Hyperloop : Cutting through the hype

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TRL THE FUTURE OF TRANSPORT

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Abstract

This paper critically examines Hyperloop, a new mode of transportation where magnetically levitated pods are propelled at speeds of up to 760mph within a tube, moving on-demand and direct from origin to destination. The concept was first proposed by Elon Musk in a White Paper 'Hyperloop Alpha' in 2013 with a proposed route between Los Angeles and San Francisco. A literature review has identified a number of other companies and countries who are conducting feasibility studies with the aim to commercialise Hyperloop by 2021. Hyperloop is a faster alternative to existing transnational rail and air travel and would be best applied to connect major cities to help integrate commercial and labour markets; or airports to fully utilise national airport capacity. Hyperloop's low-energy potential could help alleviate existing and growing travel demand sustainably by helping to reduce congestion and offering a low carbon alternative to existing transport modes. However, there are potential issues related to economics, safety and passenger comfort of Hyperloop that require real-world demonstrations to overcome. The topography in the UK presents a key challenge for the implementation of Hyperloop and its success is more likely oversees in countries offering political /economic support and flat landscapes. This paper offers an independent analysis to determine the validity of commercial claims in relation to travel time; capacity; land implications; energy demand; costs; safety; and passenger comfort and highlights some key gaps in knowledge which require further research. Through the analysis of the key strengths and weaknesses, the research is also able to outline the potential applications of Hyperloop and reflect on the wider implications for society.

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Introduction

This paper introduces and explores the viability of Hyperloop – a new transportation system.

Hyperloop will be examined in relation to travel time; capacity; land implications; energy demand; costs; safety; and passenger comfort.

The analysis will make comparisons to existing transport modes as well as considering the applicability of Hyperloop specifically for the UK context.

Conclusions will be drawn on the future potential of Hyperloop to transform the transport industry as well as reflecting on some of the wider impacts.

Will it happen in UK?

In December 2017, the Science Advisory Council for the Department for Transport produced a position paper that stated that Hyperloop is likely to be a couple of decades away but they are committed to monitoring the development of Hyperloop; supporting the design, development and delivery of Hyperloop; and to continue to explore the potential application of Hyperloop as a transport mode within the UK.

What is Hyperloop?

Hyperloop is a proposed new mode of transportation that moves quickly, safely, on-demand and direct from origin to destination. Hyperloop will see individual low capacity (28-40 people) magnetically levitated pods propelled at high speeds (c. 760mph) through an extreme low pressure (100 pascals), low friction environment contained within a tube system.

The Hyperloop concept was popularised by Elon Musk in a White paper 'Hyperloop Alpha' (2013), which proposed building a Hyperloop between San Francisco to Los Angeles as an alternative to the proposed California high speed rail development. Since then, the concept and the technology has been ambitiously adopted and advanced at pace, by a number of companies across the world such as Virgin Hyperloop One and Hyperloop Transport Technologies, with the aim to commercialise it by 2021. Feasibility studies are underway for the implementation of Hyperloop in many countries including: USA, France, India, Saudi Arabia, Russia, Sweden, China and the UK. Within the UK, Virgin Hyperloop One has been exploring a number of routes, the forerunners being Liverpool to Glasgow and London to Edinburgh .

The value proposition of Hyperloop is to provide high speed terrestrial-based travel for small ticket prices and low energy that can rival trans-national flights and rail. Rob Lloyd, CEO of Virgin Hyperloop One, stated "we will move people and goods at very high speeds, with very little energy, no noise pollution and a very small footprint, all of which gives us something that is ultimately faster, safer, cheaper and greener than other current transportation alternatives". It is thought that Hyperloop could disrupt the transportation market in much the same way as Uber did for taxis.

But is Hyperloop a revolutionary development in mass transit, or just another beneficiary of the Elon Musk effect?

Claimed top speeds of 760mph

Hyperloop: Travel time

Elon Musk claimed Hyperloop could operate at top speeds of 760mph, however to account for the required gradual acceleration and deceleration speeds would average 600mph [1]. At these projected speeds, it is suggested that Hyperloop would be 2-3 times faster than high speed rail and 10-15 times faster than traditional rail[2]. It could also act as a faster alternative to short haul flights (c.250 to 500 miles) [3].

The Hyperloop concept is still within the testing phase, and has only achieved a top speed of 240mph[4]. Assuming predicted speeds of 760mph can be achieved, evidence suggests that the station to station travel time of Hyperloop would be faster than competing modes (i.e. rail and short-haul flights). Table 1 outlines the station to station travel times for both Musk's original route and the London to Edinburgh route proposed by Virgin Hyperloop One – both of which demonstrate the speed advantage of Hyperloop.

Whilst the station to station travel time is faster for Hyperloop, this is just one of many components to consider in a true comparison of travel time. Other factors are time in transit; security screening; boarding; baggage handling; and taxiing. The transit time related to Hyperloop depends on where its terminals are located. In Musk's proposal the Hyperloop terminals were both situated in the outskirts of the cities in Sylmar (Los Angeles) and Oakland (San Francisco). It's worth noting that Sylmar is 38 minutes north of Los Angeles Union station by Metrolink, so the journey time to the railhead is ironically 3 minutes longer than the Hyperloop journey time between Sylmar and San Francisco[9]. The assessment of the London to Edinburgh route was based on locating the terminals in the city centres and so transit time would be minimal. However in order to locate these in cities there may be a requirement to build tubes and terminals underground due to space constraints. It has been suggested that an economic option would be to run out of airports to utilise existing infrastructure and enable easier access via cars[10]. In the latter case, transit time would be significant (up to 2 hours) [11] and serve to undermine the overall speed advantage of Hyperloop. Transit time is similarly relevant for flights, whereas stations for rail are located within city centres.

As Hyperloop would be a high profile asset and therefore vulnerable to terrorist activity, there could be a requirement to do security screening to manage safety risks. Both Musk and Virgin Hyperloop One have said screening would be required, whereas Hyperloop Transport Technologies have suggested not [12]. Whilst screening would not be as laborious as for international travel, which would include passport checks, it would still increase overall journey time for Hyperloop. However, due to the frequency of departure of pods, the impact of screening would be minimal compared to flights, where additional buffer time is necessary to account for any delays at security to ensure passengers pass through in time for their scheduled flight departure time. For those travelling by rail within Great Britain there is currently no requirement to undergo screening.

