, and a career as a professional engineer. He has worked in shipbuilding, on the design of train structures and suspensions, and is familiar with railway operation. He has also held senior positions in the design, build and operation of heavy industrial plant, and has been the engineering overseer of a group of nuclear power stations.

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