Table 1: A comparison of station to station travel times for different transport modes

Route	Company	Distance	Hyperloop	High Speed Rail	Air
Los Angeles to San Francisco	Space X (Elon Musk)	382 miles	35 mins[5]	2 hours 35 mins	1 hour 20 mins
London to Edinburgh	Virgin Hyperloop One	414 miles	50 mins[6]	3 hours 38 mins[7]	1 hour 10 mins[8]

The boarding process for Hyperloop is anticipated to be relatively smooth due to the regular departure of Hyperloop pods which would result in a steady and fast flow of passengers[13] . However, there could be occasions where more passengers arrive than the available pod capacity, resulting in queues forming and boarding times increasing. Trains have relatively efficient boarding times due to the presence of several carriages where passengers can enter. Those travelling by air experience longer boarding times due to passengers squeezing into few access points which creates a bottle neck in the process.

The baggage handling process for Hyperloop is anticipated to be similar to flights, where luggage is stowed in a separate portion of the vehicle and would require special handling by staff[14] . In contrast, those travelling by rail would handle their own luggage and store it with them inside the carriage which would avoid additional baggage handling time[15].

Taxiing time is applicable only to flights and relates to the time taken to transfer the airplane between the passenger terminal and the runway. Recent figures indicate that on average US domestic flights take 15.8 minutes to taxi out and 7.1 minutes to taxi in[16] .

The analysis above indicates that the speed at which a transportation system operates is not the only factor to affect the overall journey time and there are many other components to consider. These additional components impact most significantly on flights for example, whilst the flight time between Edinburgh and London is only 1 hour and 10 minutes the estimated overall travel time would in fact be 3 hours 40 minutes[17] . This overall travel time is in line with the Edinburgh to London Rail journey time of 3 hours 38 minutes[18]. Similarly, whilst Hyperloop achieves the shortest station to station travel time, other factors significantly increase the overall journey time, making it much less attractive than on first glance.

Speed is not the only factor to affect journey time

Example Projects:

GATEway Automated Vehicle Research (Innovate UK, DfT, CCAV): A stated preference choice experiment was used to explore the predicted uptake of autonomous vehicles compared to other forms of public transport.

Greater Cambridge Mass Transit Options TRL contributed to the assessment of the "Affordable Very Rapid Transit" technology from an operational point of view.

TRL Expertise

Travel time factors: Understanding the relative importance of travel time factors (such as station to station journey times, security screening, boarding, journey time reliability, values of time etc), among wider factors (such as crowdedness, cost, convenience, comfort, etc), is vital for predicting mass-market demand for Hyperloop. The most robust method for understanding the factors affecting consumer choice is a Choice Experiment. This technique allows us to predict uptake of a new product. Within transportation, choice models are particularly used by behavioural psychologists to understand preferred modes of transport (car, bus or train) based on certain attributes (like cost and journey time) and route choices (again based on journey time, levels of congestion or different speed limits). Statisticians then apply this technique to generate robust data on consumer preferences.

Boarding Process: Trials will help to determine the most efficient boarding and alighting process. To achieve short headways in a single tube there will need to be lots of consideration given to the boarding process and the related implications e.g. use of multiple boarding points.

Security Screening: The design of the built environment can also be used to deter or prevent attack. TRL has worked extensively in infrastructure protection and is well placed to understand those approaches which ought to be used to make Hyperloop secure for users.

Hyperloop: Capacity

Musk's proposal suggested average capacity would be 840 passengers per hour with pods holding 28 people departing every 2 minutes. During rush hour this capacity could be increased to 3360 passengers with pods departing as frequently as every 30 seconds[19]. Similarly, Hyperloop Transport Technologies suggested a capacity of 3600 an hour based on pods holding 40 people departing every 40 seconds[20].

The viability of pods departing every 30–40 seconds is questioned on the grounds of safety. Hyperloop pods travelling up to 760 miles per hour will have a maximum deceleration of 0.5gs, which is equivalent to 10.9 mph per second. At that rate of braking, it will take pods 68.4 seconds to come to a full stop. Safe vehicle operation dictates the minimum headway between vehicles should be equal to the distance required for the vehicle to stop safely. Therefore, the minimum separation of pods is likely closer to 80 seconds which would safely allow 45 departures per hour[21]. Based on this interval the maximum hourly capacity on Hyperloop would be between 1,260 (28 people per pod) and 1,800 (40 people per pod).

For the Los Angeles and San Francisco route, Hyperloop capacity would be higher than air capacity which is currently 400 passengers per hour; however it is significantly lower than the proposed California high speed rail which would convey up to 12,000 per hour[22]. Capacity could be increased through the use of multiple tubes, but this would have implications for the infrastructure needed to support this and would also significantly increase cost. Assuming it is necessary to move large volumes of people between Los Angeles and San Francisco, Hyperloop may not be the most suitable solution in this location, but could still be viable in other places such as the UK.

Suggested average capacity would be 840 passengers per hour

Table 2 below demonstrates daily passenger capacities for different transport modes for the London to Edinburgh route. The maximum daily capacity for flights is 7,650 which is currently constrained until the 3rd runway is built at Heathrow[23], and is therefore currently unable to compete with Hyperloop.

Transport Mode	Capacity per unit	Departure times	Services per day	Services per hour	Departure frequency	Capacity per day
Air	Average of 150	N/a	51	N/a	N/a	7650
High Speed Rail	589	5.30am–7pm	27	2	Every 30 mins	15903
Hyperloop small capsule	28	5.30am–10pm	568	32	Every 113 seconds	15904
Hyperloop big capsule	40	5.30am–10pm	398	22	Every 163 seconds	16520

Table 2: Passenger capacity analysis for different transport modes

However, rail delivers an approximate daily capacity of 15,903 which would pose viable competition to Hyperloop. For Hyperloop to match this capacity, pods would have to depart as regularly as every 113 seconds (assuming a pod capacity of 28).

This comfortably aligns with the safety parameters discussed above, however the practicalities of dealing with up to 32 pods departing per hour could be a challenge and present a "bottle-neck" for capacity. For example, the need to maintain a vacuum requires the use of airlocks at stations. When pods arrive at the station, the airlock will have to close, pressurize and open again. Then the pod has to clear the airlock before the next pod arrives. The speed at which this occurs would determine the viable distance between pods[24] . This issue only applies to a situation where the entire vehicle is supposed to be moved from the low pressure side to the external environment. The process would be much simpler if a similar concept to air bridges at airports was adopted and indeed Hyperloop Transport Technologies have included a similar proposal to this in one of their patents.

It is important to note that passenger demand would not be consistent throughout the day and there would be significant peaks in demand during the rush hour. However, based on current train services, whilst there are alterations to the number of stopping points during peak times, there is not an increase in the number of trains, and as such there would still be a maximum of 1,178 passengers arriving per hour on rail for the London to Edinburgh route. The figures in Table 2 indicate that Hyperloop could exceed this capacity by operating larger pods with a capacity of 40, which would allow up to 1,280 passengers to be transported per hour.

Based on figures reported by Virgin Hyperloop One, passenger capacities could vary between 12 to 80 passengers, dependant on the service offering they are designed for (First Class, business class or economy class)[25] . These could be varied according to peak and off-peak travel demand.

The analysis above indicates that higher capacities can be realised in Hyperloop in comparison to flights. Hyperloop is unable to compete with the capacity of high speed rail for the Los Angeles to San Francisco route. However in the UK context assuming the proposed intervals are practicable, and first class pod operation is limited, it could feasibly achieve an equivalent, or greater capacity to existing rail services.

Example Projects:

Predictable and Optimised Braking: The Intelligent Blended Braking (iBB) Approach (RSSB) – This project aimed to develop and demonstrate a prototype state of the art intelligent blended braking (iBB) control system to significantly optimise the predictability of train braking performance. This could reduce delays and cancellations associated with incidents and improve the performance of GB rail network by allowing trains to run closer together. Analysis of the whole system costs predicted benefits including:

Cost – Improved passenger demand, operating revenues and maintenance costs.

Carbon – Savings in CO2, NOX, SOX and PM.

Capacity – Reduced headway, increased service frequency, improved service reliability.

Customer – Increased service frequency and reductions in delays and cancellations. Consistent service all year round.

MERGE Greenwich is a consortium (led by Addison Lee) that has developed a transport demand model, specifically to predict demand for ride sharing using autonomous vehicles.

TRL Expertise

Pod Design / Service Offering: Transport is all about the interaction between people and infrastructure. By building mock-ups of new infrastructure and observing different segments of the population using it, then varying the infrastructure (for example the seating or door configuration) it is possible to build up an excellent scientific understanding of capacity which can help determine a service offering.

Modelling passenger flows and capacity: TRL has developed a set of integrated modelling tools (TRIO – TRL Rolling Stock, Infrastructure and Operations Economic Model) that are capable of representing a transport system as a set of people, processes and assets. This has been utilized on a number of railway projects both for the UK and across Europe but can be adapted for other transport scenarios such as CAV, Platooning and Hyperloop. TRIO allows you to model both the technical and operational performance of the railway. The performance of the assets (e.g. train, track, signalling and power) is modelled. The operating strategies (e.g. timetabling, regulation principles) and customer demand profiles are then overlaid on this model. The simulation quantifies the performance of the railway from the perspectives of both the customers and operators. TRIO enables different asset and operational strategies to be evaluated and quantifies costs and benefits to inform a business case.

TRIO would predict realistic operational capacity figures and model passenger flows for Hyperloop.

Hyperloop: Above Ground or Below?

In his proposal, Musk suggested that the cost of land acquisition could be reduced through the construction of Hyperloop on pylons and through the use of existing road and rail routes[26]. Musk implied that landlords would be prepared to sell overhead access and pylon rights for lower prices than would be required for ground level construction of the proposed high speed rail development. However, it is also argued that the high speed rail development could feasibly be built on pylons and that developers have not chosen to pursue this option which suggest that perhaps the cost savings were not sufficient to overcome the additional complexities and costs of elevated construction[27].

Due to the speeds at which Hyperloop will operate, there is a requirement to restrict lateral forces below 0.1g to ensure acceptable levels of passenger comfort[28]. To achieve this, Hyperloop tubes need to be relatively straight. Motorways in the USA are fairly straight which make them ideal land for building a Hyperloop. However, in countries such as the UK, hilly topography (see Figure 1 below); dense urban spaces; high land values; and numerous protected landscapes will be key challenges in the implementation of Hyperloop[29]. It is likely that Hyperloop would have to be built underground, which would affect capital costs and make maintenance and emergency evacuation more difficult[30]. However, the required diameter of the tubes would be much smaller for Hyperloop than those for high speed rail and therefore costs could be reduced. Also, tunnelling could greatly speed up the planning process and reduce issues associated with acquiring rights of way. Regardless of the potential merits associated with tunnelling, there may still be significant challenges in tunnelling in parts of the UK due to local geological conditions[31].

The land issues posed above are a key challenge and will result in the UK taking a cautious approach in the uptake of Hyperloop.

Figure 2: Physical map for the UK

Introducing new infrastructure requires careful management: specification, construction and maintenance strategies and safety assurance. The implications of infrastructure requirements for new technologies must be well understood before they are introduced.

Example Projects

TRL has been supporting the UK road network for 80 years; more recently TRL has been researching the feasibility of integrating wireless and conductive on-road power transfer solutions for electric vehicles on existing UK and European roads, and studying the implications of autonomous vehicle and platooning technology on the performance of UK roads.

Preparing the Strategic Road Network for Electric Vehicles – Feasibility Study – The project aimed to inform Highways England of the feasibility of implementing DWPT Systems on the Strategic Road Network to provide a safe road environment for the projected growth in electric/hybrid vehicles. TRL undertook a comprehensive review and evaluation of all available WPT and DWPT technologies and identified the ones that would be most likely to meet the requirements of highways implementation in the UK. It also performed a detailed and robust impact analysis of DWPT to date, covering elements such user benefits, environmental impacts and road construction costs. TRL coordinated its own research and the work of its partners to deliver a robust feasibility analysis of vehicle integration, grid connection and road integration of DWPT systems.

FeAsiBility analysis and development of on-Road charging solutions for future electric vehiCles – FABRIC (European Commission) - The Project addresses directly the technological feasibility, economic viability and socio-environmental feasibility of dynamic on-road charging of electric vehicles. (both contact and contactless solutions).

ERS – A solution for the future?

(PIARC -World Roads Association) - This project aims to provide a comprehensive summary of the development and implementation of ERS technology around the world. This will enable the current knowledge base and experience in this field to be shared so that the fundamental understanding of how ERS systems can benefit transport systems worldwide is improved. In particular, road administrations will be informed of the feasibility of implementing ERS technology on their road networks and how they can provide a safe road environment for the projected growth in low carbon vehicles. It will produce high level recommendations to support decision-making on infrastructure investment, innovation support, trials and partnerships

Hyperloop: Energy Demand

Musk's proposal detailed a low energy system design for Hyperloop. The system consumes relatively little energy due to rapid acceleration which enables the pods to glide as a passive maglev in a near vacuum, so that only about 10% of the route will consume energy[33]. According to Musk's predicated energy costs per passenger, Figure 2, Hyperloop is estimated to require 50MJ per passenger. This is a significant reduction compared to rail (over 800MJ per passenger) and air (over 1000MJ per passenger)[34]. However, details behind these calculations were not supplied.

These figures compare to other studies such as the findings from NASA which suggest that Hyperloop will be 5-6 times more efficient than air (for short routes) and 2-3 times more efficient than Rail[35]. Virgin Hyperloop One has stated that Hyperloop is more efficient than other high speed modes of transport but that specific energy usage will be dependent upon system requirements and the terrain[36]. Currently there are limited details for the calculation of energy usage, therefore these claims cannot be further interrogated.

In the UK, the government has estimated that operational carbon emissions per passenger for the London to Edinburgh route are approximately 26kg for aviation and 14kg for rail[37]. Based on these figures, it is predicted that the operational carbon emissions per passenger for Hyperloop on the same route could be in the region of 4-7kg.

Further to the low energy design, Musk's proposal also promotes the fact that Hyperloop could be self-sustaining through the exploitation of renewable energy sources. Musk outlined a solar power system for the Hyperloop proposed between Los Angeles and San Francisco which would generate more energy than is needed to operate the system. Based on covering the upper surface of the twin Hyperloop tubes with solar cells, this solar array is projected to supply about 57 MW of electrical power on average, while the Hyperloop is expected to consume an average of only about 21 MW[39]. Whilst the anticipated power generation through solar cells may be plausible for the conditions in California, it is unrealistic in countries at higher latitudes or with less sunny climates such as the UK. However, in reality, regardless of location, powering Hyperloop directly through renewables would be largely inefficient anyway and it would be more cost effective to generate renewable energy through large scale solar arrays (or in the case of the UK, through wind or hydro power) which could be used to power Hyperloop via the grid.

Despite the limited potential of directly powering Hyperloop through renewables, evidence still suggests that Hyperloop could be more energy efficient than other transport modes.

Example Projects

Realistic Energy Efficient Tunnel Solutions – REETS (National Roads Authority) – This project sought to reduce the use of energy associated with tunnel operations. A number of energy-reducing options for tunnels have already been investigated and more are becoming available as technology advances. This project took a whole system approach and considered installation, maintenance and operational costs throughout the asset lifecycle to determine whether a technology will result in an overall benefit.

Life cycle assessment (LCA) of the use of recycled solid waste materials in Asphalt and concrete pavements - This project aimed to conduct a full life cycle assessment (LCA) of alternative materials which substitute for virgin aggregate materials in road pavement structures. Life cycle analysis is an environmental assessment tool. TRL developed a tool to calculate embodied carbon in asphalt pavement known as – asPECT.

Zero Emission Urban Bus System – ZeEUS (UITP for EU) - ZeEUS is testing innovative electric bus and wireless charger technologies in ten demonstration sites across Europe to help facilitate the widespread uptake of electrified bus systems in Europe. TRL led the evaluation of the UK demonstrator in London.

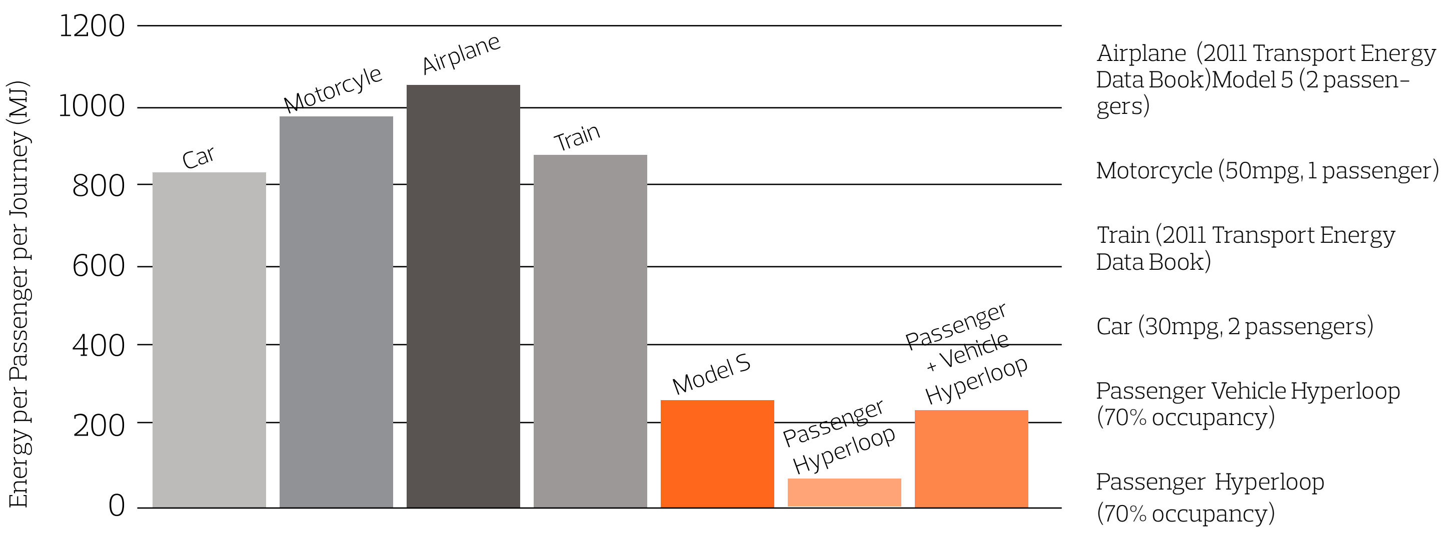


Figure 3: Energy cost per passenger for a journey between Los Angeles and San Francisco[38]

Low emission bus scheme fleet performance monitor (DfT) – TRL is monitoring and evaluating the performance and impacts of low emission buses in 13 locations across the UK. TRL will carry out data collection and analysis of bus and infrastructure performance, cost savings and environmental impacts.

Low emission Freight and Logistics Trial LEFT (OLEV and Innovate UK) – The LEFT project will see trials of vans and lorries running on hydrogen dual-fuel. The aim of the project is to encourage the widespread introduction of low and zero emission vehicles to UK fleets. TRL will carry out data collection and analysis of the performance, cost savings and environmental impacts of the trial vehicles to evidence impact.

TRL Expertise

Evaluating Energy Consumption and CO2 emissions: Through using the TRIO model, TRL would be able to evaluate energy consumption and CO2 emissions.

Whole Life Cycle Analysis: Whilst Hyperloop is proposed to be energy efficient in its operation there has been limited focus on the whole life carbon impact of this system. Construction would require a great deal of materials such as concrete and steel which are high in embodied carbon. If the tubes are underground, tunnelling is also very carbon intensive. A life cycle assessment assessing a variety of environmental impacts over the life time of the system would produce an estimate of the carbon footprint of Hyperloop.

Evaluating the impacts of low carbon technologies: Monitoring and evaluating the energy use and environmental impacts of low carbon technologies such as those proposed by Hyperloop helps evaluate the environmental performance of future Hyperloop systems and identify potential costs savings.

Hyperloop: Cost

One of the key selling points of Hyperloop is its low costs of construction and operation which translates into low ticket prices for passengers. In his proposal, Musk indicated a roundtrip ticket price for Los Angeles to San Francisco of $40 (£29) so that Hyperloop was affordable for everyone. This ticket price was to cover both the operating costs and to amortize the capital costs of the construction over a 20 year period[40]. The calculated construction and land acquisition costs for a Hyperloop passenger service between Los Angeles and San Francisco was $16 million (£12 million) per mile, which was only 10% of the projected construction and land acquisition costs for the California High speed rail Development of $177 million (£132 million) per mile[41]. Musk's proposal offered no specific details around operating and maintenance costs. As the ticket price was relatively cheap and Hyperloop's projected ridership was moderate, we can assume that Musk's projected operating costs are under representative of the true costs. This is likely to be due to the assumption that Hyperloop's largest operating cost (energy consumption) is fully covered by the self-sufficient solar panel system.

Musk's low construction costs have not aligned with projected costs in other commercial proposals. Virgin Hyperloop One gave a presentation citing an average cost for Hyperloop of $25-27 million (£18-£20 million) per mile just for the technology excluding land acquisition. Costs for specific routes proposed by Virgin Hyperloop One have been even higher. The costs of construction for the Abu Dhabi route are currently estimated at $52 million (£39 million) per mile excluding land acquisition[42]. An entirely underwater track from Helsinki to Stockholm was estimated to cost $64 million (£47 million) per mile[43]. Leaked documents from Virgin Hyperloop One indicated a 107-mile loop in California would cost $121 million (£89 million) per mile[44]. Moreover, recent analysis related to a Hyperloop System in Australia found that the cost of the system would be roughly 10 times more per mile than costs quoted by Musk[45]. From this, we can conclude that the cost of implementing Hyperloop is likely to vary significantly in different locations and that Musk's projections were on the optimistic side. Taking into account all the cost estimates, the average construction cost of Hyperloop is $73 million (£53 million) per mile.

Even if construction and land acquisition costs are realistically at the upper end of these projections, placing the cost of Hyperloop at approximately $160 million (£120 million) per mile, these costs would still be comparable with the California high speed rail development of $177 million (£132 million) per mile[46] and would be significantly cheaper than the proposed HS2 Development in the UK of $212 million (£159 million) per mile[47]. However, as discussed previously the land implications related to Hyperloop in the UK are challenging and implementation here would likely require significant tunnelling which would certainly push costs up to the upper end of the scale.

In terms of operating costs, the current model may have been based on the potential for the energy demand to be self-sustaining. As discussed previously, it is most likely that the energy needs would instead be met by the grid and so the operating costs would need to be updated to reflect this. Also, there is a range of other key costs that would need to be considered in any commercial analysis of Hyperloop which may have been overlooked by Musk in his proposal. These include daily management, dispatching and system control; management planning; stations; infrastructure inspection; infrastructure maintenance; and staff employment, insurances and licenses[48].

Musk's proposed $40 (£29) round ticket price has been viewed as ambitious and indeed Hyperloop Transport Technologies have since forecasted a higher cost of a $60 (£43) round ticket for the same route[49]. Even with this uplift, the current capacity levels and the costs associated with capital, labour and maintenance would result in a $60 round ticket price being insufficient to make a sound business case[50]. Whilst these fares could conceivably cover operating costs, they would not be able to cover the costs of construction. Therefore, the implementation of Hyperloop would rely on public funding to subsidize the endeavour[51]. Investment Capitalist Michael Zawalksky predicted that overall revenues generated by the Los Angeles to San Francisco Hyperloop could peak at $1 billion (£698.93 million) a year if a round ticket was priced at $240 (£172) - see demand projection model in Figure 3 below[52]. However, he concluded that an appropriate ticket price to provide assurance on mass market adoption would be between $120-200 (£86-144) for a round trip ticket.

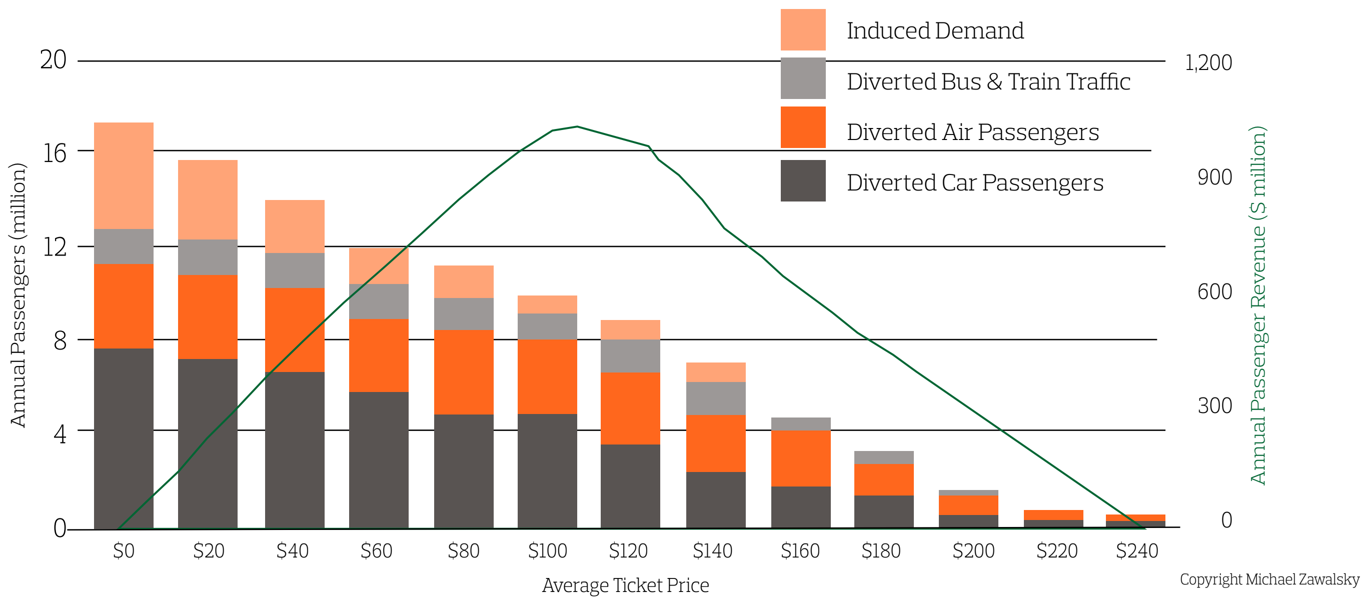


Figure 4: Effect of Hyperloop Ticket Pricing on Revenue

A round trip price of $120-$200 rather than $40-60 would mean that Hyperloop was slightly more expensive than some other transport modes for Los Angeles to San Francisco including the existing train/bus combo with a round trip cost of $118 and flights which vary between $95 (advance) -$116 (next day) for a round trip [54]. However, as Hyperloop would operate at considerably higher speeds, the round ticket price of $120-$200 would still represent good value for money and allow Hyperloop to compete well against other modes.

In the UK, the potential round ticket price for the 414 mile route from London to Edinburgh is estimated to be £93 ($128)[55]. For air the costs would be between £46 – 144 ($66-$206) for both the flight and transfers[56] and for rail the costs would be between £50 – 131 ($72-$187)[57]. The large variance in these figures is due to the fact that discounts are applied to advance tickets. This suggests that Hyperloop may only be competitive in price with existing modes of transport for next day tickets and not advance tickets. However, the estimated UK round ticket price may be inaccurate given the assumptions that: ticket prices would correlate directly with mileage; the ticket prices achievable in the US Hyperloop model would be transferable to the UK; and the Hyperloop terminals would be based within the city, reducing additional transfer costs.

The discussions above indicated that Musk's low projected costs have been understated and in reality costs are more likely to be similar to other forms of transport.

The implementation of Hyperloop would probably rely on public funding to subsidize the endeavour.

Musk's low projected costs have been understated and in reality costs are more likely to be similar to other forms of transport.

The average construction cost of Hyperloop is $73 million (£53 million) per mile.

TRL Expertise

Modelling both the CAPEX and OPEX costs helps optimise a solution. The importance of ticket price over other factors in determining passengers' choice of transport mode is also a critical element of cost.

Ticket Price: $120-200 for round ticket is proposed as appropriate to ensure mass-market adoption. A Choice Experiment with consumer representatives of the mass market would test this hypothesis. This technique allows us to predict uptake of a new product. Within transportation, choice models are particularly used to understand preferred modes of transport (car, bus or train) based on certain attributes (like cost and journey time) and route choices (again based on journey time, levels of congestion or different speed limits).

Construction and Operating Costs: Using TRIO, financial values can be assigned to benefits to analyse the trade-off with the CAPEX associated with asset acquisition and OPEX associated with asset maintenance, staff operations and energy consumption.

Hyperloop: Safety & Security

Musk claimed that the design of Hyperloop was considered with safety in mind from the start and whilst the concept throws up some unique safety challenges, elements of the proposed Hyperloop system would be intrinsically safer than airplanes and trains. He detailed some clear safety benefits related to Hyperloop compared to other transport modes for example, the pods would not interact with transport or wildlife; a fully autonomous system would not be a victim of human error; and due to being built on pylons and the pods being enclosed within a tube the system would be largely immune from adverse weather events. He also addressed some key safety challenges including:

1) passenger emergencies, which are supported by multiple emergency braking systems to bring pods to a safe stop;

2) the structural integrity of the tube, which is constructed from strong thick steel which would be difficult to puncture, but in the event of a puncture would present no harm to passengers and result in slower pod speeds due to the higher air pressure within the tube, and may be overcome by the air pumping system and pods which are built to withstand variable air densities; and,

3) pod depressurisation, where in the event of a minor leak, the on board environmental control system would maintain pressure with reserved air, and in the case of significant depressurization, oxygen masks would be deployed .

Whilst some elements of safety were discussed by Musk, there were some key gaps in information on the risks of the system. Thus many aspects related to safety of the Hyperloop have been raised by those reviewing the potential of the system. The business model of Hyperloop relies on small headways between pods, which causes safety concerns if the system fails, and would require a full system shutdown should an emergency stop be triggered by a single pod. This particular element highlights the current single point failure within the proposed systems which brings the practicalities of operation and maintenance into question. Further to this, pods travelling at 760mph will generate kinetic energy with an equivalent (depending upon the likely weight range) of somewhere between 75 and 200kg of TNT and in the event of an accident would pose too big a risk to pass through urban areas without becoming a big safety concern .

In order for new technologies to be successful, people have to perceive them to be safe. Communicating the safety risks and measures to mitigate these will be a key factor influencing the success of Hyperloop and will need to be managed carefully for all stakeholders including passenger and regulators. Whilst it is possible that safety concerns could be adequately addressed in time, the vast number of safety concerns at present hinders the chances of a passenger Hyperloop system being ready for deployment within the next decade and certainly the 2021 launch date seems unrealistic.

TRL Expertise

The design of the built environment can also be used to deter or prevent attack. TRL has worked extensively in infrastructure protection and is well placed to understand those approaches which ought to be used.

TRL Expertise

Safety review of system: A safety review of the Hyperloop, highlighting the risks and the likely implications (both to passengers and pod), would be required before it was built in the UK. This would include a review of major incidents such as crashes and minor incidents such as bangs to the head. Given the extreme speeds and built environment of Hyperloop, TRL's experience in working in relation to extreme scenarios would be highly relevant; for example, we studied the impact to people in blast conditions for Imperial College.

Design of Pod: Collisions on Hyperloop would be very serious and most likely fatal for passengers. However, there could be instances of harsh breaking/deceleration that would far exceed levels experienced in cars. The design should take into account the crashworthiness of Hyperloop, in particular the external construction of the pod and tube, the interior design of the pod, and optimal seating arrangements to enhance safety. Pod design would have to be subjected to performance testing on cushioning and appropriate restraint systems (e.g. seat belts and head restraints) in order to minimise injury to passengers.

Design of pods and stations: The reactions, preferences and behaviour of transport users play a critical role in effective, safe transport system design. A human factors team would risk assess and input into the design of pods and station layouts to improve levels of safety.

Safety Standards: Introducing an entirely new form of transportation into a world ruled by regulation will be one of the biggest challenges for the implementation of Hyperloop. The existing regulations are out of date and not supportive of innovative technologies. Safety standards for an entirely new mode of transport would have to be developed, implementated through legislation and accepted by industry.

Type Approvals: As a new mode of transport, type approvals for manufactured items e.g. chairs and tables and restraint systems within Hyperloop will have to be devised to ensure their systems meet the required (new) legal standards.

Perceived Safety: Perceived safety can be a barrier to any travel mode choice. It is therefore necessary not only to understand the actual safety risks posed to passengers of Hyperloop, but also the most salient safety concerns perceived by passengers. This requires robust attitudinal research, ideally using a mix of qualitative and quantitative research.

Testing and Simulating: New technologies and designs need to be tested and quality assured prior to use, from component parts e.g. chairs and tables and restraint systems, to entire vehicles/trains (which has parallels to Hyperloop). Typically, a Hyperloop pod would be replicated, and testing of component parts in crashes at low speeds would be undertaken, with the results being fed into a model simulating crashes at high speeds.

Example Projects

Qualitative Passenger Behaviour Study (Network Rail): TRL were commissioned to study the causes and behaviours that contribute to incidents at the Platform-Train Interface (PTI), in context of a number of high profile PTI-related incidents in the last decade. By applying our expertise in understanding human factors in transport research alongside our technical knowledge, we provided insight to inform Network Rail's approach and communications to help prevent future incidents.

London Bus Safety Trial (TfL): TRL has conducted an analysis of bus incidents that lead to passenger injuries including those related to braking events. This work is helping to inform technical recommendations in relation to their bus safety standards. The methods utilised could be applied to determine the balance between deceleration and risk to passengers. The equivalent work for the Bus Safety Standard is an evaluation of the balance between Automated Emergency Braking (AEB) and the risk to bus passengers, e.g. brake to avoid a pedestrian but injury several people on board.

The General Safety Regulation (European Commission, DG GROW) – The General Safety Regulation is reviewed every 3 years to include new safety features to improve occupant safety and protection of vulnerable road users. TRL led the study to review the feasibility and cost-benefit ratio of over 50 candidate measures to determine those that are most acceptable to industry and most beneficial to people. This information will enable prioritisation of future legislation relevant to vehicle safety and to the relevant EU type approval requirements.

New Safety Regulations for Child Seats (European Commission) – TRL has advised on new regulations for child car seats.

Hyperloop: Passenger Comfort & Experience

Further to the safety challenges, there have been concerns raised about the passenger experience of riding in narrow, sealed and windowless pods inside a sealed steel tunnel that is subjected to significant acceleration forces; high noise levels due to air being compressed and ducted around the pods at near-sonic speeds, and the vibration and jostling[58].

The impact of the windowless pod design on passenger comfort has been recognised as an issue that needs to be addressed. The earliest London deep tunnel trains had windowless carriages which quickly became known as the 'padded cells', and the line as the 'sardine box railway' due to feelings of claustrophobia caused by the lack of windows[59] . To overcome this, companies advancing Hyperloop are working closely to develop augmented reality solutions such as window scenery simulation. This could offer a view of the outside world for riders interested in watching scenery and help reduce feelings of claustrophobia[60].

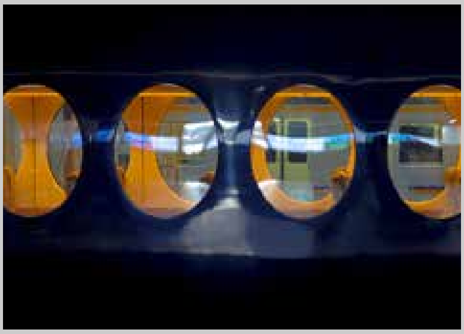
Musk described the experience of riding Hyperloop to be similar to flying in a passenger plane. The acceleration and deceleration would be gradual and the experience would mimic flying in a plane where passengers would only be submitted to an additional 0.1 to 0.3 Gs when the pod starts and stops. These proposals are deemed acceptable however, there are concerns related to lateral acceleration and passengers being uncomfortable traveling at speeds of 760mph around curves in the track. The top speed of the fastest commercial bullet train (Shanghai Maglev) hovers around 300mph and requires a banked curve with a radius of 4400 meters to ensure the comfort of passengers. So Hyperloop will have to either keep the track straight or make huge curves to prevent uncomfortable braking speeds[61]. Whilst banking would reduce lateral acceleration, it would introduce roll acceleration. The combination of compensated-lateral acceleration and roll acceleration can cause conflict in the vestibular sensory system which may, in some circumstances, increase motion sickness.

At the speeds proposed for Hyperloop, there are limited studies on the vibratory effects on the human body particularly if there is a hidden medical condition such as weakened blood vessels. This field of human factors sciences has been extensively applied within the rail industry, and continues to be an area of interest within the sector, therefore it is anticipated that this will require extensive further research to fully determine the effects[62] . Also, there is still a need to better understand the noise impact for passengers travelling in the Hyperloop pods[63] .

In existing modes of transport, passengers tend to rate rail as being quite comfortable due to the available leg room, ability to walk around and work productively, whereas air travel is commonly the target of complaint in relation to comfort[64]. For Hyperloop, there are still unanswered questions related to passenger comfort and whether conditions would be acceptable to a large enough proportion of the target travelling population. The motion environment will be unknown whilst Hyperloop remains a concept, but given the design of the system it is highly likely to be unique. Therefore, proper assessment of the impact of the motion stimuli on passenger comfort is crucial. Further to this, a challenge remains in the ability to keep the track straight to maintain acceptable levels of acceleration and this will be particularly problematic for countries like the UK.

TRL Expertise

Design of Pod: Passenger comfort is a combination of multiple constructs, including seat comfort, thermal comfort, crowdedness, psychological distress, noise, motion sickness and access to facilities. The design of the pods is integral to this. The use of simulators and simulated engineering models would support the design of the pod to ensure passenger comfort.



Acceleration and braking: Hyperloop will be at high speeds and in a controlled environment but there still may be exceptional circumstances when emergency braking might be needed – how should a pod respond? And what will be the effect for the passengers? What is the optimum acceleration to full speed for passenger comfort? This is most relevant in the start/finish phases of journey where acceleration and deceleration are limited.

Noise Impacts: An impact assessment would normally be conducted to determine the impact of noise for passengers travelling in the Hyperloop pods and for local communities where Hyperloop infrastructure connects with their environment.

Mental Health and Transport: Our mental health can heavily influence our travel mode choices, and our transport systems can influence our mental health. Understanding these factors ensures that a new mode of transport takes into consideration not just environmental factors but insuring that it is accessible to all. In addition, by understanding the factors that influence travel mode choice across different populations this ensures higher uptake and minimises the negative impact of our transport systems on mental health and wellbeing.

Motion Sickness: The motion environment to which passengers will be exposed is currently unknown, but is likely to be unique. This coupled with the lack of visual cues, or the presence of artificial visual cues, will have a substantial impact on passenger comfort, and could lead to motion sickness. Research will ensure that these factors are fully understood.

Vibration Impacts: Vibration will have an impact on comfort. Since Hyperloop is only a concept at the moment we can't be sure what the frequency spectrum will look like, but possibly the vacuum could serve to filter out high frequency vibration, while potentially exacerbating low frequency vibration. Research would determine the effects of vibration on Hyperloop passengers.

Passenger Accessibility: Accessibility for those with disabilities would be a critical factor to understand if the technology is to have an impact on travel for disadvantaged groups. TRL has undertaken extensive research over several decades into the interaction between passengers, including those with specific needs and disabilities, and the built environment to create a deep understanding of the relationship and how to design fnew modes of transport to be inclusive.

Example Projects

Mental Health and Transport (TRL Reinvestment) – This reinvestment project is investigating the relationship between mental health and transport. As part of this project, a choice experiment is being utilised to look at the relationship between journey mode choice and various attributes associated with stress and anxiety. This technique allows us to explain and predict people's decisions within a particular context. Our work has enabled us to build links with mental health organisations, key academics and trade bodies (Anxiety UK, Place 2 Be, UCL, FTA), all of which have showed and pledged their support for future work and collaborations.

Conclusion

- **Real-world trials will prove the vaiidity of the concept**
- **Cost of construction may undermine economic benefit**
- **Hyperloop for the UK at least 20 years away**
- **Viable future mode of transport to cross borders in Middle East**

This article has critically examined the viability of Hyperloop to determine its potential as a new mode of transport. The discussion suggested that Hyperloop would rival both rail and transnational air travel in relation to speed. Due to the limitation regarding a single point origin and destination for any given Hyperloop system, Hyperloop is best placed to connect major cities, supported by rail providing inter-modal connections to Hyperloop hubs. As indicated by the analysis, the potential capacity of the system exceeds that of competing modes within the UK (falling short of high speed rail in the U.S.), however the realistic capacity needs to be determined in relation to pod speeds and headway. Hyperloop also provides solutions to current airport capacity as an inter- and intra- airport connecting service to create large international transport hubs located in various regions of a country, thereby fully utilising national airport capacity and overcoming the need for the construction of additional runways . The speeds offered by Hyperloop could also have wider implications for the economy by enabling labour and commercial markets to integrate within the existing centres of commerce, which would allow countries to grow by fully utilising skills, workforces, and resources nationwide to remain competitive. However a barrier to this integration would be the cost of travelling on Hyperloop, which would far exceed the cost of the local journeys into economic centres and would be an unacceptable commuting cost for the majority of the population.

Hyperloop's low energy design may help to reduce the impact of carbon and other air pollutants, however the full energy demand of the proposed systems is yet to be determined until a real-world demonstration is established. Hyperloop will likely play an important role as both a solution to alleviate existing- and growing- travel demand on the current transport infrastructure and as a disruptor to the shape of travel demand on existing modes of transportation. Assuming the energy requirements are low, Hyperloop could also serve to reduce the carbon impacts associated with transport.

Whilst Hyperloop offers key benefits in relation to speed and energy, other factors raise doubts over the viability of Hyperloop as an alternative transport mode. Musk's claims related to low costs are currently unsubstantiated by the evidence, with multiple sources reporting significant variations in cost estimates differing in orders of magnitude. However, as proven by Musk's previous business ventures such as Tesla, a lack of financial viability in new transportation concepts is not necessarily a barrier to their implementation. Furthermore, it may be argued that with new and innovative concepts such as Hyperloop, accurate costing of the concept, and the quantification of important elements such as safety, may be unachievable in the absence of a large scale real-world demonstration.

In addition to the economic and engineering issues, there are significant barriers to overcome regarding human factors including aspects such as physical and mental passenger comfort; noise, vibration, motion sickness, accelerating and decelerating forces; and the mental strain of travelling in an enclosed environment. Further, we don't yet understand the perceived safety, and the perceived benefits of this mode which in both cases will need to be well communicated to the travelling public.

The challenges of landscape topography, which would require large-scale expensive tunnelling, present the most significant barriers to the implementation of Hyperloop in the UK. Furthermore, the imminent / near-future development of a Hyperloop system in the UK is unlikely in relation to the Department of Transport's (DfT) opinion that an operational Hyperloop system is likely to be at least a couple of decades away; and their commitment is instead: to monitor the development of Hyperloop; support the design, development and delivery of Hyperloop; and continue to explore the potential application of Hyperloop as a transport mode within the UK.

Whilst the value proposition for Hyperloop is currently limited in the UK context, this technology is being progressed at a rapid pace by many other countries across the world. For example, Saudi Arabia is exploring the potential of implementing Hyperloop to link the capital city Riyadh to Jeddah, their major commercial hub. Hyperloop would also make it possible to enhance links across borders and position the country as the gateway to three continents. The strong political and economic support, combined with the country's landscape, make the opportunities for the implementation of Hyperloop more favourable in Saudi Arabia.

Due to the aforementioned challenges, it seems unlikely that there will be fully commercialised Hyperloop system in place by 2021 within the UK. However it is feasible that through further research, testing and refinement, the Hyperloop concept could progress in some locations and will likely change both the face of the transport industry, as well as socio-political boundaries and structures as we know them.

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